

**COMOTH: A BIM- SUSTAINABILITY INTEGRATED MODEL TO SELECT
ASSOCIATED CONSTRUCTION METHODS AT THE CONCEPTUAL DESIGN
STAGE OF BUILDINGS**

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ABSTRACT

COMOTH: A BIM- Sustainability integrated model to select associated construction methods at the conceptual design stage of buildings

Construction techniques and building practices have evolved significantly, driven by a growing focus on the principles of sustainability and circular economy, particularly in energy and resource conservation and innovative construction methods. However, in construction, sustainability is a complex concept that integrates economic efficiency, environmental performance, and social responsibility to optimize technical innovation, architectural quality, and design flexibility. Therefore, sustainable construction involves the use of construction processes, materials and methods to enhance sustainability efforts. BIM is a concept used to create and monitor a project's digital information throughout its life; it integrates numerous sustainable design criteria, contributing to sustainability's social, environmental, and economic agenda. Conventional on-site construction, modular prefabrication, and 3D concrete printing-based construction are currently the three essential methods used in the construction industry. However, in adopting the Industrial Production layer of Construction 4.0 (i.e., modular prefabrication, 3D concrete printing, and BIM), scholars are steadily addressing sustainable design, high-performance buildings, and circularity in construction and their associated ambiguities, questions and conflicts as a solution to the sustainability of buildings that meet the consistent demand for living space for the globally growing population. Hence, there is a need to define the sustainability challenges, determine the sustainability assessment methods, select its essential indicators and criteria, align the project's objectives with the various needs of stakeholders, and transform these inquiries into efficient

design and construction strategies because most of the existing models have their sustainability's frameworks primarily based on the conventional design and on-site construction methods.

Consequently, this thesis presents the detailed methodology adopted in the development, testing and verification of an integrated model to be used for the selection of associated construction methods at the conceptual design stage of buildings by linking BIM and sustainability tools to help professionals during the early design stage. The said methodology includes a broad literature review to collect the necessary data and information needed for BIM (Autodesk Revit©) and sustainability tools, model development and implementation. The presented model is designed in a modular format and consists of six modules: 1) a database management system (DBMS) module for storing and retrieving the collected design data; 2) a decision support system (DSS) module; 3) an energy and thermal simulation module that facilitates the analysis of the energy performance of buildings; 4) a circular economy (CE) module for construction and deconstruction waste (CDW) management strategies; 5) a Lifecycle Assessment (LCA) module, which is used to evaluate the environmental impact of the various stages of the building project; and 6) a Lifecycle Cost Analysis (LCCA) module, to facilitate a detailed valuation of the financial implications of the different design options throughout its life cycle. The developed model will contribute to advancing the process of developing a versatile and flexible BIM-sustainability integrated model by providing users with more options during the sustainable design process and, afterwards, identifying the associated construction methods for buildings.

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Dedication

To my husband,

McNeil Ayuk

and

my son,

Aleluia McNeil-Ayuk

I love you both!

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List of Abbreviations

3D	Three Dimensions
AEC	Architecture Engineering and Construction
AGC	American General Contractors
AM	Additive Manufacturing
ANSI	American National Standards Institute
ANP	Analytic Network Process
API	Application Programming Interface
AW	Annual Worth
AV	Annual Value
BEES	Building for Environmental and Economic Sustainability
BEPAC	Building and Environmental Performance Assessment Criteria
BIM	Building Information Modeling
CAD	Computer-Aided Drafting
CDE	Common Data Environment
CDW	Construction Deconstruction Waste
CaGBC	Canadian Green Building Council
CE	Circular Economy
COMOTH	Conventional Modular Three-D
CIC	Computer Integrated Construction
CSI	Construction Specification Institutes
DBMS	Data Base Management System
DEMATEL	Decision-Making Trial and Evaluation Laboratory
DfD	Design for Deconstruction
DM	Decision Making
DOE	Department of Energy
DSA	Differential Sensitivity Analysis
DSS	Decision Support System

DXF	Drawing eXchange Format
DWG	Drawing
EA	Energy & Atmosphere
EST	Energy and Thermal Simulation
EI	Environmental Impact
FANP	Fuzzy Analytic Network Process
FPP	Fuzzy Preference Programming
GA	Genetic Algorithm
GBCI	Green Building Certification Institute
gbXML	Green Building eXtensible Markup Language
GIS	Geographic Information System
GPS	Geographic Positioning Satellite
GSA	General Services Administration
GUI	Graphical User Interface
GSA	General Services Administration
IAI	International Alliance for Interoperability
IBC	International Building Code
IE	Impact Estimator
IAQ	Indoor Air Quality
ID	Innovation in Design
IDE	Integrated Development Environment
IDF	Input Data File
IDM	Information Delivery Manuals
IEQ	Indoor Environmental Quality
IES	Integrated Environmental Solutions
IFC	Industry Foundation Class
IPD	Integrated Project Delivery
ISO	International Organization for Standardization

JPG	Joint Photographic Experts Group
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Analysis
LCC	Life Cycle Cost
LCI	Life cycle inventory
LCIA	Life Cycle Impact Assessment
LEED	Leadership in Energy and Environmental Design
MADM	Multi-Attribute Decision-Making
MARR	Minimum Attractive Rate of Return
MCDM	Multiple Criteria Decision-Making
MEP	Mechanical Electrical and Plumbing
MR	Material& Resources
NIBS	National Institute of Building Science
NIST	National Institute of Standards and Technology
NPV	Net Present Value
ODBC	Open Database Connectivity
PDF	Portable Document Format
PV	Present Value
QTO	Quantity Take-off
QTY	Quantity
RFA	Revit Family File
RFI	Requests for Information
RVT	Revit Project File
SIR	Savings/Investments Ratio
SQL	Structured Query Language
SS	Sustainable Site
STL	STereoLithography
TBL	Three Bottom Lines

TFL	Triangular Fuzzy Number
USEPA	United States Environmental Protection Agency
USGBC	United States Green Building Council
VMC	Volumetric Modular Construction
VOC	Volatile Organic Compound
VRE	Virtual Reality Environment
WASPAS	Weighted Aggregated Sum-Product Assessment
WBDG	Whole Building Design Guide
WBS	Work Breakdown Structure
WCED	World Commission Created on Environment and Development
WE	Water Efficiency
XML	Extensible Markup Language

CHAPTER 1

Introduction

1.1 General overview

The AEC industry is in need to adopt a focused approach to establish strategies for the design, construction, and deconstruction of buildings to improve its sustainability. While sustainability is considered a long-term goal, sustainable development refers to the many possible processes and pathways to achieve it (Jeronen, 2013). Some of the possible processes to achieving sustainability in buildings include: i) employing new technologies for their design, construction, and deconstruction; ii) using suitable materials to reduce environmental impact; iii) adopting strategies to manage tight construction budgets and reduce the lifecycle cost; and iv) adopting greener development of affordable urban spaces. However, external market factors, combined with fragmented and complex industry dynamics and an overall risk aversion, have made these changes difficult and slow to achieve (Ribeirinho et al., 2020).

Sustainable design strategies have been developed in response to the worldwide increase of awareness and concern regarding the negative environmental impacts of the building industry (Griffin et al., 2010). It is seen as the central concept of sustainability that is required to achieve sustainable buildings. Its objectives are: 1) to improve the efficiency of the natural resources throughout their life cycle; and 2) to create livable, comfortable, and safe facilities while minimizing their impacts on the society, the environment, and the economy. The environmental criteria include sustainable sites, water efficiency, energy and atmosphere, materials and resources, while the economic one focuses on the efficient use of resources and their lifecycle cost, whereas the social criteria cover the indoor air quality, innovation and the design process (Gültekin and Yavaşbatmaz, 2013). Previous studies have made valuable contributions in integrating BIM and

sustainability into the design, construction, operation, and demolition of the built environment, among others (Wong and Fan, 2013; Jalaei and Jade, 2013 and 2014; Alwan et al., 2014; Abanda et al., 2017; Pomponi and Moncaster, 2017; Pedro et al., 2018). However, there is still a need for advanced studies on sustainability and how it affects today's innovative construction methods of buildings.

Sustainable building approach also addresses the selection and use of materials by promoting less waste generation through a combination of improved construction materials maintenance and waste management strategies (reduce, reuse, and recycle) (Pacheco-Torgal and Labrincha, 2013). The selection of sustainable materials has a profound influence on the sustainability of a building; they impact the building's thermal performance, including internal comfort, acoustics, and durability. Materials effect in a building is closely associated with the requirements they fulfill and are classified into its functional and sustainability-related requirements. The functional requirements are primarily based on the building's regulations, such as structural, sound, thermal, durable, and cost-effective, while sustainability-related requirements include embodied energy, low maintenance, less harmful, and the ability to be recycled and reused (Goodhew, 2018). Therefore, the selection of sustainable building materials is a significant way to incorporate sustainable principles into building design (Akadiri et al., 2013; Chen et al., 2019). Various decisions govern the selection of materials in order to sustain a sustainable building at its different stages, which involve multiple stakeholders over its life cycle. A BIM-based decision support system (DSS) for multi-criteria decision-making technique (MCDM) is effective for the materials' selection. Studies showed that such systems are appropriate for evaluating, comparing, and selecting adequate, sustainable building materials and components among different alternatives (Jalaei et al., 2015; Akanmu et al., 2015; Mahmoudkelaye et al., 2018; Rahim et al., 2020).

Environmental, economic and social sustainability indicators have associated criteria such as environmental impact, lifecycle cost analysis, building operational energy demand, thermal comfort etc. and various sub-criteria, which are used to address multiple aspects of sustainability in a building by using assessment systems to evaluate and justify it.

Construction techniques and building practices have advanced over the years with increased interest in sustainability, especially in energy conservation and new construction methods. Sustainable construction involves the use of construction materials and methods to enhance the sustainability efforts. Traditional construction method is wasteful (Love 2002), which significantly impacts the environment, but other different construction methods would lead to different sustainable outcomes (Tam et al., 2002; Kubba 2010; Tsai et al., 2013). Conventional on-site construction, modular prefabrication, and 3D printing-based construction are currently the three essential methods used in the building construction industry. As the evolution in construction techniques continues to transform construction sustainability, modular prefabrication construction begins to be the most popular form of off-site construction production system; it is promoted as a sustainable alternative to the conventional in-situ construction (Mao et al., 2013; Hammad et al., 2019). The method consists of several processes where components of a building are manufactured in an off-site factory, transported, assembled and installed on-site (Bernstein et al., 2011; WBDG, 2016). The modular structures can be manufactured for temporary or permanent use. The technology has proven to be a sustainable alternative due to its potential to effectively remedy the existing challenges facing the construction industry today, such as high costs and shortage of labour. Hence, modular construction is beneficial to owners and designers because it promotes social, economic, and environmental criteria in construction.

Similarly, three-dimensional (3D) printing, also known as additive manufacturing, is another construction method that can increase productivity and mitigate the growing need for housing while reducing environmental, social, and economic impact. These emerging technologies that aim at digital fabrication may represent a new paradigm in the building construction industry. It will fundamentally change how the AEC industry designs, builds, delivers and deconstructs for the future. The capability of this technology, once matured, can revolutionize the AEC industry and the construction market by reducing construction time and cost, providing freedom of shape, and integrating functionality for sustainability (Kothman and Faber 2016). In addition, it can reduce material waste, decrease labour costs and expedite production due to its speed, direct data conversion, ability to handle complex geometry and high accuracy (Camacho et al., 2018).

Circular Economy (CE) is revealed as an effective strategy for achieving sustainability in building construction. Numerous studies have been conducted on the successful application of the CE concept in various industries ever since it gained the attention of researchers and the industry due to its significant potential, as reported for other sectors. Geissdoerfer et al., (2017) described CE as a recovering system in which resource input and the output from waste, emission, and energy are minimized through the processes of slowing, closing, and narrowing energy and material loops. CE is implemented throughout a building's lifecycle by using various concepts to enhance its sustainability (Adams et al., 2017). For example, at the design stage (Design for deconstruction (DfD)), at the construction stage (off-site construction or prefabrication), and at the deconstruction stage (selective disassembly). Modular off-site and 3D printing prefabrication construction methods are adequate methods that can implement CE since waste from construction activities is reusable through the closing resource loops of the CE principle, which is known as recycling.

Hence, the fundamental principles of CE start with designing out waste, keeping products and materials in use, regenerating natural systems, cradle-to-cradle, and regenerative design.

Additionally, with the present innovation era in science and technology that play a critical role in supporting initiatives and transition toward sustainable development (Chong and Wang, 2016); BIM is becoming the foundation of innovative digital transformation in the architecture, engineering, and construction (AEC) industry (Autodesk, 2021). BIM is a concept used to create and monitor a project's digital information throughout its life; it integrates numerous sustainable design criteria, contributing to sustainability's social, environmental, and economic agenda (Azhar et al., 2011). BIM naturally captures data needed to support sustainable design, improve building performance, reduce the consumption of non-renewable resources and waste minimization, and create healthy and productive environments at various design stages (Wu et al., 2015).

Furthermore, it allows multi-disciplinary information to be superimposed into one model, which creates an opportunity for the sustainability measures and analysis to be integrated with the design process (Lu et al., 2017). Engineers use BIM for design performance modeling (DPM) during the conceptual design phase to make cost-efficient decisions by predicting project performance concerning energy efficiency, thermal comfort, natural ventilation, and daylighting, among others. Integrating BIM with lifecycle assessment tools helps in quantifying the environmental impact of materials in a 3D design model, and it integrates all the building component's costs into that model's database to allow owners to know the running cost of a proposed building during the design stage. It effectively allows building designers to predict the life cycle costs at the conceptual design stage and select the most economical and efficient option. Modular prefabrication and 3D concrete printing construction continue to have the potential to improve the challenges associated with the traditional building construction method. Modular off-site prefabrication and BIM

integration are identified areas that have prospects to drive efficiency and improvement for the construction industry (Abanda et al., 2017). Similarly, BIM has proven to be an effective method to facilitate the implementation of 3D printing in the construction industry, which can be employed for small and large scale buildings (Wu et al., 2016). BIM can also facilitate data management in identifying building components that can be reused and/or recycled in advance, including the associated risk and cost in disposing waste at the deconstruction phase of a building (Jayasinghe and Waldmann 2020; Liu et al., 2015).

Thus, this thesis introduces the development of an integrated model that couples BIM and sustainable design for buildings that automates the evaluation and selection of associated construction methods (conventional, modular, and 3D printing) at the conceptual design stage. The said model will allow designers to assess different design alternatives at the early design stage of the building, which leads to a suitable construction method. Database management system, Decision Support System, Operational energy Analysis, Circular Economy, Lifecycle Assessment, and Lifecycle Cost Analysis are the six modules that are incorporated and used by the model to execute all the necessary calculations, evaluations, analysis, and simulation.

1.2 Problem statement

Evidence retrieved from the literature shows that there is still a conflict in understanding sustainability problems (Lu et al., 2017; Arowoshegbe, 2016; Conte, 2018; Al-kodmany, 2018; Maltese et al., 2017; Chong et al., 2017; Schroeder, 2018). Therefore, there is a need to define the sustainability challenges, determine the sustainability assessment methods, select the indicators and criteria, align the project objectives with the various needs of stakeholders, and transform these questions into design strategies (Schroeder, 2018). Moreover, researchers are steadily addressing sustainable design, high-performance buildings, and circularity in construction and their associated

ambiguities, questions and conflicts as a solution to the sustainability of facilities that meet the consistent demand for a living space for the increasing world population (Sanhudo and Martins, 2018; Ilhan and Yaman, 2016; Chong et al., 2017; Chang et al., 2017; Raouf and Al-Ghamdi, 2018). Sustainability in construction is a complex concept that integrates economic efficiency, environmental performance, and social responsibility to effectively use technical innovation, architectural quality, and design flexibility. Therefore, several methods and systems have been applied in the construction industry to analyze sustainable construction practices and evaluate the environmental performance of buildings. While BIM is a concept used to create and monitor the project's digital information throughout its life, it integrates numerous sustainable design criteria that contribute to sustainability's social, environmental, and economic agenda (Azhar et al., 2011). BIM also allows for multi-disciplinary information to be superimposed into one model, which creates an opportunity for sustainability measures and analysis to be integrated within the design process (Lu et al., 2017).

However, reviewing the existing sustainability tools, models, and frameworks reveals the existence of fundamental problems in sustainable design at the conceptual design stage. First, despite of the general knowledge and the many significant successes in the development of sustainability models, such as integrating BIM and sustainable design (Jalaei and Jade, 2013; 2014; 2015; Alwan et al., 2014 etc.), many of these models' frameworks are primarily based on the conventional design and on-site construction methods. Whereas traditional non-sustainable design, the sustainable conventional design and the on-site construction methods associated with the cost and schedule overruns are caused by the design complexities, procurement documents, and enhanced performance requirements (Raouf and Al-Ghamdi, 2018). Second, none of the existing integrated sustainability models provide options for selecting the efficient and sustainable

construction methods at the conceptual design stage. Studies related to the integration of BIM and off-site prefabrication (modular and 3D printing) mainly focus on comparing modular and conventional or 3D printing with the traditional construction methods to justify their sustainability based on the selected sustainable design criteria or simply on elaborating benefits of BIM for off-site construction. Modular off-site prefabrication and 3D printing construction are considered cleaner production methods, critical for industrialized construction (construction 4.0) and significant for facilitating the adoption of sustainability in the construction industry. Third, despite that, the current efforts demonstrated in achieving an acceptable sustainability level through the integration of assessment systems for certification in the AEC industry, there is a need for a model that incorporates additional economic sustainability dimensions because the literature reveals that most sustainability assessments favors environmental sustainability over economic and social sustainability. Previous studies indicated that reusing materials and components in construction can possibly target about three billion tons of raw materials globally, representing significant economic benefits, approximately 40 to 50% of the total flow of the global economy (Cai and Waldmann, 2019; Bertin et al., 2020). Up to 95% of reusable building components could be returned to the market at the end of their previous service life (Galvez-Martos et al., 2018). Until present, studies on quantifying the circular economy concept, such as indicators, frameworks or models in the AEC industry, are not entirely established (Mhatre et al., 2021). Furthermore, circular construction principles and sustainable construction methods need to become central parts of the building project's process (Shiers et al., 2006; Kibert 2007; Sassi 2008; Volk et al., 2014; Smith and Hung 2015), because of their capability in reducing environmental impacts and increasing economic benefits (Smith and Hung 2015; Sanchez and Haas, 2018).

Therefore, this study presents a straightforward methodology for developing a BIM-based sustainable design model that integrates sustainability indicators and criteria, including circular economy concept, to enhance construction sustainability for reliability of decision-making at the conceptual design stage of buildings through (1) design (using Design for Deconstruction (DfD) concept that integrates the circular construction); (2) construction (using sustainable construction methods that can standardize, prefabricated components and 3D concrete printing); and (3) end-of-life (using selective disassemble, and BIM-circular economy tool for construction and deconstruction waste (CDW) management). Note that decision-making at the conceptual design stage is a critical part of the design process. This stage involves making high-level decisions that significantly influence the overall direction, feasibility, and success of a project. Initial ideas and concepts are evaluated, refined, and selected based on limited fundamental project information. Hence, the methodology considers sustainability throughout the lifecycle of the building but explicitly determines and incorporates the end-of-life sustainability requirements at the design stage. The successful development of the integrated BIM and sustainable design model for buildings will automate the evaluation and selection of associated construction methods (i.e., conventional, modular, and 3D printing).

Furthermore, the model will allow designers to evaluate different design alternatives through an enhanced decision support system at the early design stage of the project's life, which will lead to a suitable construction method.

1.3 Research objectives

The main objective of this study is to present a methodology for implementing a flexible and adaptable integrated design model that automates the evaluation and selection of associated construction methods, namely conventional, modular, and 3D concrete printing. This can be

achieved by enabling users to connect their sustainable design and select the suitable construction method through six interrelated modules by using the functionalities and capabilities of BIM tools in a synthesized environment that leverages the integration between BIM, sustainability indicators and circular economy for waste management strategies. Furthermore, the proposed model is designed in a modular format consisting of six modules that are dynamically related to each other, thus making it unique and flexible for users to assess different design alternatives within an embedded decision support system at the conceptual design stage of buildings, which will lead to a suitable construction method. The main objective of this study, as stated above, incorporates the following under-listed sub-objectives:

Sub-objectives 1: Provide designers with a tool to help them assess different sustainable design alternatives and construction methods at the early design stage based on the integration of BIM with sustainable design criteria for buildings, which will lead to a suitable construction method.

Sub-objectives 2: Customize the API's of BIM tool (i.e. Autodesk Revit) to enable users to connect their sustainable design and subsequently select the suitable construction method through the different modules from within BIM tools, either by enhancing its existing functionalities or by developing new functions for the integrated model in the form of a plug-in.

Sub-objectives 3: Utilize data, tools, models, and evaluative frameworks to perform necessary calculations, analysis, and simulations based on the sustainable design criteria to make decisions related to the selection of suitable alternatives.

Sub-objectives 4: Develop a decision support system (DSS) to help the project team select the construction materials and components that are associated with the construction methods based on the predefined sustainability indicators and criteria during the conceptual design stage.

1.4 Research methodology

A detailed methodology is developed to achieve the set main objective and its incorporated list of sub-objectives. Figure 1.1 illustrates the adopted methodology. The integrated model for enhancing building sustainability based on their construction method is designed and developed in a modular format, domiciling a 3D BIM model and incorporating indicators and criteria. The development and implementation of the design model are achieved by utilizing the existing and customized functionalities of BIM and sustainability design tools and data in order to automate the evaluation and selection of associated construction methods. This will provide designers with a wide range of options to make selections and assess design alternatives at the conceptual stage.

1.4.1 Literature review

A broad review of the existing literature is conducted on various related topics covering the following areas: Sustainability: dimensions, development, tools, indicators, criteria, design and construction methods, including decision support systems. BIM: practice, implementation, tools and file exchange format. BIM Sustainability integration: Integration and interoperability processes with the individual modules such as DBMS, Energy and thermal simulation, Lifecycle assessment, Lifecycle cost Analysis and Circular Economy for design, construction and deconstruction waste minimization.

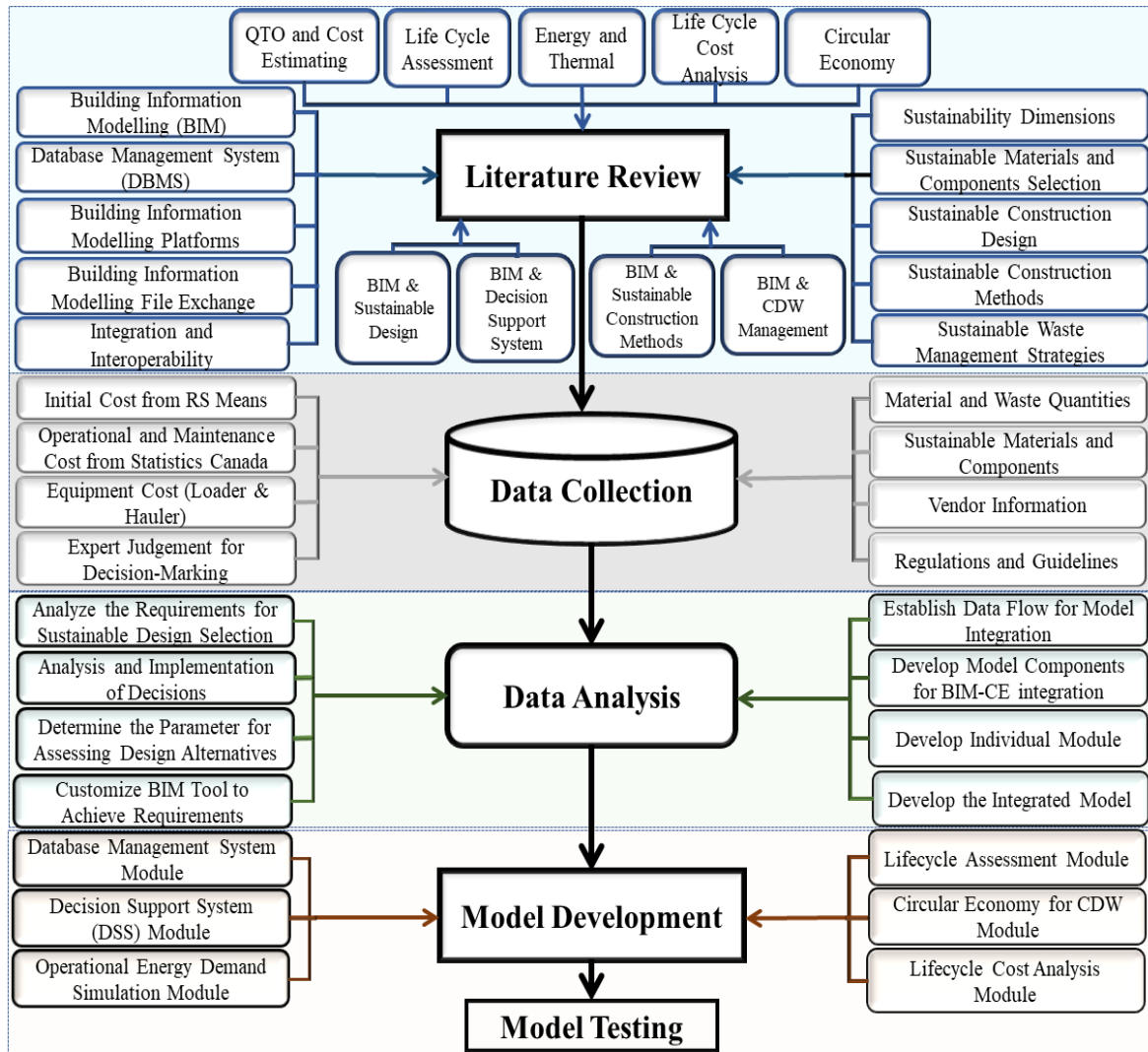


Figure 1.2 - Research methodology

1.4.2 Data collection

The data needed for this research were collected for the three construction methods from several sources, such as literature, sustainable material vendors, construction materials database, Statistics Canada, RS Means, Athena Impact Estimator, Ecoinvent database manufacturers' manuals, USGBC and CaGBC websites, among others, for the three construction methods. Conventional design data, modular design data and 3D concrete printing design data were stored in an external database design engine developed for their construction methods. Then, data will be used to create

the necessary 3D design families for developing conceptual models of construction methods. Developing and storing this design data and families in an external database ensures ease of loading them in whenever BIM tool opens for design through a direct integration process within the BIM platform.

1.4.3 Data Analysis

The collected data will be examined, cleaned, transformed, and modelled to uncover trends and support decision-making by gaining useful insights and knowledge on the compatibility and flexibility of the raw data through the conceptual modelling of the individual components associated with the BIM-based sustainable design model, which are; Database Management System (DBMS); Decision Support System (DSS), Energy and Thermal Simulation, Lifecycle Assessment (LCA), Lifecycle Cost Analysis (LCCA), Circular Economy for Construction and Deconstruction Waste (CDW) management.

1.4.4 Integrated BIM-sustainability model for selecting construction methods

The methodology to develop the integrated model will be implemented through three main stages: *Stage 1:* Examine the needs, gaps, and expectations of the AEC industry for the sustainable construction of buildings by using a feasibility survey to answer fundamental questions in order to identify the adequacy of the BIM-Sustainability integrated model by providing the expected solution as a decision-making model for the selection of sustainable design.

Stage 2: Construct a conceptual framework for the integration to establish the relationship between the needs, gaps, and expectations by mapping the insufficient functionalities of the current BIM sustainable design model and requirements to improve them in order to achieve efficient solutions.

Stage 3: Develop the integrated design model, which consists of six modules, namely Database Management System (DBMS), Energy and Thermal Simulation (EST), Lifecycle Assessment

(LCA), Lifecycle Cost Analysis (LCCA), and Circular Economy for Construction and Deconstruction Waste (CDW) management.

1.4.5 Test and verify the integrated BIM-Sustainability model

Upon the completion of integration, development and implementation, the automated design model will be tested to verify its capability and workability by using three identical building projects associated with the construction method based on the building systems and envelope.

1.5 Original contributions

The originality of this study lies in its pioneering approach to BIM with sustainability practices for the conceptual design of buildings. Unlike existing methodologies that are predominantly based on conventional design and on-site construction methods, this research develops an automated model that seamlessly integrates BIM and sustainability to evaluate and select construction methods such as conventional, modular, and 3D printing. This novel integration enhances the precision and efficiency of design processes and provides a comprehensive tool for designers. It incorporates diverse data for planning, evaluation, and decision-making across all stages of a building's lifecycle, from design and construction to deconstruction. By offering multiple design alternatives and construction methods through six specialized modules, this thesis presents an innovative framework that addresses environmental, impact waste management and cost analysis, ensuring a holistic approach to sustainable building design practice.

1.6 Thesis organization

This thesis is organized according to the following chapters:

Chapter 2 contains the literature review of previous studies on BIM and sustainability. The chapter defines the concept of BIM and sustainability, including tools, enablers and applications.

It will elaborate on the concept of sustainable design and how BIM will be integrated and utilized to enhance sustainable design.

Chapter 3 provides an additional literature review on sustainable construction methods that are used in the AEC industry and BIM implementation. Furthermore, it will thoroughly discuss circular economy, the implementation concept, and its application for the Construction and Deconstruction of Waste (CDW) management by using the circular economy principles and BIM implementation in the circular economy.

Chapter 4 presents the methodological approach regarding developing the BIM-sustainable design model for selecting construction design alternatives that will be designed in a modular format, including the model's components, architecture, data flow and information exchange.

Chapter 5 describes the development of the BIM sustainability model, including the design, its implementation steps, and associated phases.

Chapter 6 discusses the testing and verification of the presented BIM-sustainable design model.

Chapter 7 details the research conclusions, contributions, limitations and recommendations for future research.

Chapter 8 provides a list of references used in the literature review and methodology chapters.

CHAPTER 2

Literature Review

BIM and Sustainable Design

2.1 Introduction

The current practice of the Architecture, Engineering and Construction (AEC) industry is slowly shifting towards digitalization supported by the emergence of BIM, a process facilitated by technology and driven by people, which has become the foundation of digital transformation in the AEC industry (Autodesk, 2021). BIM has become a way of working and managing information rather than merely using one tool or another, although a range of tools and resources facilitates its adoption. Hence, two essential keys are needed to implement BIM models listed as 3D modelling tool and common data environments (CDEs) (NBS, 2019).

BIM is defined by the National Institute of Building Sciences (NIBS) and the National Building Information Modeling Standards (NBIMS) committee of the USA as a digital representation of physical and functional characteristics of a facility that serves as a source of information for a facility's resources, which forms a reliable basis for decision-making during its lifecycle. In addition, BIM potentially eliminates design errors, thereby improving design quality. It helps the management of construction processes, deepens collaboration and communication between project partners, and provides new forms of collaboration with clients (Miettinen & Paavola, 2014). Thus, BIM is a set of emerging technologies and solutions that provide users with correct and consistent data and information for a project. Additionally, it holds the functions needed to model projects by providing a virtual view of the model, enhancing inter-organizational collaboration and productivity while improving the design, construction and maintenance practices (Gha et al., 2017).

2.2 Fundamentals of Building Information Modeling (BIM)

BIM is fundamentally a set of interrelating policies, processes and technologies that generate a systematic approach to manage the critical information of a building's design and data in a digital format throughout its life cycle (Wong and Zhou, 2015). Hence, the AEC industry acknowledges BIM as a predominant term to describe various object-oriented Computer-Aided Design (CAD) activities to support building elements in terms of their 3D geometric and non-geometric (functional) attributes and relationships. Hence, BIM 3D models became popular during the design, construction, management, and end-of-life of a project, including visualization, collision detection, and virtual walkthroughs. BIM is viewed as an evolution of CAD systems that provides more "intelligence" and interoperable information (Miettinen and Paavola, 2014). BIM model allows increased collaboration and improvement in the design and construction processes by enabling visual controls. However, the visualization that BIM 3D model brought was not enough to achieve faster delivery; the "time" factor became the 4th dimension of such models, and the project cost embraced the 5th dimension in the BIM environment. Indeed, many other sizes can be added, which include sustainability, asset management, accessibility, safety management, energy saving, and acoustic, among others (Charef and Emmitt, 2018). Eastman et al., (2008) defined BIM as a modelling technology with associated processes to produce, communicate, and analyze building models. These have the following characteristics: 1) Building components are represented in intelligent digital representations (objects) that, knowing what they are, can be associated with computable graphic and data attributes and parametric rules; 2) Components include data describing how they behave, as needed for analyses and work processes, (e.g., quantity take-off, specification, and energy analysis); 3) Consistent and non-redundant data such that only change in a component's data is reflected in all the component views; 4) Coordinated data such that all

model's views are presented in a one coordinated way (Dastbaz et al., 2017). Gha et al., (2017) reported an extensive benefit associated with the use of BIM, ranging from technical superiority, interoperability capabilities, communication and collaboration, economic, whole building lifecycle, integrated procurement, lifecycle cost management, construction cost savings, planning and scheduling, conflict reduction to decision support benefits. However, BIM, as an emerging innovative technology, has significantly influenced the application of sustainability during the design and construction process. Yet, its effectiveness relies on the integration of five key elements: processes; policies; people; information; and technologies. The process elements involve a specific order of work activities with clear starting and finishing times and identifying the inputs and outputs for each stage (Liu 2017). Information encompasses two types: models, which are digital representations or reproductions of objects or buildings, and documents, which are digital versions of papers, prints, images, drawings, and videos. Finally, technologies comprise the software and hardware tools utilized to manage the various stages of the BIM process.

2.2.1 BIM evolution and extension

According to Doumbouya et al., (2016), the technical capabilities of BIM, which start with a visualization and coordination of an architectural design and construction work are complemented with numerous tools used at all stages of the construction lifecycle. This capability ranges from clash detection, requirement management, calculation of energy consumption, comfort simulation, environmental analysis, lighting simulation, facility and space management, and lifecycle cost evaluation of design and building components. Evolution in BIM practice is a continuous technological advancement where 6D BIM (i.e., BIM 3D model components linked to project lifecycle sustainability information) and 7D (for holistic facility management information for whole lifecycle) are essential for creating flawless, innovative building construction (Nicał and

Wodyński, 2016). Yung and Wang (2014) developed a 6D CAD model that automates LCA for sustainable buildings as a design aid rather than a post-construction evaluation tool. It was motivated by the inability of existing building assessment tools to provide quick and reliable decision support for designs. Jalaei and Jrade (2014) developed an automated building information model that links BIM, lifecycle assessment, energy analysis, and lighting simulation tools with a green building certification system. The integration included newly created plug-ins in BIM tool (i.e., Autodesk Revit), which is capable of measuring the environmental impacts (EI) and embodied energy of the building's components at the conceptual design stage.

Furthermore, mobile technologies are other emerging trends in BIM, used to exchange construction project information. BIM integration in mobile-based applications (e.g., iPad, smartphone) with real-time cloud-based collaboration collects, tracks, and shares field data amongst project stakeholders. It can significantly facilitate the collection of instantaneous feedback design decisions without delays (Abanda et al., 2015).

2.2.2 BIM platforms

BIM process has existed for some decades now. However, continuous advancement in CAD and ICT has created more development of BIM tools for various applications such as architecture, structures, sustainability, MEP, project management, design coordination facility management, and building services simulation. Abanda et al. (2015) examined 122 BIM systems for construction domains by classifying their tools according to their interoperability, fields of use, specific applications, import and export files, associated plug-ins and availability in terms of cost. In addition, they stressed the difficulty in determining the global number of BIM software types. National Building Specification (NBS), in a report from 2017 to 2019, highlighted five major BIM tools that are used in the industry: 1) Autodesk Revit; 2) Graphisoft ArchiCAD; 3) Nemetschek

Vectorworks; 4) Bentley Microstation; and 5) Trimble SketchUp. Table 2.1 lists the properties of each of the five major BIM tools. Whereas sustainability evaluation software applications, such as EnergyPlus, IES VS, Graphisoft EcoDesigner, Green Building Studio, BEES, IDA ICE, are available for calculations, analysis, and simulation for the wide range of building's performances within the BIM environment. Despite of the availability of several BIM tools, Autodesk Revit, with its integrated products: Revit Architecture, Structural, and MEP, is used by numerous designers, from architects and designers to construction and project managers, which makes it the most popular BIM tool used in the AEC industry. As the understanding of BIM continues to grow with its implementation globally, the US has the largest market driven by the government's requirement for all major infrastructural contracts to be BIM-enabled (Gha et al., 2017).

Table 1.1 - Summary of the common BIM tools used in the AEC industry

	Autodesk	Graphisoft	Nemetschek	Bentley	Trimble
Software	Revit	ArchiCAD	Vectorworks	MicroStation	SketchUp
Usage (2019 report)	70%	15%	4%	4%	1%
Specific applications	Design building and components, documentation and analysis	Design, documentation precision and quality	Design in 3D with free-form surface and solids modelling	2D and 3D CAD and information modelling	Intuitive 3D modeling application for 2D and 3D models
File extension	.rvt	.pln	.wmx	.dng	.skp
Import Format	DWG, DXF, RVT, IFC, gbXML	IFC, DXF, IFCXML, IFCZIP, DWG	DXF, DWG, IFC	DXF, DWG, 3DS	DWG, IFC
Export Format	DWG, DXF, RVT, IFC, gbXML	IFC, DWG, IFCXML, IFCZIP, DXF	DXF, DWG, IFC	DXF, DWG, 3DS, IFC	DWG, IFC
API	.NET API	GDL API	VectorScript	MDL API	Ruby, C and API
ODBC Support	Yes	Yes	Yes	Yes	Yes
Language	C#, VB.NET, VC++, F#	C++	C#	C++	Ruby, C
License	Proprietary	Proprietary	Proprietary	Proprietary	Proprietary

Therefore, this study will integrate Building Information Modelling (BIM) and sustainability concepts through: 1) List of design criteria (energy and thermal analysis, circular economy, LCA, and LCCA); 2) Type of construction methods (modular off-site prefabrication and 3D concrete printing considered to be circular economy concepts); and 3) End-of-life (deconstruction and waste management based on circular economy) to select associated construction methods at the conceptual design stage of buildings.

2.3 Sustainability and sustainable development

Sustainability is apparent in one of the earliest and most frequently used definitions the World Commission created on Environment and Development (WCED), commonly known as the Bruntland Report 1987 (Robertson, 2017). The report explicitly points to the connection between environment, economics and equity. It defines sustainable development as a development that meets present needs without compromising the ability of future generations to meet their own needs. Yatim et al. (2005) defined sustainability as a global concept to answer global problems by balancing and safeguarding the future's society, economy, and environment to meet the needs of today and future generations without compromising, anchoring on the service life of a building design not exceeding design life by meeting eco performance requirements without disturbing what we have today for the future generation. The theory of sustainability's dimensions and practice became a priority in North America's AEC industry through the essential contribution of government initiatives. This shift is largely due to the conventional methods of designing, building, operating, and demolishing buildings, which consume significant amounts of non-renewable materials and energy and generate substantial waste as noted by Kibert (1994). Sustainable development has multiple definitions and interpretations, but the general concept remains the same for the AEC industry. According to Gladwin et al. (1995), sustainable development is a process of

achieving human development in an inclusive, connected, equitable, prudent, and secure manner. This definition of sustainable development focuses on the development over time and the quality of human life while striking a balance between ecosystems (Illankoon et al., 2017). Kibert (1994) provided the first definition of sustainable construction during the First World Conference on Sustainable Construction (FWCSC), which is responsible for creating and managing a healthy building environment, considering the ecological principles and efficient use of resources. That definition is established over six principles for sustainable construction, which are: (1) Minimize resource consumption; (2) Maximize resource reuse; (3) Use renewable or recyclable resources; (4) Protect the natural environment; (5) Create a healthy and non-toxic environment; and (6) Pursue quality in creating the built environment. Hence, those six principles for sustainable construction are established within three main dimensions for sustainable development, known as environmental; economic; and social-cultural dimensions.

2.4 Sustainability indicators and criteria

Fiksel et al. (2012) described a sustainability indicator as a measurable aspect of environmental, economic, or social systems based on the concept of the three useful pillars for monitoring changes in the system's attributes, which are relevant to the continuation of human and environmental well-being. Therefore, the indicators related to sustainability apply to financial considerations, environmental protection and stewardship, and social and individual human well-being. They are also known as the triple bottom line, as shown in Figure 2.1. On the other hand, Elkington (1997) argued that the three bottom lines (TBL) should be measured equally instead of solely considering the economic value. Thus, TBL is also known as the three P's (people, planet, and profit) sustainability pillars. The AEC industry refers to the three bottom lines: the social, environmental, and economic factors used to achieve sustainable buildings. It means improving the economic and

social quality of life while limiting impacts on the environment to the carrying capacity of nature (Arowoshegbe, 2016), which requires technical and other criteria to achieve other core elements. Therefore, it is useful to classify sustainability indicators accordingly to clearly defined criteria and sub-criteria in order to support the selection of indicators for specific applications (Fiksel et al., 2012).

Furthermore, sustainability criteria and their indicators should be linked to the understanding of sustainable development and sustainability objective. Hence, Pavlovskaja (2014) described sustainability criteria as requirements for the sustainable quality of a product and its production, which have to be fulfilled entirely in order to acquire a sustainability status or certification.



Figure 2.1 - Triple bottom line of sustainability (Kinay, 2015)

Schroeder (2018) argued that sustainability must be understood as a specific form of problem framing that emphasizes the interconnectedness of different sub-problems and scales and the indirect effects and actions that result from it. However, sustainability goals can be reached through sustainability criteria by increasing the efficient use of energy, water, and materials by

buildings while reducing their impact on human health and the environment over their lifecycle (WBDG, 2018).

2.4.1 Sustainable building materials

Sustainable building materials are natural materials that offer specific benefits to the users regarding energy efficiency, low maintenance, improved occupant health and comfort, and increased productivity while being less harmful to the environment (Ding and Sydney, 2007; Ding, 2013). Sustainable construction materials are the foundation of a sustainable building, and they play essential roles in building sustainable development as all construction materials impact the environment during their lifecycles (Ding and Sydney 2007). Khaled et al., (2016) claimed that selecting sustainable materials is the first step in developing sustainable buildings. Karolides (2010) listed six essential elements that describe sustainable construction materials, which are: 1) materials that are healthy for the interior environment; 2) materials that are healthy for the outdoor environment; 3) materials that help minimize building energy; 4) materials that do not often need replacement, which are durable, reusable, recyclable, and biodegradable; 5) materials with low embodied energy; and 6) materials that can be locally obtained. The National Institute of Building Science (NIBS) characterized green products as those containing recycled materials, saving water and energy and decreasing the amount of toxic materials consumed. Hence, a simple definition is that green construction materials are environmentally responsible because their impacts are considered over their whole lifecycle. Depending on the project's goals, an assessment and selection of sustainable materials may involve a multicritical evaluation due to its importance in achieving a sustainable design in the construction industry (Akadiri et al., 2013).

Furthermore, the certification rating system devoted an assigned criterion for materials and resources (MR) that focuses on construction wastes, local materials, recycled and re-used

materials, rapidly renewable materials, and emissions during fabrication, hauling, and installation. The process of selecting sustainable materials involves the following three steps: 1) A technical review of the information, such as geometric properties, test results, and characteristics; 2) An assessment of the different alternatives that have the same function by using LCA, and 3) A selection of the best alternative based on specific sustainability criteria. There are several international guidelines and techniques to assess materials based on their environmental credentials. However, lifecycle assessment (LCA) is one of the most suitable methods for determining materials' environmental impact in the construction industry. Therefore, this study will use a multicritical evaluation to establish the characteristics of sustainable materials, and a decision support system will be developed to select adequate, sustainable materials for achieving the objective of designing and selecting the associated construction methods at the conceptual design stage of buildings.

2.4.2 Sustainable building design

A sustainable construction approach accounts for a building's entire life cycle: design, construction, operation, maintenance, renovation and demolition. Sustainable and green construction, which will be used interchangeably in this study, describe the practice of increasing the effectiveness with which buildings use natural resources such as: building materials, energy, water, and the reduction of building impacts on human health and the environment during the building's lifecycle (Frej, 2005). Sanchez and Haas (2018a) cited examples of green design methods as being the design for assembly, supply chain management, life cycle assessment, design for disassembly, design for remanufacturing, and disassembly sequence planning adaptive reuse. Sustainable design symbolizes a holistic, integrated, multidisciplinary approach in which every decision is evaluated against multiple criteria to find the best solution. It is a detailed approach to

selecting and integrating products and processes that account for long-term consumer satisfaction and environmental conservation through a project life cycle (Frej, 2005). It also integrates cost, schedule, operations, maintenance, quality and employee considerations in five general parts listed as: 1) Optimize site potential; 2) Energy efficiency and renewable energy; 3) Conservation of materials and resources; 4) Water quality, conservation and efficiency; and 5) Enhance indoor environmental quality. USGBC defined green building as environmentally responsible, profitable, and a healthy place to live and work. Green buildings are also described by the Environmental Protection Agency (EPA) as structures that have been created using environmentally responsible and resource-efficient processes throughout a building's life cycle. Robertson (2017) considered sustainable design as an integrated approach that comprises a whole system and collaboration by providing a simultaneous solution to multiple problems. However, sustainable design is achieved when it can positively affect all three areas (environmental, economic and social). Previous studies described sustainable design as an integrated design approach that reflects an in-depth understanding of how buildings and their environment interact and affect each other. For instance, Krygiel and Nies (2008); Azhar et al., (2011); Dowsett and Harty (2013), and Jalaei and Jade (2014) outlined several ways of utilizing BIM for sustainable design such as: 1) Building orientation (selecting a good orientation can reduce energy costs); 2) Building massing (to analyze building form and optimize the building envelope); 3) Daylighting analysis (maximizing the use of natural daylighting); 4) Water harvesting (by reducing water needs in a building); 5) Energy modelling (improving energy efficiency, analyzing renewable energy options, and contributing to low energy costs); 6) Sustainable materials' selection (in reducing material needs and embodied energy); and 7) Site and logistics management (by minimizing construction waste and carbon footprints). There are many existing and ongoing research efforts that focus on using BIM to achieve sustainable

design. Lu et al., (2017) examined twelve types of BIM tools and documented the following six aspects in which BIM supports sustainable building design: 1) for energy performance analyses and evaluations; 2) for carbon emissions analyses and evaluations; 3) for natural ventilation system analyses and optimization; 4) for solar radiation analysis; 5) for water usage analyses; and 6) for enabling the simulation of acoustic.

2.4.3 Database management system (DBMS)

The AEC industry has been using DBMS in various applications for seamless interfacing, integration and automation of sustainable design. DBMS is a collection of electronic records that can be processed to produce useful information. According to Raza (2018), the data can be accessed, organized, modified, managed, and controlled to perform several data-processing functions. For instance, the data is typically indexed across rows, columns, and tables, making workload processing and data querying efficient. There are different types of databases: relational, distributed, hierarchical, network and others. According to Begg (2014), a DBMS enables users to define, create, maintain, and control access to a database. It also optimizes and manages the storage and retrieval of data from the database.

A database allows a set of commands to perform different DBMS operations, including creating, deleting, restoring, cloning, and other database maintenance tasks. A database application is accessible through APIs that allow users to create, read, write, and delete databases. DBMS is accessed through an Open Database Connectivity (ODBC), a standard application programming interface (API), independent of database systems and operating systems. Since BIM repository is a database system that stores and facilitates the management of all building information for the lifecycle of a project, the object-oriented nature of BIM calls for a database system to represent abstract data types that capture their behaviours, relationships, and relationship properties

(Sanfilippo, 2015). Jalaei (2015) suggested a specific workflow rather than an anyone-fits-all approach to achieve an integration between an external database and BIM tool. Unfortunately, there is no single method to determine the feasibility, estimate, or design of such integration requirements and workflows. Liu (2017) identified a BIM-DBMS consisting of three items: a) BIM Model (i.e., Autodesk Revit as a BIM-authoring tool to build information modelling and act as a BIM model container); b) Data synchronization program (i.e. using a computation script with a built-in algorithm in Dynamo to link the BIM Model with an external database), and c) External database (i.e., using a graphical relational management system known as Neo4j as the external database, which is appropriate for storing COBieformat facility data).

2.5 Decision support system for material selection

Arroyo (2016) justified that methods used in making decisions for choosing alternative materials, components, assemblies, systems, and building shapes must take the complexity of the design process into account and help the design team understand the trade-offs that must be made. Besides, the product life cycle must be considered in complex decision-making processes such as selecting conceptual schemes and manufacturing processes and disposing of end-of-life methods. Decision-making for sustainable material selection has been studied from several perspectives, such as processes, classification approach and characterization. For example, Jalaei et al., (2015) and Lu et al., (2007) categorized the traditional systems as decision-making problems. They noted three different classes: 1) Structured, where the best solution is recognized as the standard method, described by using statistics for comparing products in terms of cost or quality; 2) Unstructured, for problems with fuzzy natures in which human instincts are the basis of most the decision making; and 3) Semi-structured, for problems that are based on both the standard approaches and the human judgements. However, Rahim et al., (2020) proposed six decision-making classification

methods for the materials' selection listed as: 1) screening method (using cost per unit property and questionnaire); 2) comparing and choosing a method (using weighted properties and multi-criteria decision-making technique (MCDM)); 3) artificial intelligence method (using a decision support system (DSS) and knowledge-based systems (KBS)); 4) optimization and mathematical methods (using grey relational analysis, data envelopment analysis, digital logic, neural network (NN), linear and nonlinear programming and genetic algorithm (GA)); 5) strategies (using lifecycle analysis and case-based reasoning); and 6) fuzzy and uncertainty. They noted that the problems of selecting the materials and their associated decision-making would fit within the domain of multi-criteria decision-making techniques.

2.5.1 Multi-criteria decision-making (MCDM) technique

MCDM originated from operations research, with foundations in economics, psychology and mathematics, but its implementation requires dedicated systematic tools and involves several methodologies. Kumar et al., (2017) classified MCDM into three different methods: 1) Multiple Objective Decision Making (MODM), which is used for the design of alternatives that optimize decision-making based on multiple objectives; 2) Multiple Attribute Decision Making (MADM), which is used for selecting the best option from pre-specified alternatives described in terms of multiple attributes; and 3) Combination of MODM and MADM, which distinguishes the number of alternatives under consideration. While the differences between the two methods are often accommodated, both methods have similar features. Therefore, the selection of materials involving sustainability criteria and alternatives is a multi-objective problem that is subject to multiple attributes, conflicts and constraints, which can be viewed as complex MCDM problems that require trade-offs amongst critical criteria (Zhang et al., 2017). Rahim et al., (2020) categorized conventional MCDM models for the materials' selection process into three: 1) multi-attribute utility model (AHP, ANP, SAW, DEMATEL and MAUT); 2) outranking model (ELECTRE and

PROMETHEE); and 3) compromise model (TOPSIS and VIKOR). Zhang et al., (2017) affirm that other mathematical techniques have been developed and used in the selection of sustainable materials, including extended and integrated methods that have successfully overcome the limitations of using a single MCDM model. At the same time, Emovon and Oghenenyero who (2020) examined the existing scientific literature on MCDM application for the materials' selection, the study reveals that: 1) MCDM is applicable to several industries, including the construction industry for the selection of materials; 2) cost is the most common decision criteria for selecting the materials' alternative; and 3) hybrid MCDM method (a combination of two or more MCDM) is the most adopted technique for selecting the materials in all the identified industries.

Specifically, Do and Kim (2012) applied AHP to solve the MCDM problem of selecting the optimal material for concrete repair where cost and environmental impact were among the criteria in consideration. Uğur and Baykan (2017) also used AHP to select the suitable alternative of materials for walls by considering the cost, eco-friendliness and recycling, among other criteria. Finally, GRA and AHP were combined to rank alternatives for materials in terms of their economic, environmental, and social performance when selecting plastic pipe materials for water supply (Zhao et al., 2016). Multi-criteria decision-making (MCDM) has been studied as a practical application technique for materials' selection, and its framework(s) centres on balancing environmental, social and economic sustainability through the use of materials for building construction (Wang et al., 2020; Emovon and Oghenenyero who, 2020; Kraujalienė, 2019; Kumar et al., 2017; Zhang et al., 2017; Zavadskas et al., 2017; Jalaei et al., 2015; Singh, 2014). Generally, MCDM problems involving the selection of materials consist of five main components: 1) Goal (the essence of the decision); 2) Alternatives (to be ranked or chosen from); 3) Criteria (how the

alternatives will be evaluated and compared); 4) Weights (the comparative importance of the criteria); and 5) Decision-makers (stakeholders whom preferences are to be represented).

2.5.2 BIM and decision support system

The decision-making process is a significant way of using BIM to improve the building design, reducing the amount of work involved in evaluating multiple options early during the design process (Bank et al., 2011). Jalaei et al., (2015) developed a BIM-integrated DSS using Entropy-TOPSIS techniques to assist the design team in facilitating decisions and selecting the optimum sustainable materials and building components at the conceptual design of buildings. The outcome confirms the suggested idea of a decision support system (DSS) as a valuable tool in making intelligent and critical decisions during the material selection process (Yang & Ogunkah, 2013). Decision support systems (DSS) are usually associated with techniques that aim to help stakeholders to make decisions by collecting and determining relevant information from several sources (Papathanasiou et al., 2016). The process involves developing and implementing computer and information technology to support pertinent decision-making in business sectors, including construction. DSS has the capacity to improve the decision-makers' efficiency, productivity and effectiveness in a sustainable design. It can also simplify the communication between different parties in an organization and contribute to quick problem-solving (Jalaei et al., 2015). Power (2002) categorized decision support systems into five based on their primary sources of information: i) data-driven; ii) knowledge-driven; iii) document-driven; iv) communication-driven; and v) model-driven. Model-driven or model-oriented DSS includes accounting and financial models, representative models, and optimization models. They emphasize access to and manipulation of a model and generally leverage simple statistical and analytical tools, using data and parameters provided by decision-makers, but usually not data-intensive. For the design of sustainable buildings, the use of model-oriented DSS ranges from single to combined models. For

instance, Akanmu et al., (2015) integrated BIM with a modified harmony search algorithm and supplier performance rating in developing their DSS. Fazeli et al., (2019) proposed a BIM TOPSIS-Fuzzy integrated framework to enhance the selection of sustainable building components using functions and tools of MCDM techniques by linking MATLAB software to apply Fuzzy functions on the users' priority. Hence, this study will develop a BIM-DSS integrated model by utilizing a hybrid DANP - WSPAS fuzzy for decision-making and evaluating the processes of selecting materials. It has the capability to integrate and select materials for three different design and construction methods (i.e. conventional, modular and 3D concrete printing) using predefined components from a BIM tool (i.e., Autodesk Revit) via developed plug-ins based on owners' needs. Furthermore, the decision model will adequately employ the direct and indirect relationships among criteria to evaluate sustainability principles in order to select the optimal sustainable materials. Therefore, this study will develop an integrated decision support system (DSS) module for sustainability design that consists of Building Information Modelling (BIM), Database Management System (DBMS), fuzzy decision-making trial and evaluation laboratory (DEMATEL) integrated with analytic network process (ANP) and fuzzy Weighted Aggregated Sum-Product Assessment (WASPAS) methods.

2.6 Life cycle assessment (LCA)

LCA is a holistic approach to quantifying the environmental sustainability of a product, project, process or system and has increasingly been used to assess the environmental sustainability of the built environment (Harvey et al., 2018). The methodology evaluates the environmental impact of buildings with respect to their input processes, materials and use (energy) and their output (waste and pollution) throughout the whole life cycle of a building, as illustrated in Figure 2.2. SETAC (1990) defined LCA as an objective process to assess the environmental burdens connected with

a product, activity, and process by identifying energy and material usage, releasing waste, and implementing opportunities to affect environmental improvements. It is globally accepted in the environmental research community as an appropriate method for the scientific quantification of an environmental footprint. Typically, LCA gathers and reports information at every phase of a product's life and is viewed through the lens of defined environmental impact measures where the typical environmental effects due to a product, building or service are categorized into damage to human health, ecosystems and available resources (Acero et al., 2016). An LCA system boundary that includes the entire product life cycle from raw materials extraction, manufacturing, transportation, on-site construction, operation, maintenance, demolition, disposal, or re-use/recycling is called cradle to grave and is shown in Figure 2.3, while evaluations focusing solely on raw materials extraction to manufacturing are known as cradle to gate.

ISO (14040) outlines four significant steps to LCA methodology, as shown in Figure 2.4. The first step is the definition of goal and scope, which determines and defines the purpose of the study, system boundaries, and selection of suitable functional units. The stage also specifies the objectives of the assessment, the product or process being analyzed, and the associated assumptions and limitations of the study. The second step is the life cycle inventory (LCI), which involves collecting data (on energy and raw material, emissions to air, water, and other environmental releases) and quantifying all inputs and outputs within the system boundaries. The third step is life cycle impact assessment (LCIA), which evaluates a product's potential environmental impacts from inventory data gathered in the LCI phase. This process involves categorizing and characterizing the inventory data into specific environmental impact categories. Common impact categories include global warming potential, ozone depletion, acidification, and eutrophication.

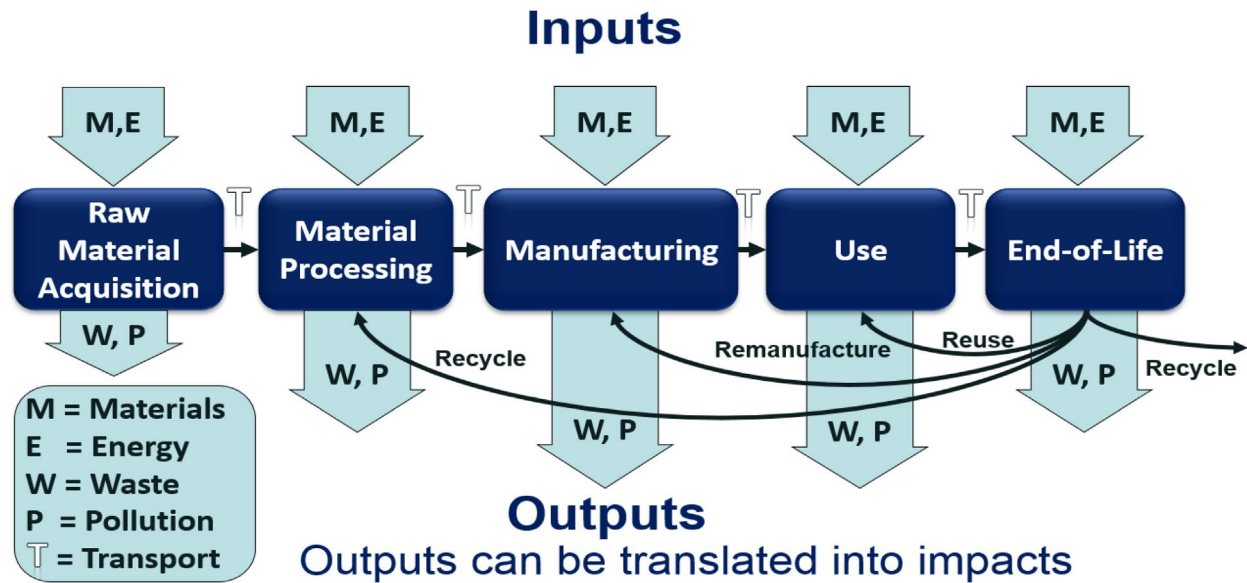


Figure 2.2 - Generic life cycle of a production system for LCA (Kendall 2012)

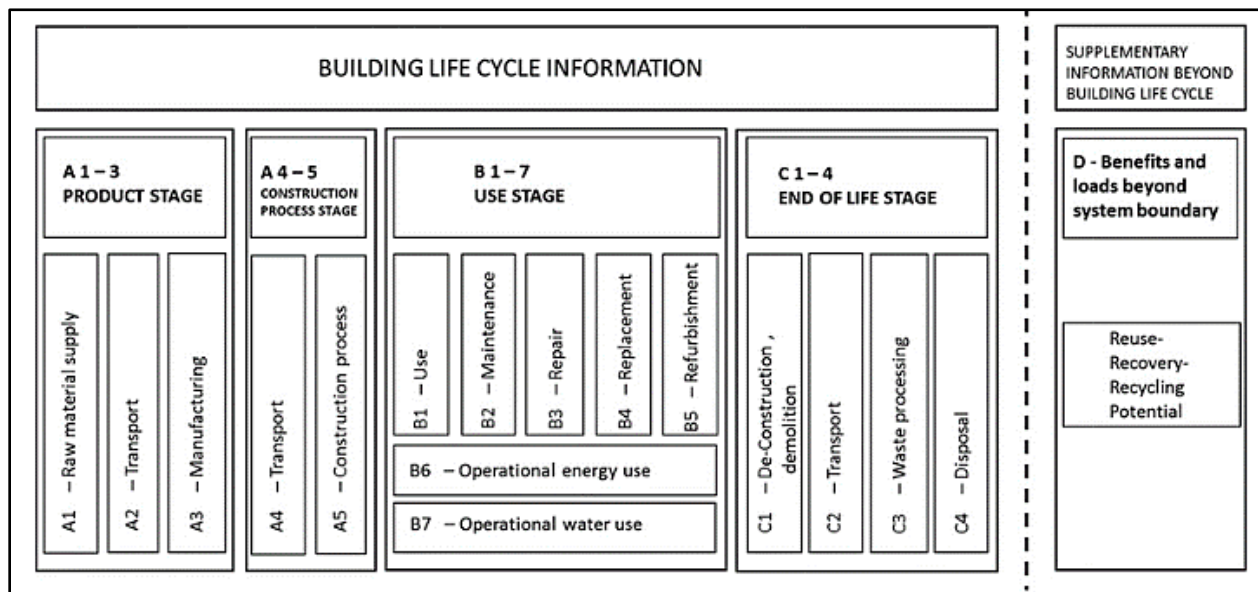


Figure 2.3 - General scope (system boundary) of the LCA study (BS EN 15978:2011)

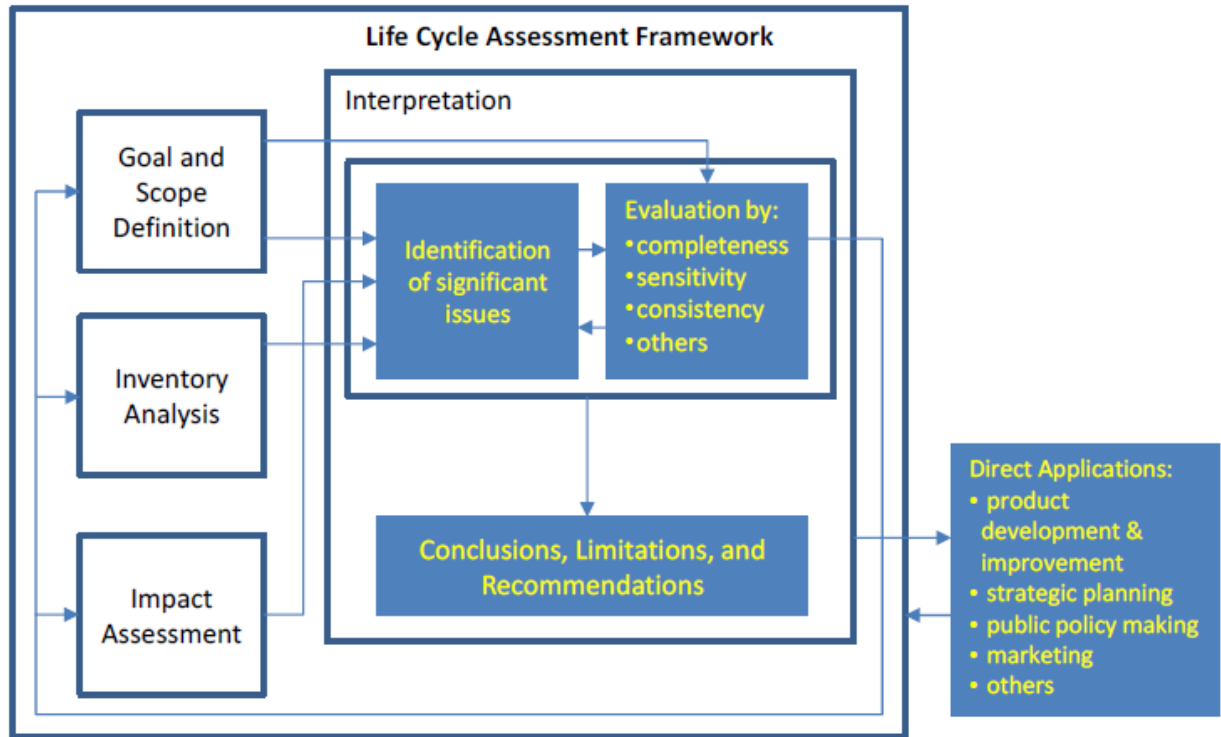


Figure 2.4 - LCA ISO 14040 framework (Harvey et al., 2016)

The fourth step (interpretation, which identifies significant issues, assesses results to reach conclusions, explains the limitations, and provides recommendations) (Ajayi et al., 2015). According to Simonen (2014), all buildings have environmental impacts; hence, the challenge of developing genuinely sustainable buildings has led to a desire to understand their structure and construction from a systems-based perspective. Understanding a building, assembly or product from this perspective of its entire life cycle is the first step in developing sustainable buildings. Hence, LCA is an in-depth, standardized, analytical framework that studies the construction sector and operates in four levels: 1) building material; 2) building components; 3) whole building; and 4) building industry by quantifying environmental impacts and comparing design options for effective decision-making.

The EeBGuide handbook recognized the inadequacy of developing the LCA method for the building sector at the same level of detail as other sectors. Therefore, it established three types of

LCA studies for building's environmental impact as follows: 1) screening LCA; 2) simplified LCA; and 3) complete LCA. Criteria to define each level are based on the goal and scope of the assessment, practitioner's experience, data availability, and the development stage of a building. ENSLIC guidelines classification level involves performing the LCA and the practitioner's experience, which includes: 1) limited or no experience for basic calculation, developed in Excel, considers simple input and output data, taking a few environmental impact indicators into account; 2) medium level of experience for calculations by using specific tools such as Ecosoft, Equer, Athena (Impact Estimator and EcoCalculator); and 3) advanced level experience in LCA software such as Simapro and Gabi (Soust-Verdaguer et al., 2017). LCA methodology recognizes and analyses various possibilities that help reduce energy and resource consumption and the environmental impacts of building's materials over their life cycle in five main stages. The first stage (characterized as embodied energy), is the extracting and manufacturing phase of raw materials. The second stage is grey energy, which refers to the transportation phase of building materials from the production site to the construction site. The third and fourth stages are the energy used for the construction and operation phases. The types of energy consumed in these two phases are induced energy and operation energy. The fifth stage is the energy used for demolition and recycling, and it refers to the end-of-life phase of a building (Najjar et al., 2017). While LCA is a well-established, rigorous science guided by international standards, it is not entirely accurate. There are several assumptions and variables in LCA and some data gaps, thereby increasing uncertainty in the results, especially with complicated products like buildings (O'Connor, 2020). Therefore, this study will develop a realistic and transparent methodology for integrating BIM with LCA tool to enable effective control and analysis of the environmental impact by using a dedicated

evaluation tool, LCI database, and impact assessment method, namely openLCA, Ecoinvent and ReCiPe, respectively.

2.7 Life cycle cost analysis (LCCA)

Fregonara et al., (2018) considered the LCCA technique as one of the practical tools to incorporate economic sustainability in construction projects. Dhillon (2010) emphasized that 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) described LCCA as a management tool for forecasting the total expenses incurred during a building’s life and a decision-making tool for selecting alternative projects (Ifeoluwa, 2015). The primary purpose of LCCA is to enhance the decision-making process to form reasonable judgments on the economic performance of a building through its useful life cycle (Kehily and Underwood 2017). Whereas its main objective is to assess the economic impact, including costs associated with various alternatives and, notably, the initial capital investment costs, which significantly influence the overall expenses throughout a project’s life cycle (Rad et al., 2021). 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: i) initial cost (construction cost); ii) operation and maintenance costs; iii) replacement cost; and iv) end-of-life costs, including revenues and residual value (Marzouk et al., 2018). The lowest life-cycle cost (lowest LCC) method is the most easily interpreted measure of economic evaluation in construction projects. Other economic measurement methods in use are Net Savings (or Net Benefits), Savings-to-Investment Ratio (Benefit-to-Cost Ratio), Payback Period and Internal Rate of Return. 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 (Sieglinde, 2016). The LCCA method converts cash flows to present values (PV) by discounting them to a common time horizon, usually the base date.

Generally, the main focus on costs tends to centre 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 during the operational phase of buildings, which is recognized for consuming roughly 40% of the total global energy (Altaf et al., 2023; Wei et al., 2018). According to Ürge-vorsatz et al., (2015) and Altaf et al., (2023), the high building operating cost is linked to the energy consumption necessary to sustain thermal comfort within the building, affected by several factors, including climate, occupant behaviour, and energy systems requiring heating and cooling. 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 alternative building designs, including the energy performance and associated environmental impacts. These challenges arise from limited access to reliable cost data, disparities in life cycle cost standards, accessibility of design information, and other essential attributes of the design stage (Rad et al., 2021). Further complexities extend to quantifying these impacts and expressing them in monetary terms that are easily understood by investors at the design stage (Fuller, 2016). In tackling 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 economically sustainable Buildings (Teng et al., 2022 and Altaf et al., 2023).

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 asset life-cycle (Azhar, 2011). 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 naturally captures data to support various design options (McNeil-Ayuk and Jrade, 2023; Wu and Issa, 2015). 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 decision-making through its life cycle (K. Lu et al., 2023), thereby empowering architects and designers to perform real-time evaluations to achieve low-carbon buildings and explore various design options. Altaf et al., (2023) 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 associated reduced costs. Rad et al., (2021) adopted a detailed LCC methodology within the early design phase to integrate a model that combines LCC and BIM to support the design of resilient buildings and 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-time early design and investment decisions on the cost of an asset over its life cycle. Its integration with various tools and data through energy analysis, Life-cycle Assessment (LCA), and Life-cycle Cost Analysis (LCCA) modules within BIM tool aids in facilitating the execution of a detailed 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 lifetime costs and to precisely predict the life-cycle cost. The study considers initial construction costs and accounts for long-term operational, maintenance, and salvage value. Part of the development of the integrated model is the development of a new plug-in inherited into BIM tool (i.e., Autodesk Revit) to enhance its functionalities in forecasting life-cycle cost, including the creation of cashflows, and running scenario and sensitivity analysis.

2.8 Energy and thermal simulation (ETS)

Historically, energy efficiency has been considered as the most critical attribute of a sustainable building (National Renewable Energy Laboratory). The United Nations Environment Programme (UNEP) alleged that the building construction sectors and activities represent about 40% of the global energy consumption and account for more than 30% of greenhouse gas emissions. However, with technological advancements, it is becoming more efficient to design buildings using less energy. Cabeza and Chàfer (2020) stated that many technologies can reduce the energy use in buildings, which can be categorized as passive and active. Passive technologies can achieve a passive, sustainable design by adapting building geometry, lighting, and ventilation. At the same time, the active group uses energy savings techniques like building envelope design, heat storage system and lighting design (Elnagar and Köhler, 2020; Tzortzaki, 2017). Furthermore, national and international systems, assessments and regulations, such as LEED, BREEM and others, have defined standards and parameters to evaluate the sustainability of buildings with a higher priority on reducing energy (Picco and Marengo, 2015).

Several fundamental factors, such as materials properties, quantities of materials, size and configuration of space(s), and the building location, are necessary to determine the amount of

energy required to heat or cool a building (Kim and Anderson, 2013). However, the American Institute of Architects (AIA) stated that energy modelling is a computation mechanism that accepts inputs in the form of building geometry, system characteristics, and operations schedules and produces outputs (analysis) such as performance comparisons and compliance reports. They described the following four common energy modelling: 1) design performance modeling; 2) building energy modeling; 3) building operations modeling, and 4) project resource modeling. Hence, adopting building design performance simulations at the conceptual phases encompasses more than energy but includes thermal and visual comfort and air quality, which enhances cost-efficient design decision strategies. The analysis fosters rapid, iterative exploration of various design solutions and allows the design team to prioritize performance, cost, and aesthetics in real-time (Overbey, 2017). Furthermore, the performance simulation uses a 3D virtual building model, geometry, weather data, and building usage patterns to determine the building's energy usage.

2.8.1 Energy demand in buildings

Maintaining thermal comfort within an occupied space in a building requires energy. Therefore, optimized solutions and techniques for balancing energy use with indoor environmental quality are needed since the indoor environment is where inhabitants spend almost 90% of their lifetime (USgbc, 2017). According to Müller et al., (2017), there are three key areas of comfort that have a direct influence on the energy demand of buildings: 1) thermal comfort (ISO 7730, ISO 10551, ANSI/ASHRAE 55); 2) visual comfort (lighting) (ANSI/IESNA RP-1-04, EN 12464, ISO 8995; and 3) air quality (ISO 16814). Therefore, the design team needs to balance between the comfort and energy efficiency requirements at the conceptual design stage of buildings.

2.8.2 BIM and energy analysis

Sustainability practice, building life cycle cost awareness, and environmental impacts have increased the importance of analyzing energy performance in buildings' design. The purpose of energy analysis at the conceptual building design is to help simulate the amount of energy utilized in a building; this process must meet the cost, schedule and sustainable decisions related to energy efficiency. Reeves et al., (2015) emphasized that the design of energy-efficient buildings requires validation of building performance, usually achieved using building modeling and simulation software. Furthermore, automation of the modeling process is one of the significant benefits of applying BIM to simulate the energy of buildings that could save time, lower cost, and reduce human error (Kamel and Memari, 2019). Building Energy Modelling (BEM) technology is an effective way to achieve building's energy efficiency. It aims to evaluate design alternatives, compare and select systems and subsystems, allocate annual energy budgets, achieve compliance with energy standards, and optimize the building design process (Gao et al., 2019). Hence, BIM and BEM tools are helping the AEC industry, and building owners to move toward by increasing the energy-efficient of buildings. For instance, using BIM-based energy modelling provides numerous benefits, including accurate and complete energy performance analysis at the conceptual design stage, improved lifecycle cost analysis, and opportunities for monitoring actual building performance during the operation phase (US General Services Administration, 2015). In addition, the model can reduce the effort and time spent in generating the model's geometry; furthermore, by transferring building parameters into the BIM-based BEM model, the data exchange and information consistency can be maintained (Chen et al., 2018; Elnabawi, 2020). BIM accepts performance assessments building's conceptual design phases, such as orientation, window-to-wall ratio and location of material properties (Chen et al., 2017; Gao et al., 2019); while BEM

tools efficiently evaluate the building performance in more advanced stages (Jin et al., 2019). The approach explains a growing demand for the combined application of BIM and Building Energy Modeling (BEM) for sustainable design within the architecture, engineering, and construction (AEC) industry. In addition, existing standards enable the extraction and sharing of data between BIM and BEM tools, including the Industry Foundation Classes (IFC) and Green Building XML (gbXML). However, these involve a middleware conversion utility, where there is room for potential errors along the way (Lack, 2019). Two methods for integrating BIM- BEM were proposed by the Chartered Institution of Building Service Engineers (CIBSE, 1998), listed as: 1) applying simplified simulation tools at the conceptual design phase and detailed tools in the later design phases; and 2) using a sophisticated single simulation tool at the entire design phase. The second approach benefits from the use of a single tool. This approach also reduces the errors that may occur due to the use of various BEM tools. Abad (2017) examined a semi-automated approach of BIM adoption that uses an authoring CAD tool to develop a BIM file containing all the required information for energy simulation. The process required the energy tool to import files, modifying other data that might not be transferred correctly, and performing the energy simulation, which starts by converting the BIM model's file to a readable file in the BEM tool. Outputs will be limited to what the specific BEM tool, is capable of presenting. For instance, a BIM model's file is generated by a BIM tool such as Autodesk Revit, will be manually imported into OpenStudio, and additional data related to other components such as HVAC and lighting systems will be added. Finally, an energy simulation will be performed, and the energy consumption in each thermal zone will be calculated.

2.8.3 BIM and energy analysis tools

The building energy software tools (BEST) directory record shows that the U.S. Department of Energy (DOE) listed more than four hundred tools in 2014 (Elnabawi, 2020). However, selecting these tools is a significant concern since each stakeholder is interested in specific aspects of the project. Therefore, Solmaz, (2019) identified eight selection criteria: (1) level of accuracy and detail; 2) Usability and information management; (3) Data exchange capacity; (4) Database support; (5) Interoperability with building modelling; (6) Integration of building design process; (7) Speed and cost; and (8) Ease of use. Among the many Building Energy Software, a few are dominantly used in academics and industry for analysis and simulation, such as Insight 360, DesignBuilder, EnergyPlus, eQUEST, Green Building Studio (GBS), IES-Virtual Environment (IES-VE), OpenStudio and TRNSYS. Their general properties, simulation engine, interoperability and sustainability capability have been selected and compared, as shown in Table 2.2. Kamel and Memari (2019) studied four categories of energy simulation tools and their compatibility with BIM model's files:

- 1) Energy simulation Graphic User Interface: such as OpenStudio, DesignBuilder, BEopt, or eQuest this set of tools only facilitate the energy modelling by providing more graphical interfaces for the inputs and outputs, including improving the geometric model of the building or detailed graphs on energy consumption data. They do not perform energy simulations.
- 2) Energy simulation engines, such as EnergyPlus, DOE2.2, eQuest, and TRNSYS, perform energy analyses based on different mathematical tools and thermodynamic equations. However, they cannot directly import BIM model's files such as gbXML and IFC.
- 3) Independent energy simulation engine with a graphical interface: such as OpenStudio, IES-VE, GBS - that have the capability of using BIM model's files

- 4) Space Boundary Tool (file generators): EnergyPlus can import a BIM tool's file and generate a text file in a suitable format for an energy simulation engine.

Hence, this study will develop a conceptual energy performance simulation methodology for comparing and selecting from three construction methods. It will integrate a BIM tool (Autodesk Revit) with an energy simulation GUI, employ DesignBuilder, and use energy simulation engines such as EnergyPlus.

Table 2.2 - Comparison of selected EnergyAnalysis Tool (Solmaz, 2019; BEST 2021)

Building Performance Analysis (BPA) tools	Major Capabilities	Design Tool	Simulation Engine	Interoperability	License	Energy	Thermal	Daylighting	Air Quality	Carbon Emission	Lifecycle assessment	Energy Lifecycle Cost	Renewable Energy analysis	Code/Certification	Optimization
Insight 360	Whole building energy simulation Parametrics and optimization Lighting simulation Solar and photovoltaic analysis Energy cost range	Revit	DOE-2.2	Standalone	Free for academic use, License required commercial use	✓	✓	✓				✓	✓		
Design Builder	Whole building energy simulations Load calculations HVAC system selection and sizing Parametric and optimization Airflow simulation Ratings and certificates Code compliance check	Own	EnergyPlus/ Radiance	File exchange	License is required, 30 days free trial.	✓	✓	✓	✓		✓	✓		✓	✓
EnergyPlus	Whole building energy simulations Load calculations HVAC system selection and sizing Lighting simulation Air flow simulation Ratings and certificates Code compliance check	SketchUp Revit	EnergyPlus	Standalone (IFC, gbxml)	Free/Open source license	✓	✓	✓	✓						
eQUEST	Whole building energy simulations	Own	DOE 2.2/EnergyPlus	Standalone	Free/Open source license	✓						✓		✓	
Green Building Studio	Whole building energy simulations Parametrics and optimization Energy conservation measures Annual carbon footprint Renewable energy potential (photovoltaic and wind) Water preliminary analysis for LEED	Revit	DOE 2.2	File exchange	Free for non commercial & academic use, free to try	✓		✓	✓					✓	
IES Virtual Environment (IESVE)	Whole building energy simulations Load calculations HVAC system selection and sizing Lighting simulation Ratings and certificates Code compliance check	Revit, Own	Independent	File exchange	License is required, 30 days free trial.	✓	✓	✓	✓	✓	✓	✓		✓	✓
OpenStudio	Whole building energy simulations Energy conservation measures Lighting simulation	SketchUp Revit	EnergyPlus/ Radiance	File exchange	Free/Open source license	✓	✓	✓	✓	✓		✓			
TRNSYS	Whole building energy simulations Parametrics and optimization Detailed component simulation Airflow Modeling Coupled Multizone Thermal Wind and Photovoltaic Systems	Own	Independent	Standalone	Reduction for non commercial & academic use	✓	✓					✓	✓		

2.9 Interoperability and Integration

Interoperability is the ability to ensure that the data generated by BIM tool can be appropriately interpreted by other tools (Shen et al., 2010; BIEG, 2020). Eastman et al., (2008); Cemesova, (2013); and Elnabawi, (2020) defined interoperability as the capability to exchange data between applications faultlessly to accomplish a smooth workflow for models' automated transactions. The data exchange should avoid possible human error and data repetition and accelerate the reproduction of the model (Elnabawi, 2020). Furthermore, interoperability should enable bidirectional updates, exchange of data for building information, and modification in tools involved in the interchanging process (Kumar, 2008; Moon et al., 2011; Elnabawi, 2020). Existing literature has shown no particular BIM tool to support all the functions required at all building life cycle stages for adequate decision-making and to meeting stakeholders' needs. Therefore, interoperability is necessary for various integrations in sustainable design. For instance, Eastman et al., (2008) illustrated the importance of exchanging and integrating data between applications by the project team, listing four ways to exchange a model's information between two different software tools: 1) Direct links between specific BIM tools; 2) Proprietary exchange file format; 3) Public level exchange formats; and 4) XML-based exchange formats. Negendahl (2015), proposed a thorough integration method for the conceptual design stages known as combined, central, and distributed; however, these three methods are supported by different data schemas. Therefore, this study will combine the three proposed integration approaches to develop the methodology for the integrated BIM sustainability model.

2.10 Summary

This chapter provided a broad overview of the literature related to BIM and concepts of sustainability, including sustainable development in construction. The literature review covered

various sustainability-related areas, dimensions, development, tools, indicators, criteria, design and construction methods, and decision support system. It highlighted practice, implementation, tools and file exchange formats related to the BIM. It described the integration and interoperability processes with the different modules such as DBMS, Energy and thermal simulation, Life Cycle Assessment and Life Cycle Cost Analysis. Sustainability is used as a general term to describe technological, material, economically and environmentally stable building design. Additionally, previous studies uphold sustainable design as the core instrument for achieving sustainability and sustainable development in buildings, with BIM tool being the functionality and foundation that continued to provide essential functions, software, data, and information to meet project design objectives. Various literature outlined several ways of utilizing BIM for sustainable design, including the requirements for BIM tools and functionality. However, there were still recommendations that revealed conflict in understanding sustainability problems and the means in achieving sustainability. Therefore, this study will adopt a methodology for integrating BIM with sustainable design that will be designed in a modular format and consist of six interrelated modules to make the integrated model unique, flexible, and yet versatile. Furthermore, the developed model aids in selecting the suitable type of construction method associated with the selected design at the conceptual stage by considering 1) users' interactions and input (facilitate design choice from conventional, modular and 3D printing); 2) users' access to accurate and real-time data about green construction materials and associated families for the three construction design methods; and 3) users' evaluate the sustainability of the design using energy analysis, lifecycle assessment, and lifecycle costing analysis.

CHAPTER 3

Literature Review

Sustainable Construction Methods and CDW Management

3.1 Introduction

This chapter examines the two main sustainable construction methods used in the construction industry building projects, namely modular off-site prefabrication and 3D concrete printing. Furthermore, it explores the use of Circular Economy (CE) concept associated with waste management strategies during the construction and deconstruction stages.

As innovations in construction techniques continue to transform the construction toward sustainability, modular prefabrication construction has become the most popular off-site production system. It is promoted as a sustainable alternative to conventional in-situ construction (Mao et al., 2013; Hammad et al., 2019), resulting in noticeable changes in the construction sites. Al-Hussein et al., (2009) identified notable improvements from modular construction, including safer work environments, reduced site injury severity, and lowered on-site noise. Modular Building Institute (MBI) defined modular construction as a process in which buildings are constructed off-site, in a controlled plant condition by using the same materials and designed to the same codes and standards as traditionally built facilities about half the time (Murali and Sambath, 2020). Hence, the process involves pre-fabricating modules under industrial and automated conditions, hauling them and assembling them on the construction site. Kamali et al., (2019) described off-site modular construction as categorized into different levels consisting of component subassembly, non-volumetric preassembly, volumetric preassembly and complete construction. The construction method has attracted growing interest from the industry and academia in the AEC

industry (Yin et al., 2019), because it integrates various techniques and concepts (Li et al., 2020), such as BIM and sustainability. According to Xu et al., (2019), modular construction is gradually adopted as an effective means to embrace productivity, reduce construction time and labour-intensive activities, minimize disruption to the adjacent services, and improve quality. Tavares et al., (2019) predicted prefabrication construction to be one possible way to reduce costs, construction time, energy, and environmental impacts in the building construction sector.

Furthermore, the 3D printing process is another modern innovation that is developed and standardized to print large and complex structures through a rapid prototyping system with good mechanical properties, building a three-dimensional objects by connecting layers of materials, which can be applied to convert waste and by-products into new materials (Siddika et al., 2019). It is generally called cementitious 3D construction printing (3DCP) or 3D concrete printing in the construction domain, which is a form of additive manufacturing used to fabricate complex building enclosures or construction components in completely new shapes that were not previously possible to create with traditional concrete formwork. These advanced technologies have rapidly moved from a conceptual, experimental stage to a feasible building construction stage due to their sustainable, resource-efficient practices and innovative designs and structure trends. Pioneers like Contour Crafting, D-Shape and DUS architects, and several research institutions have actualized 3D construction printing techniques. Potential benefits of 3D construction printing technologies include: 1) faster construction; 2) reduced labour costs; 3) enhanced complexity and accuracy; and 4) greater integration of function and less waste production. In addition, the method allows the contribution of buildings to be undertaken in harsh or dangerous environments unsuitable for a human workforce, such as in space using construction 3D printing (Wu et al., 2016; Sakin and Kiroglu, 2017; Hager et al., 2016).

Moreover, building deconstruction is considered a sustainable alternative to traditional demolition. According to the US Environment Protection Agency (2008), deconstruction is the careful dismantling of a building in a way to recover its construction materials and components by promoting reuse and recycling that can be applied on several levels to salvage usable materials, thereby significantly reducing waste and disposal. Kibert et al., (2001) highlighted several advantages of the buildings' deconstruction as follows: (1) reduces the rate of demolition waste to landfills; (2) reuses potential building components; (3) increases the materials recycling; and (4) enhances environmental protection. Furthermore, deconstruction conserves the use of embodied energy for materials by reducing the input of new embodied energy in remanufacturing those materials. Bertino et al., (2021) affirmed that deconstruction plays an essential role in buildings' circularity and represents a sustainable alternative to conventional demolition. Hence, the provision of materials and components from deconstruction and CDW management strategies for future reuse, repurposing, or recycling is highly aligned with the circular economy for building principles. Therefore, this study will incorporate the CE principles for CDW management by using Design for Deconstruction (DfD) and sustainable prefabricated components (for modular and 3D printing), which are intended to be the way to design and construct buildings.

3.2 Modular prefabrication application and trends

Modular construction is applied to various types of buildings, such as multistory multi-family structures, schools, hotels, health care facilities, and other building types that are found in conventional on-site construction (WBDG, 2016). Literature has demonstrated that modular construction is becoming a popular choice for various sectors globally, with active savings that range from 20% to 50% (Bekdik et al., 2018). This is due to simultaneous site and factory work,

as shown in Figure 3.1, and faster factory's production rate than on-site framing, thereby removing artificial and nature-caused delays such as subcontractor and weather in on-site construction.

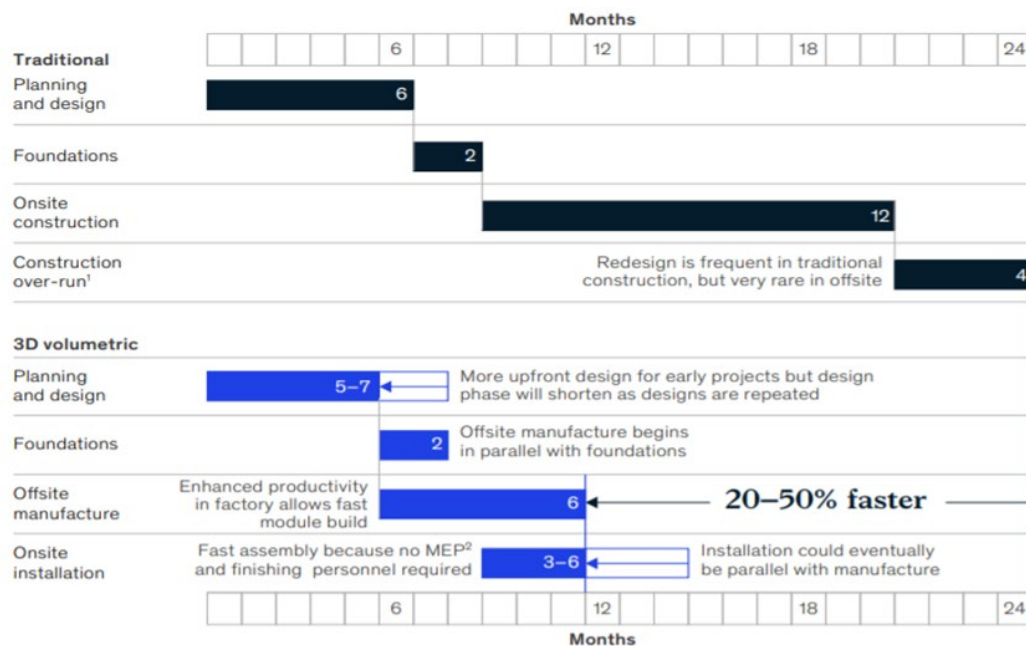


Figure 3.1 - Analysis of time savings in modular construction (Bekdik et al., 2018)

The U.S. Bureau of Labor Statistics' comparison of on-site construction to off-site manufacturing shows that 57% of construction activities are wasteful, non-value-adding, and not compensated. In contrast, 62% of all manufacturing activities are value-adding. In order to achieve time-saving and value addition, modular manufacturing uses an inside-out approach to the building; the frames are constructed as planes, fitted as boxes, and then finished from the inside out following the traditional sequence, which consists of outside in, restricting multiple trades working on top of one another during the build cycle. Smith (2016), in his study, distinguished two segments in the modular industry, which are re-locatable or temporary modular and permanent modular. The study noted that although permanent modular construction has flourished for a decade, especially in the UK and the US, it is still an emerging market in North America compared to the site-built structures that meet the International Building Code (IBC) regulations. The current state of application and

learning that can be applied to the emerging market of the North American commercial modular industry were studied by Smith and Rupnik (2018), who uncovered major parameters that contribute to the successful use of modular construction in the UK, Sweden, Japan, Poland and Australia by using case studies of major modular companies in these countries in order to determine the applicable lessons.

Their study outlined the benefits of modular construction based on the advancement of individual countries as follows: a) In the UK, offsite construction comprises an estimated 7% of the total construction output, amounting to £1.5 billion/year using wood and steel, consequently reducing carbon emissions and promoting the automation of BIM construction; b) Sweden has produced over 10,000 housing units since 1994 through modular construction methods; c) Sekisui Heim in Japan stands as the largest volumetric modular company globally, having produced over 10,000 housing units utilizing steel components and wood frames, thus leading in the areas of reuse and recycling; d) Australian modular companies demonstrate a higher level of diversification, offering various modular solutions, including steel, concrete, and wood frame modules tailored for both urban and suburban housing development.

Hence, similar to conventional construction, modular structures can be constructed from various materials, such as wood, steel, concrete framing, or a combination of material assemblages governed by conventional structure building codes.

3.2.1 Volumetric and non-volumetric modular construction

According to Acero et al., (2016), prefabricated off-site modular building elements are generally constructed as non-volumetric components or as volumetric units. Volumetric modular construction (VMC) is an industrialized construction approach that enables the production of buildings in prefabricated volumetric modular three-dimensional units in a factory but does not constitute the whole building. These units are then transported to the construction site and assembled, interconnected through modular connections (Chourasia et al., 2023). Their benefits include reduced self-weight, less maintenance complexity, and overall cost reduction (Chauhan et al., 2022). Volumetric modular construction is commonly applied in multiunit residential projects such as hotels, dormitories, and apartment buildings. It is also utilized for elements like patient rooms, bathroom pods, and elevator or stair core segments, as shown in Figure 3.2.

Furthermore, non-volumetric modular construction involves off-site prefabrication of building elements into sub-assemblies, which are now assembled on-site without enclosed usable space (The American Institute of Architects, 2019). While non-volumetric elements may enhance transportation efficiency compared to volumetric units, potentially decreasing transportation costs, they require additional on-site assembly and sealing. Nevertheless, it is worth noting that the overall time and labour costs for non-volumetric modular construction are typically substantially lower than those for traditional on-site construction. Examples include precast concrete, wall panels, mechanical, electrical, and plumbing (MEP) corridor elements, and precast staircases, as shown in Figure 3.2. Its advantages include improved structural performance, reduced ergonomic risk, and decreased cost and time (Chauhan et al., 2022).

Notably, this study primarily focuses on non-volumetric modular construction, applying the principles of off-site fabrication technologies, including panelized construction.

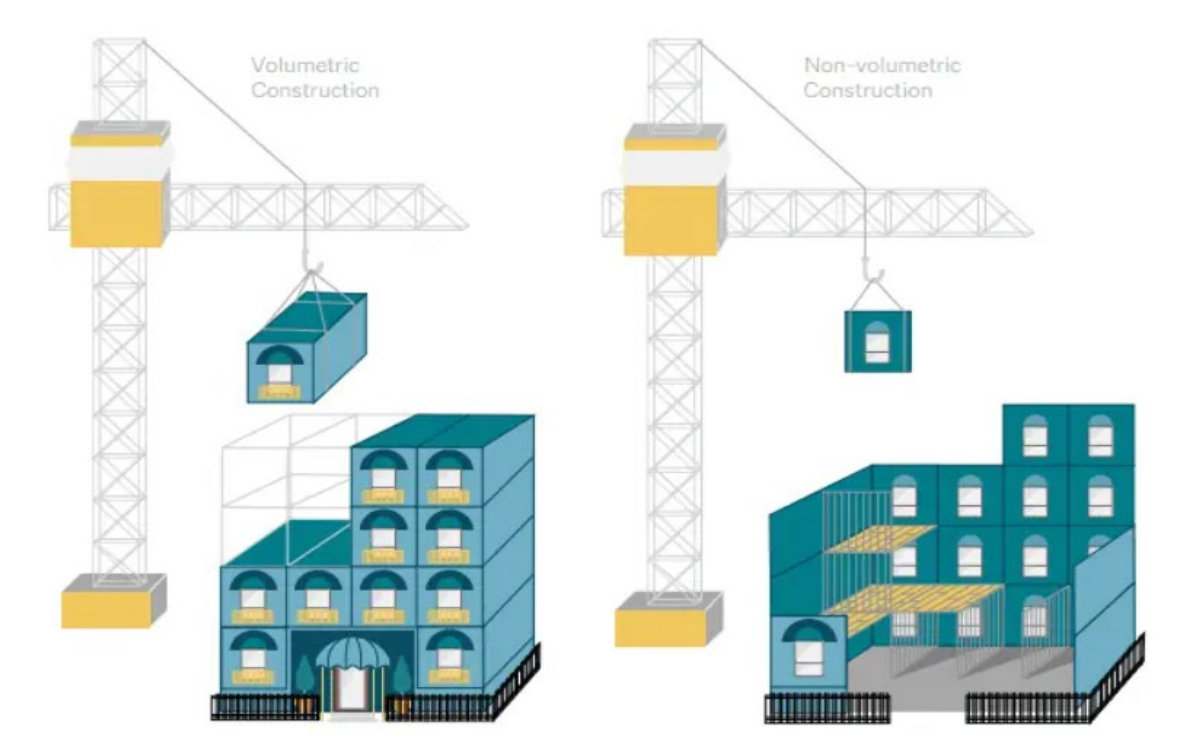


Figure 3.2 - Categories of modular construction (American Institute of Architects, 2019)

3.2.2 BIM in modular construction

The recent development of the Construction 4.0 framework, which is at the centre of the current state of practice by emerging trends and technologies; people and process issues that surround the AEC industry's transformation; BIM; lean principles; digital technologies; and offsite construction, is at the edge of this extensive transformation (Sawhney et al., 2020). Presently, there are strong recommendations for the uptake of modular construction and BIM in order to improve the sustainability performance of the construction industry, their benefits have been well-explored in several studies such as Kamali et al., (2019); Xu et al., (2019); Abanda et al., (2017); and Smith (2016). However, some studies still acknowledge specific reasons that hinder BIM application in modular construction. An example of such a review was conducted by Yin et al., (2019) to gain an in-depth understanding of the domain knowledge and research trends in BIM and offsite

construction. The study revealed a lack of corresponding codes, policies and changing requirements to the company's organizational structure, which weakened the value of BIM's application in off-site construction. However, Barkokebas et al., (2021) expressed that BIM and off-site construction are closely interconnected and can be combined to optimize their advantages for the construction industry. Furthermore, Abanda et al., (2017), in their five-stepped review, examined the benefits and barriers hindering BIM uptake for off-site construction and summarized the following key barriers: 1) lack of capable skills workforce to implement BIM for off-site manufacturing; 2) initial set-up expensive; 3) high cost of crane installation; 4) intercity or intercounty transportation; 5) need for project's pre-planning by potentially increase project lead times and may eliminate any overall time saving and advantages; 6) low level of IT integration in the construction industry; 7) difficulty in producing facility's logistics and stock management (e.g. limited access onsite for manoeuvre, restricted access to the site for delivery, with sized components; 8) use of paper-based drawings inhibits off-site manufacturing; and 9) poor integration of construction supply chain. BIM is acknowledged as beneficial for off-site construction, lean construction, and sustainability, with the construction method being recognized to contribute significantly to buildings' sustainability.

Hence, this study leverages the competence of BIM tool (Autodesk Revit) to conceptually design a non-volumetric modular building as one of its construction methods for evaluation, analysis, calculation, simulation and comparison for adequate decision-making regarding suitable construction methods.

3.3 Application of 3D concrete printing (3DCP) in construction

3D printing took a revered position in the construction after Behrokh Khoshnevis, a professor at the University of Southern California, constructed the first-ever 3D concrete printed wall. Since

then, the application of 3D printing in construction has seen significant development (Hwang and Khoshnevis, 2004; Khoshnevis et al., 2006; Zhang and Khoshnevis, 2013). Several studies have examined and evaluated the design, technology, material, machine, process, and final product of 3D printing construction to leverage emerging innovations in overcoming the challenges of conventional construction methods. Dixit (2019) argued that 3D concrete printing and associated technologies might represent a paradigm shift in the design, construction, and management of buildings, which requires validations such as LCA or material flow analysis (MFA) to maximize their sustainability benefits. The process of 3DCP is divided into seven categories: 1) material extrusion; 2) material jetting; 3) binder jetting; 4) powder bed fusion; 5) directed energy deposition; 6) vat photopolymerization; and 7) sheet lamination (Paolini et al., 2019). The literature shows that currently, the construction industry is concerned with the process, technology and material application of the 3D concrete printing.

3.3.1 3D concrete printing (3DCP) process and technology

The printing processes follow a similar procedure and begin with the creation of a 3D computer-aided-design (CAD/BIM) model, which is sliced into several 2D layers and incrementally printed with an assigned material to obtain the prototype, as illustrated in Figure 3.3 (Tay et al. 2017; Valente et al. 2019; Yin et al., 2018). Mechtcherine and Nerella (2018) described the approaches for concrete digital building as a process based on extrusion, selective binding, alternative layered concrete laying process, and adaptive slip forming (Smart Dynamic Casting).

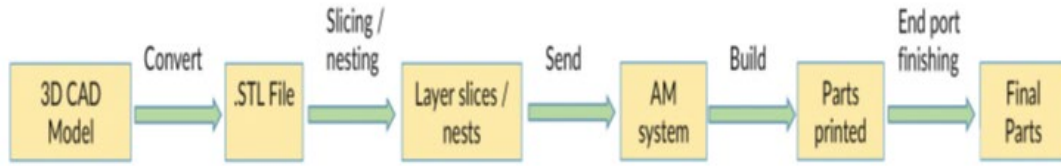


Figure 3.3 - Workflow in the 3D printing process (Yin et al., 2018)

Furthermore, other processes include: 1) the FreeFAB (from the Engineering Excellence Group Sydney, for the production of formwork from recyclable wax employing a 6-axis gantry robot); 2) ETH Zurich's Smart Dynamic Casting (it allows printing of complex-shaped columns with changing cross-sections); and 3) Mesh Mould (with all autonomous mobile robot named In-situ Fabricator, which creates a metal mesh by bending and welding steel wires and reinforcement in integration processes that are used in aggregate-base, metals, and polymers 3D printing) (Paolini et al., 2019). According to COBOD International (2021), 3D printing technologies for construction are currently used in several ways. However, the two specific methods presently adopted by the industry are: 1) Gantry-type 3D printers (used for large construction and on-site); and 2) Robotic arm 3D printers (used for smaller but more complex components). Moreover, the robotic arm generally has a smaller reach and will print modules/parts/elements of the whole building, typically done off-site. In contrast, the gantry system can print the entire building on site because it can reach considerably long distances. Although there are some similarities between the two methods, the difference in their applications is illustrated in Table 3.1.

Previous studies have investigated the idea of freedom in construction through 3DCP processes, analyzing its three main methods and utilizing granular materials to maximize the environmental advantages of on-site 3D printing and large-scale building printing (Al Jassmi et al., 2018; Dixit 2019; Siddika et al., 2019). Some of the methods are: 1) contour crafting (CC), introduced by Khosnevis (2010), who proposed a gantry-based system of nozzles to pour concrete in layers

within a mould; 2) D-shape, which involves depositing a structural ink (magnesium oxide or magnesium chloride) over sand; and 3) 3D concrete printing using extrusion of cement mortar.

The three methods (printer and process) are shown in Figures 3.4 through Figures 3.6.

Table 2.1 - Comparing 3D printers: gantry vs. robotic arm (COBOD, 2021)

Attributes	Gantry System	Robotic Arm
Optimal/typical location	On-site	Off-site
Volume printed	High	Low
Market drivers	Costs and free forms	Free forms and special from customers
Promise to industry (on productivity)	Entire buildings on-site, high productivity, repeatable quality	Single, complex elements site, high agility, complex geometry
Competitors in the current market	General contractors (low skill)	Specialized contractors (high skill)

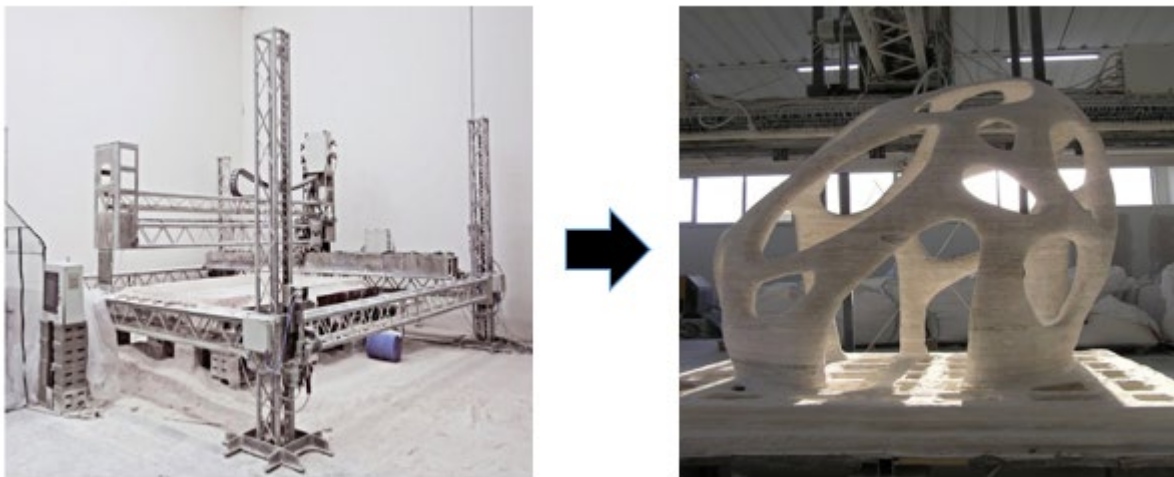


Figure 3.4 - D-shaped printer and the printed structure

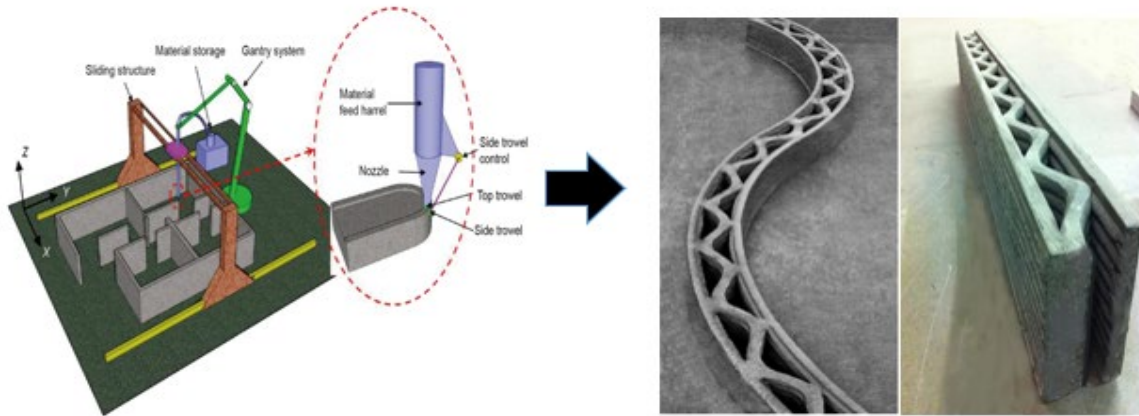


Figure 3.5 - Contour Crafting and the printed structure

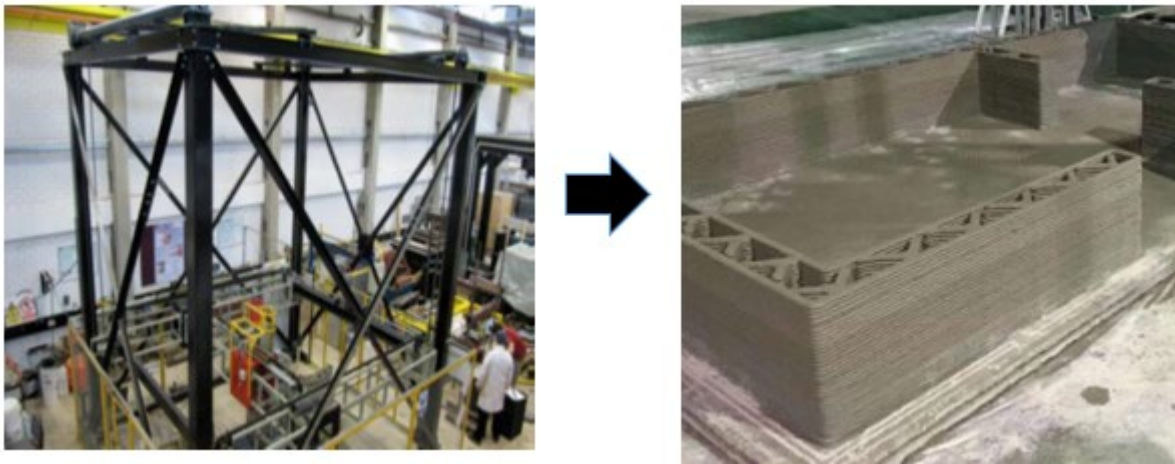


Figure 3.6 - 3DCP machine and the printed structure

3.3.2 3D printing materials

3D printing materials are found in four typical states, which are: 1) solid-like (bonded with glue-like material or 3D weaving); 2) viscous-like (extruding via a printing nozzle); 3) powder-like (transformed to solid-state using melting or sintering; and 4) liquid-like (transformed to solid such as stereolithography using lighting source) (Al Jassmi et al., 2018; Labonnote et al., 2016). Figure 3.7 illustrates the four typical states of 3D printing materials.



Figure 3.7 - States of 3DCP materials (solid, viscous, powder and liquid) (Labonnote et al., 2016)

The main characteristics of the extrusion-based process were identified by Lim et al., (2012) as: i) permeability, the ease and reliability with which material is moved through the delivery system; ii) printability, the ease and reliability of depositing materials through a deposition device; iii) buildability, the resistance of deposited wet materials to deformation under load; and iv) open time, the period where the above properties are consistent within acceptable tolerances. Presently, the type of materials used in 3D printing include: polymer; fibre-reinforced polymer; metals; ceramics; and granular materials like cement and sand; however, polymer and granular materials are the most commonly used (Duty et al., 2017; Yin et al., 2018). Granular materials (i.e.sands, cementitious materials, and dirt) are used in binder jetting and extrusion deposition. Those materials are in wet form in the extrusion process, premixed with water and additives to accelerate curing or setting and then extruded through the printing head to create the 3D structure. At the same time, the polymer-based materials are used in the extrusion deposition process in a dry form. The dry process involves the printing head extruding a binding agent onto a bed of powdered material, where it reacts to fuse the structure (Yin et al., 2018). Recent studies are more devoted to developing new printable mortar for concrete materials, recycled glass aggregates, and crushed rock dust (basalt), which are also being tested to enhance appropriate formulation for sustainable construction (Tay et al., 2017).

3.3.3 Challenges and limitations in 3D-printing application

3D printing technology can revolutionize the construction industry. However, studies have shown that despite the continuous progress of reviews and implementations, the application of the 3D printing process is still confronted with numerous limitations. Siddika et al., (2019) highlighted challenges and proposed solutions concerning low bond strength between successive layers, deformation and apparent complexity from a formwork-less system, drying shrinkage, plastic deformations, and high cost. Dixit (2019) highlighted the issues and listed recommendations about reinforcement integration, which include workability, extrudability, buildability, printing size, speed, nozzles, scale and printer cost. Other documented challenges include: (1) continuous and uniform extrusion; (2) building codes change for the construction permit; (3) inadequate rheological, stiffening properties, and appropriate curing of 3D printed elements; and (4) digital data triplet challenges. The literature clearly indicated the limitation in studying the sustainability of 3D printing construction, especially in using lifecycle assessment (LCA) to balance the advantages and disadvantages of additive technologies in the context of environmental impacts in a complex manner. Saade et al., (2020) noted that there are no documented review of Additive Manufacturing's (AM) life cycle impact. Tay et al., (2017) indicated a lack of research on the use of LCA tool to measure the environmental impacts of all stages of the product's life and provide insights into the environmental improvement of 3D printing. Hence, there is still a lack in the fundamental understanding of the economics that printing technology could offer. Moreover, a decision-support system based on a quantitative environmental assessment at a building scale is lacking, which hinders the efforts to maximize energy and environmental benefits of 3D-printed construction (Al Jassmi et al., 2018). LCA serves as an additional lens to select an optimized manufacturing approach from the environmental perspective before applying AM on a large scale

within any industry (Saade et al., 2020). Therefore, this study will establish an LCA and LCCA framework to use when measuring the environmental, economic, and social sustainability of 3D printing construction of a building in response to the limitations found in other studies.

3.3.4 BIM and 3D printing in construction

Building Information Model (BIM) tools are the bedrock of the 3D printing applications in the AEC Industry. BIM produces and manages sophisticated data structures by specifying all information about the geometry, materials and element characteristics printed in a digital 3D model, followed by process automation and finally transmitted to the printer via a specific programming language. The benefits of using BIM throughout the 3D printing lifecycle from design to end of life cannot be overemphasized. According to Tay et al., (2017), BIM-based 3D printing can be a method for the construction industry to look forward to bringing obvious benefits and substantial savings in cost and labour. BIM is proven to be an effective method to facilitate 3D printing implementation in the construction industry and can be used in a small and large-scale 3D printing buildings (Wu et al., 2016). Various BIM-based 3D printing applications have been discussed and implemented in the literature, for instance, Smarsly et al., (2020) designed and implemented a BIM-based PIM application model that consists of process, material and geometry parameters. Thus, the PIM application consisted of: (i) BIM models and (ii) user-defined inputs such as printhead and pump parameters. In addition, an algorithm for calculating slicing (to obtain contour line data) and an algorithm for calculating filling (to obtain toolpaths) was implemented into the PIM application, at the same time, the output is CNC code for hardware control of concrete printers. Davtalab et al., (2018) proposed a construction operations control software named Planning and Operations Control Software for Automated Construction (POCSAC), which receives and processes an architectural/engineering digital CAD model, extracts required data, and

sends them to different units. At first, the 3D model of the structure is sliced into 2D layers of desired thickness, followed by a toolpath optimization by POCSAC for layers of the sliced model. Then, numerical control commands (G-code file) and data regarding mixture proportions are generated and sent respectively to the robot and the material preparation unit. In both cases, BIM models are exported by using IFC file format. As discussed earlier and shown in Figure 3.4, all 3D printing follows a similar procedure, which is described in six stages, starting with the 3D-modeling application (Autodesk Revit) and exported to an STL file format. However, Smarsly et al., (2020) acknowledged that the current data models in conventional AM are based on Standard Tessellation Language (STL), and G-code, ISO 6983-1, are not suitable for concrete printing of components of high load-bearing capacity and geometric precision (Bonnard et al., 2018). They also emphasized that the significant shortcoming in AM modelling is the lack of knowledge on how processes, materials, and geometries interrelate in AM data modelling that causes redundancy, information loss, and inconsistencies. In addition, Tay et al. (2017) noted numerous challenges related to scaling, materials, delivery system and suitability to adverse environments in combining BIM and 3D printing. The usage of BIM for 3D printing is still not widely practised, and additional research on this construction method is required to bridge the gaps between BIM and 3D printing (Tay et al., 2017).

3.4 Circular Economy overview

Circular economy (EC) is transitioning towards greener options, fostering a cleaner and more competitive economy in the AEC industry, which traditionally adhered to a linear approach of taking, using, and disposing of products (Campbell-Johnston et al., 2019; Minunno et al., 2020). Up to present, the construction sector stands as one of the world's largest consumers of energy and raw materials, exerting a significant impact on the environment through activities that contribute

to greenhouse gas emissions, with construction and demolition waste being a particularly substantial contributor (Won and Cheng, 2017; Zuo et al., 2012).

Leising et al., (2018) defined CE as a lifecycle approach that optimizes buildings' useful life, integrates the end-of-life phase in the design stage, and uses new ownership models to temporarily store materials in a building that acts as a building material bank. Hence, CE is considered as one of the most viable approaches to sustainability (Geissdoerfer et al., 2017), enhancing building construction advantages by minimizing its negative environmental, economic and social impacts. Van Sante, (2017) referred to the adoption of CE in the construction industry as circular construction, although its application to the construction sector is still limited (Gallego-Schmid et al., 2020; Campbell, 2019). Besides, CE uses practices in all phases of the life cycle of a building to keep the materials longer in a closed-loop to reduce the use of new natural resources in building construction projects (Benachio et al., 2020). Adams et al. (2017) stressed that the application of circular economy in construction is mainly limited to construction waste minimization and recycling. Liu et al., (2017) considered CE as an appropriate approach to managing construction waste by reusing products. Sanchez and Haas, (2018a) recognized the adaptive reuse of building components as attractive because of their restorative and regenerative nature, which aligns with circular economy building principles. Minunno et al., (2020) explored the environmental benefits of building by using three CE practices: (1) design for disassembly (DfD) to enable components second life; (2) integration of reused materials at the construction stage; and (3) implementation of adaptable design to eliminate waste during the operation stage. However, most scholars focus on the “design for deconstruction” (DfD) as a critical solution to facilitate materials’ reuse in the building construction, although the potential carbon benefits of reusing construction materials are not immediately gained (Gallego-Schmid et al., 2020). Pomponi and Moncaster, (2017) listed the

following six dimensions: i) government; ii) economic; iii) environment; iv) behaviour; v) society; and iv) technology, as the drivers and barriers for adopting CE by conceptualizing the AEC industry for the material and component, building unit and city levels. Nuñez-Cacho et al., (2018) proposed the following seven weighted dimensions: energy; materials; water; and 3Rs (Reduce, Reuse, and Recycle) for the scale of resource management; waste and emissions for environmental impact; and CE principles. Meanwhile, Mhatre et al., (2021) highlighted various CE strategies throughout a building's life cycle, to include: policies; economic instruments; prefabrication; design for disassembly; waste prevention; and waste management; including collection, segregation, distribution, selective deconstruction, and demolition audits for effective material recovery at the end-of-life. However, the shared principles of CE lie upon adequate resource management and waste minimization by closing material and energy loops (Lacy and Rutqvist, 2015; Geissdoerfer et al., 2017; Pomponi and Moncaster, 2017). Thus, waste from construction activities is reusable through the closing resource loops of the CE principle known as recycling; while the construction activities, on the other hand, generate substantial employment opportunities, provide essential services to meet human needs, and contribute to nations' gross domestic product (GDP) (Akanbi et al., 2019; Smol et al., 2015). Therefore, this study will develop a framework for an innovative approach that will integrate BIM, CE principles for CDW management at the conceptual design stage of building projects.

3.4.1 Implementing Circular Economy through CDW management

According to Yeheyis et al., (2013) the waste due to construction has always been generated due to the following reasons: 1) design errors; 2) inadequate procurement and planning; 3) inefficient construction material handling; 4) residues of raw materials, and 5) unexpected changes in building design. As a result, it is obvious that the design stage is a strategic element that influences the

waste generated during the construction of projects (López Ruiz et al., 2020). Furthermore, 90% of relevant decisions to the building's configuration, composition, process and schedule are made at the conceptual design stage, therefore, the most effective opportunity to integrate CDW strategies such as materials' selection and design for deconstruction, should be as early as possible. Adams et al., (2017) studied the CE aspects of construction waste minimization and recycling across a building's life cycle to categorize various CE applications within the project life, such as design, construction and end-of-life, as shown in Table 3.2. The study identified three main design strategies for CDW management, which are categorized as: (i) design for waste prevention; (ii) design for deconstruction; and (iii) use of prefabricated elements.

Table 3.2 - Circular Economy applications within the project lifecycle stages (Adams et al., 2017)

Life Cycle	Circular Economy
Design stage	Design for deconstruction Design for adaptability and flexibility Design for standardisation Design out waste Design in modularity Specify reclaimed materials Specify recycled materials
Construction stage	Minimize waste Procure reused materials Procure recycled materials Off-site construction
End of life	Deconstruction Selective demolition Reuse of products and components Close-loop recycling Open-loop recycling

3.4.2 Design for deconstruction (DfD)

The literature review has promoted the design for deconstruction (DfD)/design for disassembly as a lifecycle circular economy technique to facilitate sustainable waste management at the design stage of buildings (Akinade et al., 2017; López Ruiz et al., 2020; Jaillon and Poon, 2014; Ghisellini et al., 2018b; Huang et al., 2018). DfD is a method where a building is designed to facilitate adaptation, renovation, and reuse of materials and components at their end of life for materials' recovery, building relocation, component reuse, and materials' recycling or remanufacture (Kanters, 2018; Akinade et al., 2017). Zizzo et al., (2017) described it as a building “designed with the end in mind” in a cost-effective manner that can be rapidly taken apart at the end of life, and its components can be reused or recycled. The process involves the design team who is creating a disassembly plan that sets out the disassembly method of major systems during renovations and end of life and the properties of major materials and components. DfD approach is seen as a dynamic technique to overcome challenges associated with reusing building components, including the underdeveloped market for salvaged materials; the unreliable quality of salvaged components due to damages; the lack of standards and codes to help regulate the use of salvaged materials (Cruz-Rios and Grau, 2020; Kibert et al., 2001; Kibert and Chini, 2000; Nakajima, 2014). Hence, DfD is a fundamental strategy for achieving more sustainable buildings that promote a closed-loop system for building components (López Ruiz et al.; 2020). In addition, the environmental benefits of DfD are the preservation of embodied energy, the reduction of carbon emissions, and a reduction of pollution; a social benefit of creating jobs for unskilled workers; and the economic benefits are the creation of a new market for salvage materials and cost reduction (Akinade et al., 2017; Kanters, 2018; Rios et al., 2015). According to Cruz-Rios and Grau, (2020); Guy & Ciarimboli, (2007) the fundamental principles of DfD include: 1) proper documentation of

materials, components, and methods for deconstruction; 2) design of accessible connections to ease dismantling (e.i., using bolted, screwed, and nailed connections); 3) separation of non-recyclable, non-reusable, and non-disposal items; 4) standardization of components and dimensions; and 5) design that reflects labour practices, productivity, and safety (Guy and Ciarimboli, 2007). However, it is necessary to consider the ease of disassembly during the design phase with the aim to reuse, upgrade or recover individual components, if the consideration is not made, reusing individual parts at the end of their lifecycle might be limited (Tao et al., 2012). According to Kibert (2013), to achieve circularity and shift downwards to closed-loops of material production, DfD implementation is considered as mandatory. Rios (2018) illustrated the process of closing the production cycle in the construction industry, as shown in Figure 3.8.

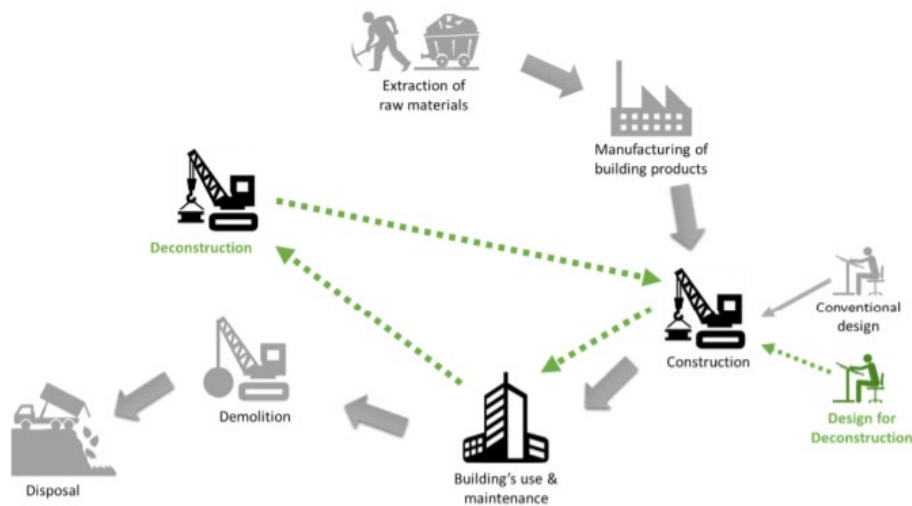


Figure 4.8 - Design for deconstruction (DfD) approach using CE (Rios, 2018)

The literature review shows that prefabrication is a source of opportunities for DfD. Therefore, this study will focus on DfD by using prefabrication structures for waste management of modular and 3D building construction methods at the conceptual design stage of the building.

3.4.3 BIM and Design for Deconstruction

Building Information Modelling (BIM) concept is one of the most commonly used to support the design team in designing for deconstruction in the construction sector. In addition, BIM tool plays a significant role in developing DfD tools; it is a platform to store and model a sophisticated 3D building, including its schedule, cost estimate, analysis, management etc. (Kanters, 2018). Despite these advantages, few studies have investigated and demonstrated an eagerness to use BIM and DfD tools to achieve adequate life cycle management and data transparency (Akbarieh et al., 2020; Akinade et al., 2017; Akanbi et al., 2019; Akinade et al., 2015; Akinade et al., 2017). Akinade et al., (2017) assessed existing DfD tools and identified essential functionalities of a BIM-based tool for DfD. They identified the following seven key functionalities as results of focus group interviews: i) improved stakeholders' collaboration; ii) visualization of deconstruction process; iii) identification of recoverable materials; iv) deconstruction plan development; v) performance analysis and simulation of end-of-life alternatives; vi) improved building whole life management; and vii) interoperability with existing BIM tool. Akinade et al., (2015) developed a BIM-based tool for deconstruction based on a mathematical model describing the set of materials, components, and connectors, how and if they are reusable, etc. By assigning a specific Deconstructability Assessment Score (BIM-DAS), they described a model to determine how a building could be deconstructed right from the design stage of a building. Akinade et al., (2017) revealed the following (technical and non-technical) success factors as acceptable for effective material recovery through DfD to approach the EoL disposal of buildings in a sustainable way. Those include: legislation and policies; design for material recovery design process and competency for deconstruction; design for building flexibility, and design for material reuse. However, despite of those studies based on the idea of using BIM and DfD tools to achieve adequate life cycle

management in construction, some have revealed substantial hindrance in the application of BIM-based DfD as a result of the perceived disconnection between BIM and EoL/DfD management and planning tools (Akbarieh et al., 2020). Some of the mentioned reasons are the amount of DfD documentation, the availability of deconstruction documents in the future, and the unknown time frame of actual deconstruction activities (Akbarnezhad et al., 2014).

3.4.4 BIM and Circular Economy for CDW management

Won and Cheng, (2017) identified potential opportunities for BIM to be used for efficient CDW management, such as design review and coordination, quantity take-off, phase and site utilization planning, construction system design, digital fabrication, and 3D control and planning. Liu et al., (2015) developed BIM-aided CDW management framework to address factors that cause design waste to aid designers in making effective decisions related to their building projects. Studies show that utilizing BIM tools can significantly mitigate the primary factors causing CDW by integrating design and construction processes. These studies suggest that BIM can reduce CDW through improved accuracy and quality of design and construction data, which in turn reduces design errors, rework, and unexpected modifications (Ge et al., 2017 and Cheng et al., 2015). Akinade et al., (2017) explored the limitations of existing DfD tools to clarify the essential BIM functionalities that could provide effective decision-making processes for DfD. Elmaraghy et al., (2018) investigated the possibility of extending BIM functionalities to support deconstruction processes in line with lean principles. Ge et al., (2017) developed a BIM-based system to improve the accuracy in managing demolition waste with a reconstructed 3D model. Jayasinghe and Waldmann, (2020) proposed a BIM-based tool that supports the circular economy by efficiently documenting material information and building components, accounting for recycling materials and reusable components. BIM can also facilitate data management in identifying building

components that can be reused and or recycled in advance and identify cost and risk in the waste disposal at the deconstruction phase of a building (Jayasinghe and Waldmann, 2020 and Liu et al., 2015). However, despite of these studies, there is still no adequate understanding and a developed framework for integrating BIM tools for applying Circular economy in CDW management in the construction circular economy. Therefore, this study will develop an integrated framework that integrates BIM with CE strategies for effective waste management during the conceptual design stage of buildings.

3.5 Summary

This chapter reviewed the literature related to sustainable construction methods and waste management during the construction and deconstruction of a building. Sustainable construction methods are considered effective techniques for achieving sustainability in buildings. Therefore, this chapter examined the literature on modular off-site and 3D printing construction methods as the AEC's current state-of-art in building digitalization for sustainable practice, including their application and current trends in the AEC industry. The chapter also provided a literature review on the various applications of BIM on modular off-site prefabrication and 3D printing construction methods. Additionally, construction and deconstruction waste (CDW) management employing circular economy principle was revealed to be a viable approach to sustainability, not just at a building's end-of-life, as argued by some literature. Instead, CE uses practices in all construction life cycles to attain sustainability. The literature identified three specific phases in the construction life cycle and its associated CE practices for enhancing sustainability, which are: 1) design phase using design for deconstruction; 2) construction phase using off-site construction or prefabrication, and 3) deconstruction phase using selective disassemble. Therefore, this study will develop a methodology for integrating BIM with construction methods and construction and deconstruction

waste (CDW) management employing circular economy strategy. The conceptual 3D models are modular off-site and 3D printing, designed individually using the design for deconstruction (DfD) approach to make the intended model unique and flexible and represent sustainable construction methods. Each construction design method will use the associated design data collected and stored in the external database engine for the design type. Second, the construction and deconstruction waste (CDW) management module uses the integrated BIM-based Circular Economy model to evaluate the various equipment required for CDW management, ultimately translating into the project's lifecycle cost.

CHAPTER 4

Model Development Methodology

4.1 Introduction

This chapter describes the methodological approach to be used in developing the model that integrates Building Information Modelling (BIM) and sustainability to select the suitable type of construction method associated with the selected type of design at the conceptual stage. Therefore, the analysis and development scope will focus on using the three constructions to evaluate and justify environmental and economic sustainability indicators, associated criteria, and various sub-criteria. These include environmental impact, lifecycle cost analysis, building operational energy demand, and thermal comfort. These indicators and criteria are used to address multiple aspects of sustainability in a building. The associated process considers 1) users' interactions and input to facilitate the design choice for modular and 3D concrete printing; 2) users' access to accurate and real-time data about sustainable construction materials and associated design families for the associated construction methods; and 3) users' evaluation of the design's alternative to compare construction methods and select the most suitable of the three methods using energy analysis, life cycle assessment, and life cycle costing analysis.

Moreover, the methodology for developing the model will automate the integration by customizing BIM tools' application programming interface (APIs) to help users connect their sustainable design and select the suitable construction method through six different modules from within BIM tool (i.e., Autodesk Revit). The model's flexibility will make it applicable to any of the three design and construction methods (i.e., conventional, modular, and 3D concrete printing). This will provide owners, designers and general contractors with different options to select from when assessing the design alternatives at the conceptual stage of the project's life and accordingly

identify the suitable construction method. The path in developing the integrated model is implemented through three main phases, as illustrated in Figure 4.1, phase one will encompass a literature review and data collection to determine the actual needs, gaps, and expectations associated with integrating BIM and sustainability tools in the selection of construction methods; phase two, will develop the conceptual integration framework by using gaps analysis to identify their effective solutions; and phase three, will develop the integrated model, that holds the proposed solutions for the identified gaps, through six interrelated modules: 1) DBMS module; 2) Decision support system module; 3) Energy and thermal simulation module; 4) Circular economy for CDW module; 5) LCA module; and 6) LCCA module.

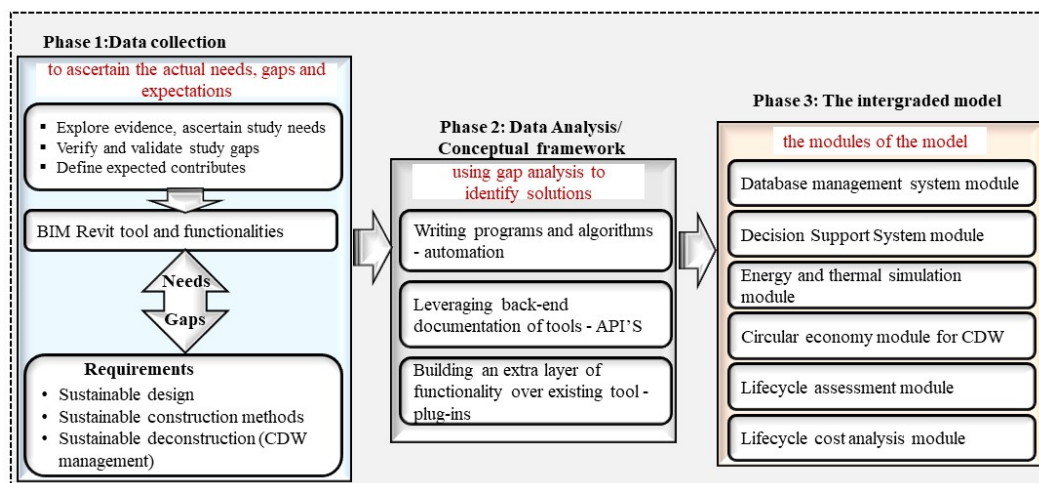


Figure 5.1 - Development workflow of the integrated model

The model's development process will include harmonization and automation, which will be achieved by using a plug-in application in BIM tool (Autodesk Revit). At the same time, the capabilities and functionalities of that plug-in will be finally tested and verified with an actual sustainable building project. The expected novelty in this methodology is in implementing the

elements of “Construction 4.0” (i.e., additive manufacturing, prefabrication, modularity, circular economy, and BIM) within an integrated BIM-sustainable design model to enhance the construction innovation and to provide users with additional design options at the conceptual stage. Therefore, three different categories of materials and components will be used in the design (i.e., conventional, modular, and 3D concrete printing), which will be collected and stored in a design engine, incorporating sustainable-certified elements that are required to improve the workability and capability of BIM tool during the design stage.

Generally, part of the methodology will test the data transmission approach, interoperability, extendibility, and capacity of BIM tools for their seamless integration with other analysis tools. The successful implementation of such a methodology will help building owners and practitioners make rational decisions about selecting construction methods by using relevant building sustainability strategies to evaluate and verify their decisions.

4.2 Model’s requirements

The model’s requirements were formulated based on the listed research objectives and the condensed literature review, which include: 1) sustainable design philosophy (using skillful and sensitive design to reduce the consumption of non-renewable resources such as raw materials, energy and water; eliminating the negative environmental impact all over buildings lifecycle; thereby improving the health and comfort of occupants); 2) selection of the sustainable construction method (provide designers with a tool to help them assess different construction alternatives at the early design stage of the building, which will lead to the selection of the suitable construction method); 3) sustainable construction and deconstruction waste management using circular economy principles to facilitate the future circular use of building materials and components at the design stage, focusing on producing less waste and potentially to reuse high-

quality recycled building major elements after deconstruction. Based on the primary objectives of sustainability, which are to reduce consumption of non-renewable resources, minimize waste, and create healthy, productive environments, the trends and technologies are to reshape how the built environment assets are designed, constructed, and operated. Essential data and metadata necessary for the integrated model will be sourced from related literature, vendor sites, materials databases, and other credible outlets. The study will also identify the critical challenges resulting from the fragmented state of the built environment and its inability to meet demands for a new and refurbished structure that is accessible, healthy and productive while minimizing the impact on society, the economy and the environment. Therefore, one of the requirements of the integrated model is to support flexible and practical design for buildings with a net positive benefit throughout their lifecycle to ease current and future sustainability requirements and challenges by leveraging automation processes. Hence, the model will use a BIM tool (Autodesk Revit) and 3D BIM design model to anchor the integration of sustainability assessment tools and frameworks to perform the necessary calculations, analysis, and simulations within the design criteria for adequate decision-making related to the selection of suitable construction alternatives. Finally, the model will be designed and distinguished through the following characteristics:

- **Data-Driven:** the model will offer a rich pool of information and details about sustainable materials and families across three distinct databases. These datasets will be collected, stored, and leveraged to enhance the functionality of BIM tool, aligning with predefined criteria for the overall sustainable performance of buildings.
- **Practical:** the approaches will incorporate methods for executing fast calculations by using available tools, expressions, equations, and Structured Query Language (SQL).

- Flexible: the design will adopt a modular approach, ensuring an ease of management for maintenance and modifications. This includes incorporating additional functions based on data from past and present studies to enhance the model's versatility and sustainability. Users will be able to conveniently add and modify the data in a user-friendly manner.
- Efficient: the process will facilitate a range of tasks, including design reviews, constructability assessments, and simulations of process and construction costs, which will be achieved through digital visualization of the design, particularly emphasizing its 3D modeling, tailored to three distinct construction methods.
- Automatic: users will receive instant assistance in identifying the optimal construction method that aligns with the specified sustainable design's parameters. Moreover, it will ascertain the feasible height and size of the building based on the chosen construction method and type of design.

4.3 Model's components

The integrated model will be developed to instantly connect, analyze, and share data within its components. The model's components, shown in Figure 4.2, consist of six modules: 1) a database management system (DBMS) module for collecting, storing and retrieving design data; 2) a decision support system (DSS) module; 3) an energy and thermal simulation module that facilitates the analysis of the energy performance of buildings; 4) a circular economy (CE) module for construction and deconstruction waste (CDW) management strategies; 5) a Life Cycle Assessment (LCA) module, which is used to evaluate the environmental impact of the various stages of the building project; and 6) a Life Cycle Cost Analysis (LCCA) module, to facilitate a detailed assessment of the financial implications of the different design options throughout its life cycle.

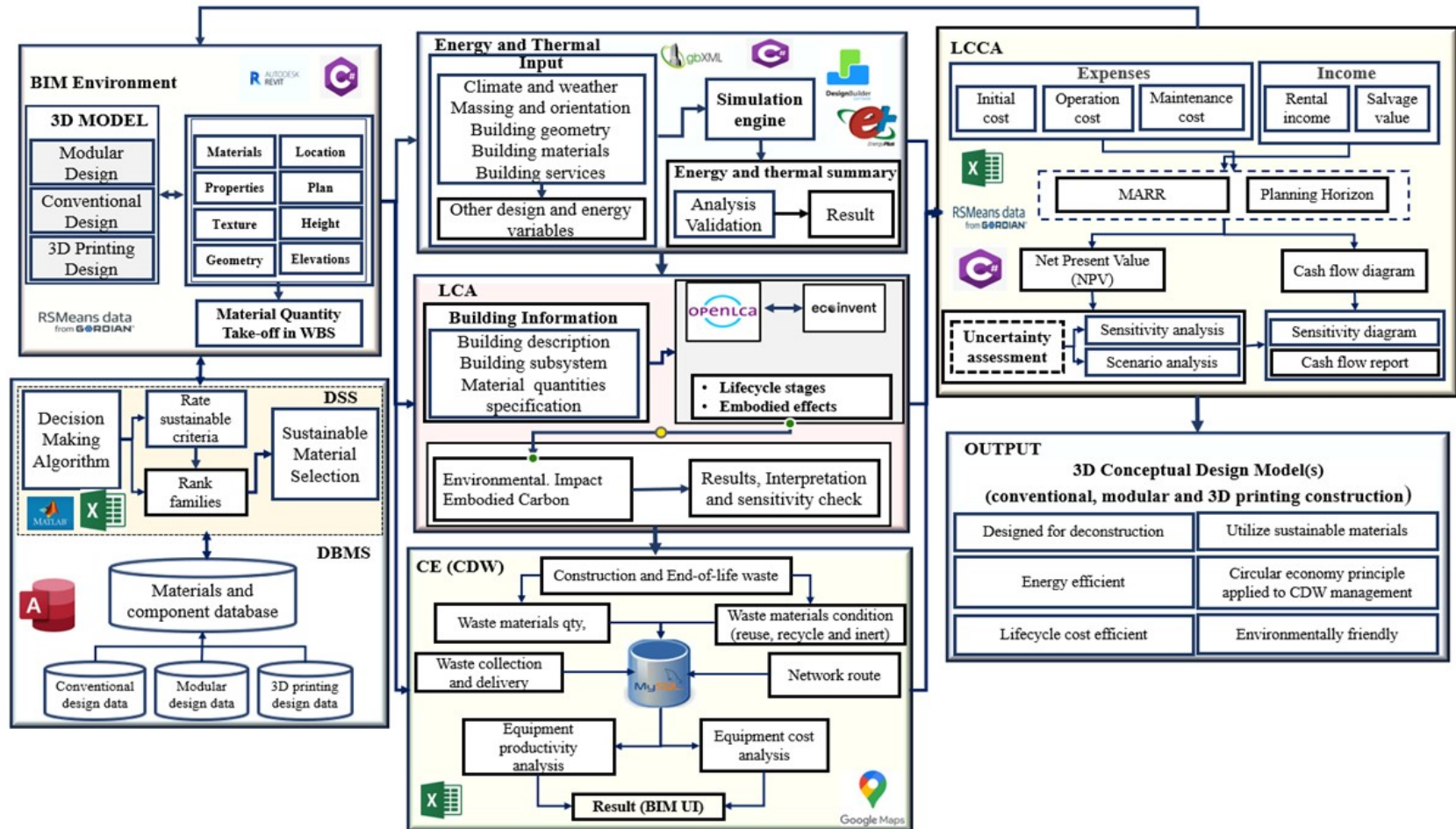


Figure 4.2 - Components of the integrated model

The modules listed above are interrelated to each other to make the integrated model unique, flexible, and versatile. Furthermore, BIM serves as the foundation for all the functions performed by each component by using its associated plug-ins that will be capable to unlock the full potential of these integrated modules and maximize the correctness of the information, data, and technology. The model's components will be developed following a broad review of the literature with a thorough understanding of the gaps, needs, requirements, and expected outcomes. In the first module, data on sustainable materials will be collected and stored in an external database; those materials will be used to create new 3D design families and objects that will be recognized by BIM tools during the modelling stage of the building envelope. The newly created families and design families are obtained from vendors and will undergo the evaluation and selection by utilizing a fuzzy-based decision support system before being incorporated into the conceptual design model. Upon completing the 3D design model, the materials' quantity take-off will be extracted from the BIM model to assess the environmental impact and to estimate the energy demand of the building for thermal comfort. The quantity take-off will be used in the cost domain to estimate initial project, operational, and end-of-life, including CDW equipment costs and the resulting lifecycle cost will be normalized after running the sensitivity analysis.

4.4 Model's architecture

The architecture of the integrated model, which is shown in Figure 4.3, consists of four sections: 1) input data and information as required for each module; 2) specific criteria as required by the related module to initiate and execute the analysis based on the input; 3) various types of analysis that will be performed by each module directly or via a new plug-in in BIM environment for an outcome; 4) the outputs of the model will be an analysis, evaluation and cost reports to support decision making at the conceptual design stage. BIM tool (Autodesk Revit) is at the centre of the

model's data integration due to its capability and ability to use add-in to unlock the full automation design potential.

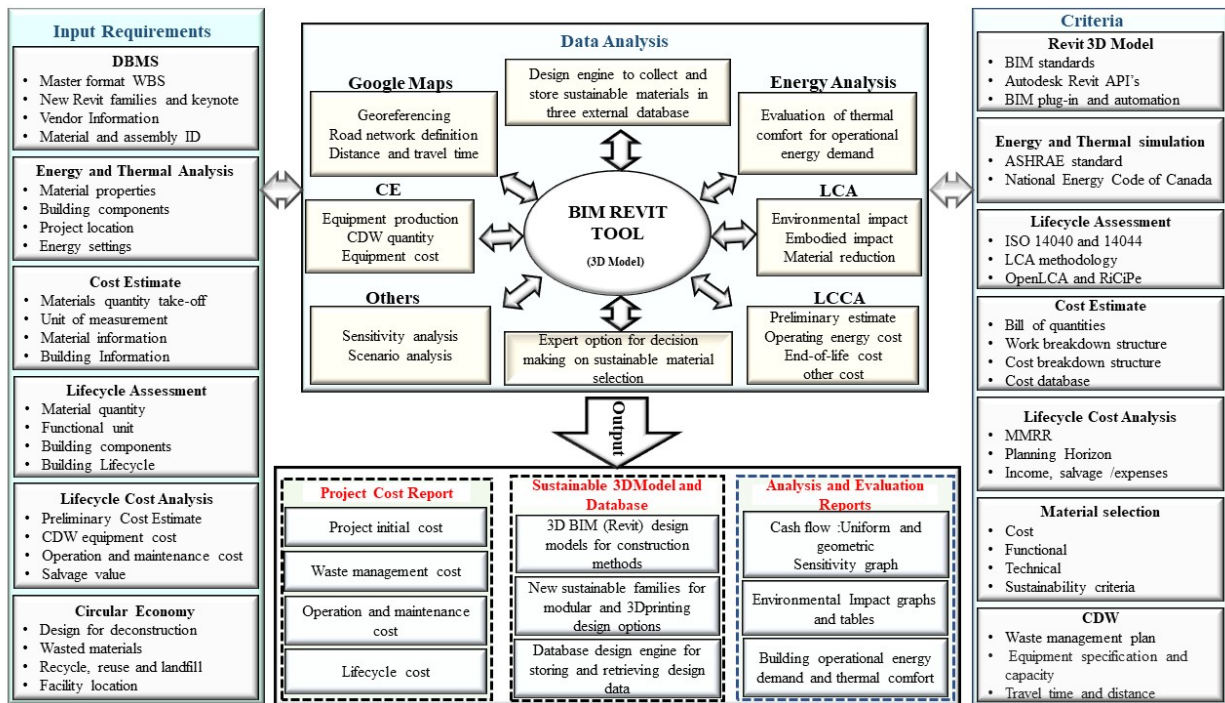


Figure 4.3 - The model's architecture

Moreover, Figure 4.4 illustrates the model's data inflow, outflow, and exchange of information, starting with the BIM conceptual design model in Autodesk Revit through an interaction with the model's six modules and finally the output. Data from the different components will be integrated into one another through an automated process either directly or by improving the functionality of BIM tool through the creation of new plug-ins. This enhances the ability to exchange information in an easy and efficient way to help users initiate and complete sustainable design and select the suitable construction method for a building project.

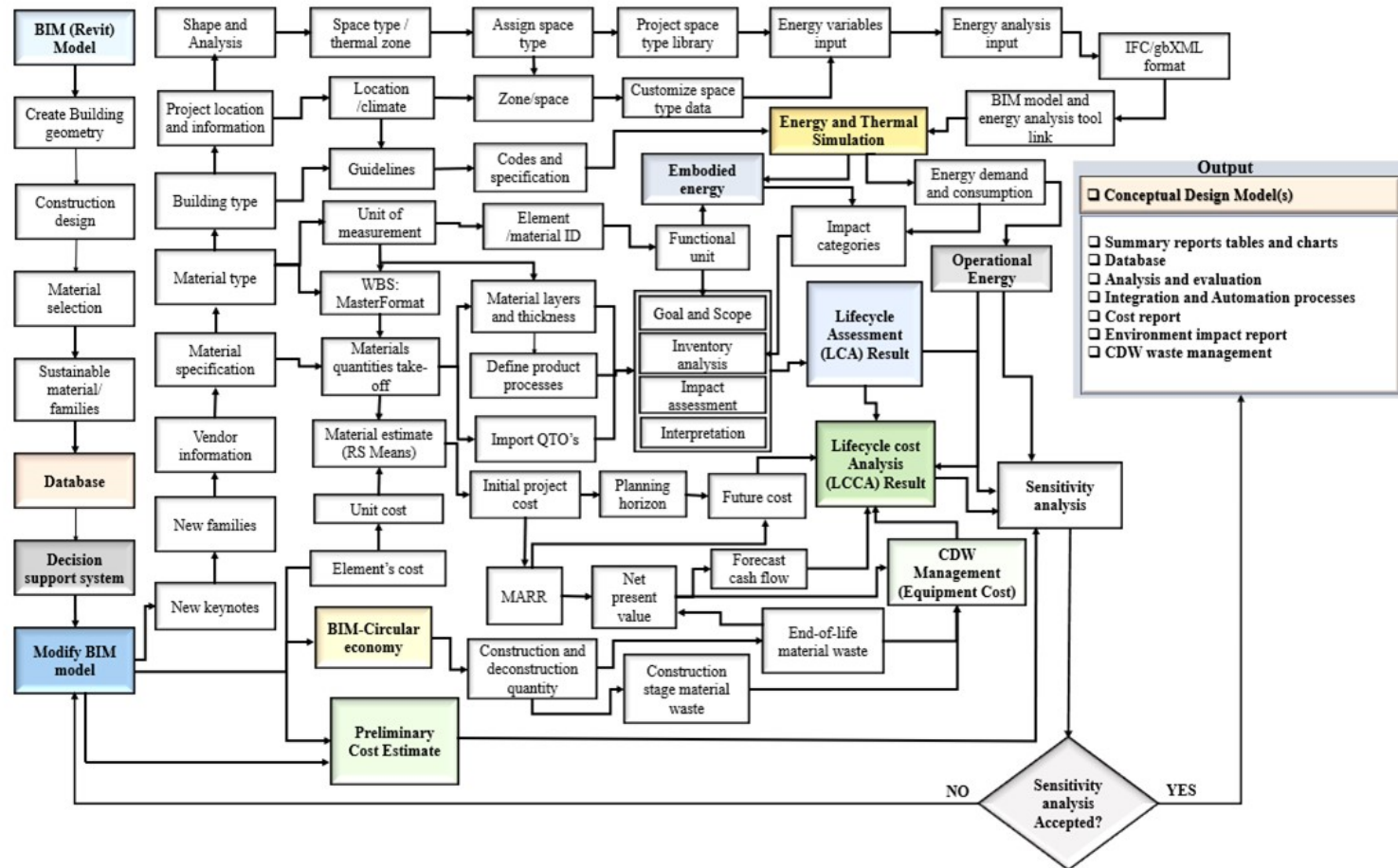


Figure 4.4 - Model's data flow and information exchange

4.5 Modules of the integrated model

The integrated model will provide a paradigm for the design team to address the project's sustainability attributes at the early design stage of a project. The model will host the integration framework by benefitting from BIM tools, which will enhance the collaboration and integration of several stakeholders throughout the entire lifecycle, thereby providing design alternatives based on various parameters at the early stage of designing a construction project. The modules will follow a defined approach for matching their functionalities requirements in a BIM environment by using Autodesk Revit as an authoring and several sustainability evaluation tool. To achieve a successful integration, the modules whose requirements can be met immediately with their existing functionalities will link their requirements directly, while the ones with complicated requirements will be customized or combined for a joint functionality with different tools. Any module that is lacking functionality for its requirements will undergo screening through either of the two ways: 1) data contribution facilitated by IFC and gbXML intermediation; or 2) development of new functionalities via the Application Programming Interface (API) and integration as a plug-in within BIM tool. The six modules of the integrated model are described as follows:

4.5.1 3D BIM design module

The main purpose of this module is to create three detailed (conventional, modular and 3D printing) 3D BIM design models that can be deconstructed at the end of their life cycle by incorporating the 3D design families that will be created with sustainable materials following the various sustainable design requirements in BIM environment. Autodesk Revit, version 2020, will be used for the 3D modelling due to three main reasons: 1) Revit is a well-established and widely used BIM tool (Gerges et al., 2017); 2) Revit provides more significant integration domains for AEC data, such as building sites, building products and materials, certifications, scattered and

distributed in different sources, formats, and systems; and 3) Autodesk provides other fully compatible tools with Revit and can be used to develop new add-ins.

The APIs of Autodesk Revit will be used to access the functionality and data of other tools, systems or services by utilizing C# programming language to foster the integration with the components that anchor the complete 3D model's development. The 3D design model will be automatically coordinated by BIM tool, which will be used for visualization and to carry out several analyses to implement sustainable practices during the conceptual design stage of a project as follows:

1. Quantity take-off will be automated in BIM tool to provide the capability to extract counts of components, area and volume of spaces and material quantities from BIM 3D models; the quantities extracted will be used for sequence analysis.
2. BIM tool (Revit) will be linked to energy analysis tools to perform energy analyses throughout the design process to determine the operational energy demand and to evaluate various options for energy savings;
3. BIM 3D models and material quantities will be used to perform life cycle assessments by providing data and analyzing the materials that can significantly increase the sustainability of the building over its lifecycle.
4. Material quantities and other cost databases will be integrated with the BIM tool to generate detailed cost information, including initial costs, waste management, energy, and lifecycle costs

4.5.2 Database Management System (DBSS) module

The objective of the DBMS module is to build a data structure and to organize the contained data for a consistent flow of information by considering their integration ability, selected programming languages, and software structure. The steps for developing the module are shown in Figure 4.5.

The development process of the database will adhere to the size and structural requirements of a relational database model, involving two key steps: conceptual modeling and physical implementation. The primary focus of the relational database model will be to facilitate the conceptual design of buildings. Its conceptual modeling commences with an analysis of data requirements, problem investigation and user requirements, which are identified through a broad literature review.

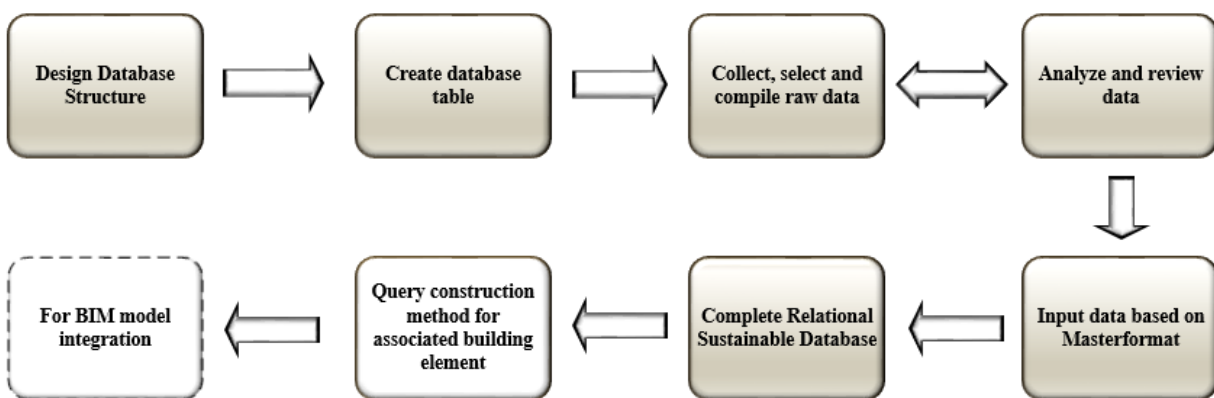


Figure 4.5 - Workflow for developing a relational database

Subsequently, the database entities, attributes, and relationships will be established based on the identified requirements since there is limited detail at the conceptual design stage. The database will be prepared for implementation upon deriving the conceptual schema.

The physical implementation entails the development of a DBMS to systematically compile, organize, store, and retrieve data for building design at the conceptual stage. At the physical implementation stage, the specific details of the schema are translated into actual database structures by transforming the entities into tables, records/values into rows, and attributes into columns, then, the database tables will be created. Finally, the relevant raw data will be gathered and analyzed based on the MasterFormat divisions for appropriate organization of the project's element in BIM model. The required functionality of BIM tool for modelling the database

structures is reviewed to create three separate databases for materials and families as conventional, modular and 3D printing, as shown in Figure 4.6.

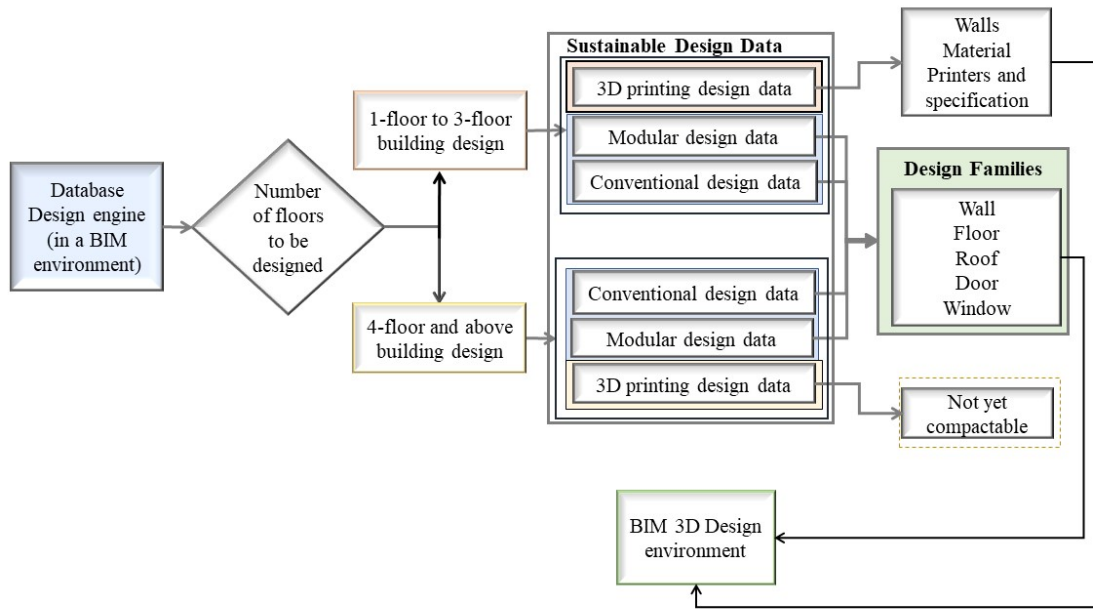


Figure 4.6 - Workflow for integrating database design engine in BIM

The relevant, sustainable families for the design elements of a building will be stored in the external database and linked into a BIM environment through the Revit tool, which will be used for the conceptual design. The model will load design families or printers for that specific design from an external database based on users selection and linked to BIM tool in a way that when a design is initiated for a design and there will be a prompt message asking the designer to confirm the construction method for the proposed design.

4.5.3 Decision Support System (DSS) module

The DSS module aims to enhance the decision-making process in complex or uncertain situations. Hence, this section discusses the development methodology for implementing a BIM integrated decision support system (DSS) for selecting sustainable materials at the conceptual design stage

of buildings. The framework for developing the proposed BIM-DSS integrated module follows three main components, as shown in Figure 4.7: 1) database management system (DBMS); 2) 3D BIM design model, and 3) decision making and decision evaluation. In this study, Fuzzy-based DANP is a hybrid method that combines the Decision Making Trial and Evaluation Laboratory (DEMATEL), Analytic Network Process (ANP), and the Weighted Aggregated Sum Product Assessment (WASPAS) as the decision-making model. Furthermore, BIM tool serves as the foundation for all the functions performed by each component by using its associated plug-ins, which can unlock the components' full potential, thereby increasing the validity and efficiency of their data, knowledge and processes.

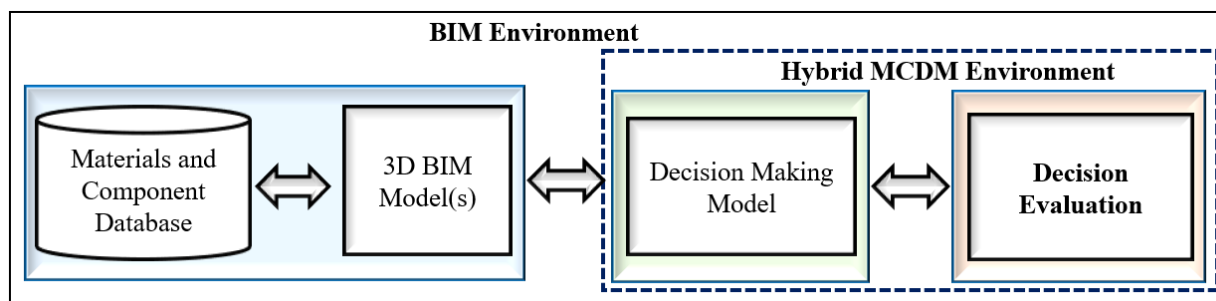


Figure 4.7 - DSS module components

Figure 4.8 shows the structure for integrating BIM with DSS, including its development process, which consists of five stages. In the first stage, a detailed literature review will be conducted to uncover the objective of selecting sustainable materials; determine the selection's indicators, criteria and sub-criteria; to define the needs, gaps and expectations for the decision method and ascertain the ways to improve the functionality of BIM tool in order to develop the integrated BIM-DSS model.

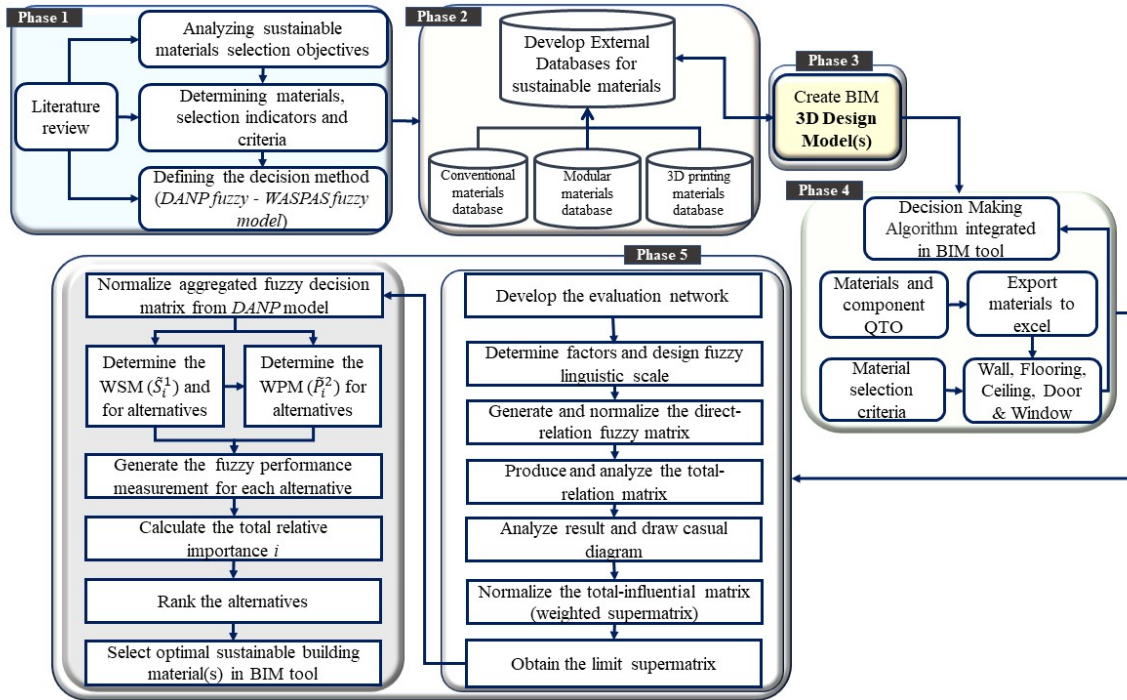


Figure 4.8 - Structure of the integrated DSS module

The second stage involves designing and developing three external databases to store and organize the collected information and data about construction materials and components associated with the three design and construction methods (conventional, modular, and 3D concrete printing) for appropriate retrieval, modification and update. One critical focus of this study is the collection and storage of sustainable design families that are created as Revit family (RFA) or Revit project (RVT) file formats. The elements for the three mentioned construction methods are door, window, wall, floor, ceiling, etc.) and their associated parameters (such as keynotes, assembly code, specification, and description). The three databases are integrated with BIM tool (Autodesk Revit) through an automated link to help with the adequate evaluation and careful selection of the materials. Hence, developing a separate external database for each method will allow the associated families to be loaded upon opening BIM tool and making the components accessible for designers to make the right decision during the design process. The three databases will be

adequately maintained by constantly updating their stored data from various sources, including literature reviews, interviews, material suppliers, material information and specifications.

In the third three, the conceptual 3D BIM model will be created, which is one of the essential applications of a BIM tool due to its modelling capability, hence, users are able to use the information and data of the associated materials stored in the database (from stage two) directly and import the created families into the design model. This functionality represents one of the benefits of BIM tool, enabling the seamless selection and integration of materials into a 3D design model. Furthermore, the BIM 3D model established the interface for all evaluation, analysis, and calculation for the building design's material decisions; thus, a 3D model is created to capture all the objects and their associated quantities.

The fourth stage entails developing the MCDM model and creating a new plug-in that integrates a decision-making algorithm with BIM tool to assist in selecting sustainable building components by using BIM 3D model, external material databases, decision-making parameters and material selection criteria to execute and complete materials selection. The newly created plug-in starts by extracting and exporting all the associated design data from the external materials' databases or the BIM 3D design model into Microsoft Excel. Once the design elements are generated and sorted into the five listed categories (walls, floors, ceilings, doors, and windows) with their alternatives, the next step is implementing the materials' selection, which starts with rating the sustainability criteria using linguistic terms. The linguistic terms utilize five basic point influential-type scales of importance to define the level of influence of particular criteria on each other. A fuzzy logic approach using fuzzy sets, membership functions and fuzzy triangular numbers has been adopted to overcome human assessment errors, convert qualitative linguistic attributes into quantitative scales and evaluate the decision-making process. At the same time, fuzzy triangular numbers were

utilized to define three parameters in the three linguistic values' points (l , m , and u). Where l is the smallest, m median, u is the upper bound value that describes a fuzzy set, and the number range $(0-1)$ represents the membership function. The values associated with influential-type scales of importance for the sustainability criteria of every element to each other and the rating for evaluating alternative components will be determined by the AEC industry experts and will be integrated into BIM tool. Hence, users are expected to utilize the predetermined decision-making parameters to rate the criteria for the set of material alternatives to generate the potential criteria weighting needed for the selection of the optimal element/material. The calculated criteria's weights and a five-point evaluation rating will then be applied to rate each element's alternatives for the five categories (walls, floors, ceilings, doors and windows) to determine their level of sustainability. The implemented rating evaluation serves two advantages: 1) calculates the total score of the alternative as a weighted sum of the criteria, and 2) prevents alternatives with poor attributes or criterion values. Based on the evaluated result, the system ranks the outcome in preference order, with the optimal sustainable building components/material having the highest K_i ranking. Notably, previous studies suggested that a sample size between three and nine samples is adequate for data collection and analysis by MCDM methods like DEMATEL, AHP, and ANP (Liang et al., 2016). Therefore, three experts in the AEC industry will be interviewed to determine influential-type scales of importance for the sustainability criteria of every element to each other and the rating for evaluating alternative components.

Stage five focuses on creating another plug-in that links MATLAB tool with BIM tool (Autodesk Revit) to accomplish the decision-making model and the associated evaluations leveraging MATLAB tool's computational algorithms and sophisticated functions, such as inverse and eigenvalues. The collaborative capability of BIM tool enables seamless data transfer from the

design model to MATLAB tool to complete the decision evaluation processes using DANP-fuzzy and WASPAS-fuzzy techniques. The steps below explain the implementation of the fuzzy-based DSS using the MATLAB tool in BIM environment:

Step 1: Develop the evaluation network for DANP-fuzzy

There are two significant challenges in designing the conceptual DANP network model; the first involves identifying indicators, criteria, and sub-criteria that influence sustainable materials selection. The second is to structure the network model to represent the dominant factors and interrelationships that define the goal material selection. Figure 4.9 illustrates the conceptual network model for decision-making. The network consists of a control layer and a network layer. The control layer contains a goal, while the network layer consists of clusters of elements that interact and depend on each other on various levels. The sustainability indicators will be grouped into three groups for the purpose of expert judgement, from which nineteen sub-criteria, grouped into eight main criteria, will be identified as 1) Environmental Impacts; 2) Energy and Atmosphere; 3) Material and Resources; 4) Cost; 5) Time; 6) Circular Economy; 7) Indoor Environmental Quality, and 8) Design Innovation. The described criteria have a direct association with indicators that affect users' sustainability assessment decisions, namely: (1) Environmental (S_1), (2) Economic (S_2), and (3) Social (S_3), with the selection of sustainable materials being the single objective for the decision, (i.e. goal).

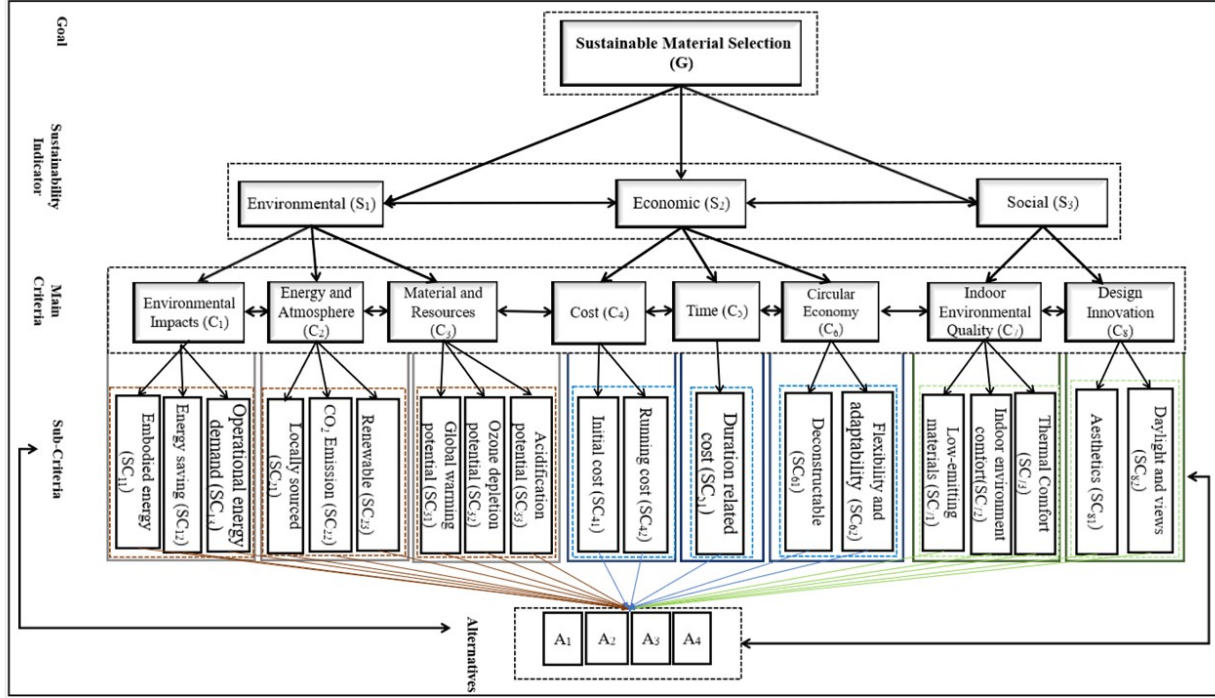


Figure 4.9 - Network model for DANP-fuzzy decision-making

Step 2: Determine factors and design a fuzzy linguistic scale

Linguistic variables, once defined, can overcome human assessment errors, linguistic terms, such as words and sentences, define a linguistic variable. For example, $\tilde{A} = (l, m, \text{ and } u)$ on X is a triangular fuzzy number (TFN) defined by three parameters in three points, $(l, m, \text{ and } u)$ as shown in Figure 5, where l is the smallest value, m median value, and u is the upper bound value that describes a fuzzy event with $\mu_A(x): X \rightarrow [0,1]$ as the membership function is given by Equation

(1)

$$\mu_A(x) = \begin{cases} 0, & x < l \\ \frac{(x-l)}{(m-l)}, & l \leq x \leq m \\ \frac{(u-x)}{(u-m)}, & m \leq x \leq u \\ 0, & x > u \end{cases} \quad \text{Equation (1)}$$

Individual Triangular fuzzy numbers (TFN) in the membership function have linear representations on the left and right sides of Figure 4.10 and are defined by Equation (1). This

study adopted triangular fuzzy numbers due to their widespread use in MCDM implementations. They are also easier to handle compared to more complex fuzzy numbers and can effectively model human reasoning and subjective judgments, which are often imprecise and vague.

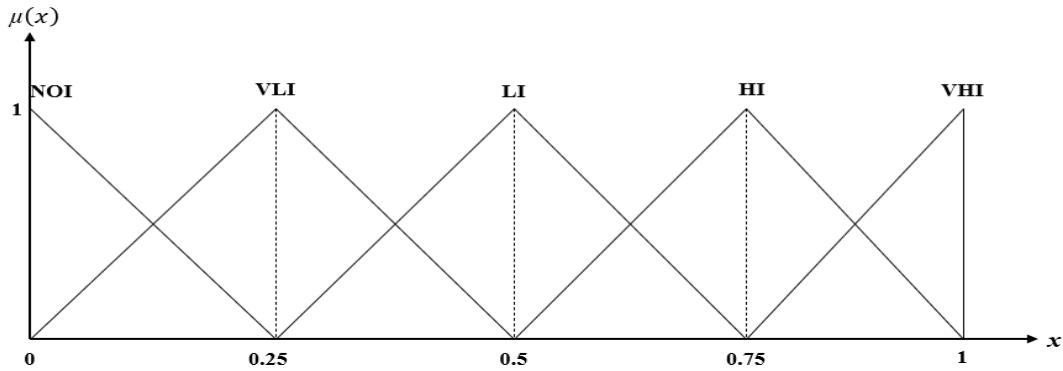


Figure 4.10 - Triangular fuzzy values and membership functions

The TFN uses five basic linguistic terms described as “Very high”; “High”; Low”; “Very low” ;and “No” influence as the scales of importance. Table 4.1 shows the fuzzy scales of these linguistics.

Table 4.1 - Linguistic scales for rate elements

Linguistic Terms	Linguistic Values
Very high influence (VHI)	(0.75,1.0,1.0)
High influence (HI)	(0.5,0.75,1.0)
Low influence (LI)	(0.25,0.5,0.75)
Very low influence (VLI)	(0, 0.25,0.5)
No influence (NOI)	(0, 0,0.25)

Step 3: Generate and normalize the direct-relation fuzzy matrix

Consider that only one objective motivates the decision-making, represented as goal G in the control layer and N element (indicators, criteria, sub-criteria) groups in the network layer. (k) judges are invited to evaluate the influence of criteria and sub-criteria of the network layers $\{C_{i1}, C_{i2}, \dots, C_{iN_i}\}$ and $\{SC_{i1}, SC_{i2}, \dots, SC_{iN_i}\}$ in group $SI_i = C_i (i=1,2 \dots, N)$ on element SC_{jl} considering

G as the main criterion and element SC_{jl} ($l=1, \dots, n_j$) in group $SI_j = C_j$ ($j=1, 2, \dots, N$) as the secondary criterion. Expert opinions are converted into a linguistic variable to construct a pairwise comparison matrix using linguistic scales for relative importance given in Table 1. Therefore, the judgement of k decision-makers forms the fuzzy comparison matrix. The fuzzy initial direct-relation matrix constructed by the k th decision-maker is formed as an $n \times n$ fuzzy matrix $\tilde{Z}_{(k)}$ described by Equation (2)

$$\tilde{Z}_{(k)} = \begin{bmatrix} 0 & \tilde{Z}_{12}^{(k)} & \dots & \tilde{Z}_{1n}^{(k)} \\ \tilde{Z}_{21}^{(k)} & 0 & \dots & \tilde{Z}_{2n}^{(k)} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{Z}_{n1}^{(k)} & \tilde{Z}_{n2}^{(k)} & \dots & 0 \end{bmatrix}; k = 1, 2, \dots, p \quad \text{Equation (2)}$$

Where $\tilde{Z}_{ij}^{(k)} = (l_{ij}^{(k)}, m_{ij}^{(k)}, u_{ij}^{(k)})$.

To normalize the direct-relation fuzzy matrix from an initial direct-relation matrix, $\tilde{\alpha}_i^{(k)}$ and $\beta^{(k)}$ are considered as fuzzy triangular numbers with the following values in Equations (3) and (4);

$$\tilde{\alpha}_i^{(k)} = \sum \tilde{Z}_{ij}^{(k)} = (\sum_{j=1}^n l_{ij}^{(k)}, \sum_{j=1}^n m_{ij}^{(k)}, \sum_{j=1}^n u_{ij}^{(k)}) \quad \text{Equation (3)}$$

$$\beta^{(k)} = \max(\sum_{j=1}^n l_{ij}^{(k)}), 1 \leq i \leq n \quad \text{Equation (4)}$$

Furthermore, the criteria can be compared by applying the linear transformation scale then the normalized direct-relation fuzzy matrix as $\tilde{X}^{(k)}$ is then obtained using Equation (5)

$$\tilde{X}_{(k)} = \begin{bmatrix} \tilde{X}_{11}^{(k)} & \tilde{X}_{12}^{(k)} & \dots & \tilde{X}_{1n}^{(k)} \\ \tilde{X}_{21}^{(k)} & \tilde{X}_{22}^{(k)} & \dots & \tilde{X}_{2n}^{(k)} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{X}_{n1}^{(k)} & \tilde{X}_{n2}^{(k)} & \dots & \tilde{X}_{nn}^{(k)} \end{bmatrix}; k = 1, 2, \dots, p \quad \text{Equation (5)}$$

$$\text{where } \tilde{X}_{ij}^{(k)} = \frac{\tilde{Z}_{ij}^{(k)}}{\beta^{(k)}} = \left(\left(\frac{l_{ij}^{(k)}}{\beta^{(k)}} \right), \left(\frac{m_{ij}^{(k)}}{\beta^{(k)}} \right), \left(\frac{u_{ij}^{(k)}}{\beta^{(k)}} \right) \right).$$

Supposing that there is at least one i such that $\sum_{j=1}^n l_{ij}^{(k)}$. The average of the matrix of $\tilde{X}$, is solved using Equations (6) and (7).

$$\tilde{X} = \frac{(\tilde{x}^{(1)} \oplus \tilde{x}^{(2)} \oplus \dots \oplus \tilde{x}^{(p)})}{P}, \quad \text{Equation (6)}$$

$$\tilde{X} = \begin{bmatrix} \tilde{X}_{11} & \tilde{X}_{12} & \tilde{X}_{1n} \\ \tilde{X}_{21} & \tilde{X}_{22} & \tilde{X}_{2n} \\ \vdots & \vdots & \vdots \\ \tilde{X}_{n1} & \tilde{X}_{n2} & \tilde{X}_{nn} \end{bmatrix} \quad \text{Equation (7)}$$

$$\text{Where } \tilde{X}_{ij} = \left(\frac{\sum_{k=1}^p \tilde{x}_{il}^{(k)}}{P} \right).$$

Step 4: Produce and analyze the total-relation matrix

The fuzzy total-influential matrix $\tilde{T}$ can be determined by ensuring $\lim_{w \rightarrow \infty} \tilde{T}^w = 0$. Equations (8) and (9) show the total-relation fuzzy matrix.

$$\tilde{T} = \lim_{n \rightarrow \infty} (\tilde{X}^1 + \tilde{X}^2 + \dots + \tilde{X}^w), \quad \text{Equation (8)}$$

$$\tilde{T} = \begin{bmatrix} \tilde{t}_{11} & \tilde{t}_{12} & \tilde{t}_{1n} \\ \tilde{t}_{21} & \tilde{t}_{22} & \tilde{t}_{2n} \\ \vdots & \vdots & \vdots \\ \tilde{t}_{n1} & \tilde{t}_{n2} & \tilde{t}_{nn} \end{bmatrix}, \text{ where } \tilde{t}_{ij} = (l'_{ij}, m'_{ij}, u'_{ij}). \quad \text{Equation (9)}$$

$$\text{Matrix } [l'_{ij}] = X_l \times (I - X_l)^{-1}$$

$$\text{Matrix } [l'_{im}] = X_m \times (I - X_m)^{-1} \quad \text{Equation (10)}$$

$$\text{Matrix } [l'_{iu}] = X_u \times (I - X_u)^{-1}$$

Step 5: Analyze result and draw casual diagram

The row and column sums of the matrix $\tilde{T}$ are acquired from Equation (11) and are expressed as vectors D and R , respectively, using Equations (12) and (13), where the superscript (') denotes the transpose of matrix components.

$$T = [t_{ij}], \quad i, j \in \{1, 2, \dots, n\} \quad \text{Equation (11)}$$

$$D = [\sum_{j=1}^n t_{ij}]_{n \times 1} = [d_i]_{n \times 1} = (d_1, \dots, d_i, \dots, d_n). \quad \text{Equation (12)}$$

$$R = [\sum_{i=1}^n t_{ij}]'_{1 \times n} = [r_j]'_{n \times 1} = (r_1, \dots, r_j, \dots, r_n). \quad \text{Equation (13)}$$

Once $(D + R)$ and $(D - R)$ is calculated, a diagram of the correlations among the criteria can be drawn. The horizontal $D + R$ axis is obtained by computing the sum D and R , which defines the importance of the criteria i . Similarly, the vertical $D - R$ axis is obtained by computing the difference between D and R , which will separate the attributes into causal and effect clusters, respectively. The criteria i is classified under causal cluster when $(D - R)$ is positive; otherwise, its an effect cluster. Based on this relation, an influential network relations map can be established by plotting $(D + R)$ as an independent variable and $(D - R)$ as a dependent variable.

Step 6: Normalize the total-influential matrix T^{nor} (weighted supermatrix)

The matrix T^{nor} can be calculated as $T^{nor} = [t_{ij}^{nor}]_{n \times n}$, where $t_{ij}^{nor} = \frac{t_{ij}}{t_j}$, and $t_j = \sum_{i=1}^n t_{ij}$.

This normalized matrix also represents the column stochastic (weighted) supermatrix, which is expressed in Equation (14) as:

$$T^{nor} \begin{bmatrix} t_{11}/t_1 & \dots & t_{1j}/t_j & \dots & t_{1n}/t_n \\ \vdots & & \vdots & & \vdots \\ t_{i1}/t_1 & \dots & t_{ij}/t_j & \dots & t_{in}/t_n \\ \vdots & & \vdots & & \vdots \\ t_{n1}/t_1 & \dots & t_{nj}/t_j & \dots & t_{nn}/t_n \end{bmatrix} = \begin{bmatrix} t_{11}^{nor} & \dots & t_{1j}^{nor} & \dots & t_{1n}^{nor} \\ \vdots & & \vdots & & \vdots \\ t_{i1}^{nor} & \dots & t_{ij}^{nor} & \dots & t_{in}^{nor} \\ \vdots & & \vdots & & \vdots \\ t_{n1}^{nor} & \dots & t_{nj}^{nor} & \dots & t_{nn}^{nor} \end{bmatrix} \quad \text{Equation (14)}$$

Step 7: Obtain the DANP limit supermatrix

The weighted supermatrix (matrix T^{nor}) will be raised to limiting powers φ to calculate the overall priorities. The cumulative influence of all inner dependence on every other element it

interacts with will be obtained. Raising a matrix to powers will give the relative effects of the elements on each other, and the new matrix resulting from it will be called the limit supermatrix. Subsequently, WASPAS approach is applied at this stage to calculate the ranking for the alternatives. The approach helps to determine each alternative's ranking score by multiplying the scale rating of each criterion of strength by the criterion's significance weight. While the WSM part calculates the total score of the alternative as a weighted sum of the criteria, the WPM approach prevents alternatives with poor attributes or criterion values.

Step 8: The aggregated fuzzy decision matrix

The aggregated fuzzy decision matrix for evaluating alternatives is constructed using a linguistic variable shown in Table 4.2. However, the fuzzy criteria weights are obtained from *DANP*.

Table 4.2 - Linguistic values for evaluating the alternatives

Linguistic Terms	Linguistic Values
Very low (VL)	(1,1,3)
Low (L)	(1,3,5)
Medium (M)	(3,5,7)
High (H)	(5,7,9)
Very high (VH)	(7,9,9)

Step 9: Determine the weighted sum (WS) and weighted product (WP)

The relative importance of the *i*th alternative is determined based on the Weighted Sum method described in Equation (15)

$$S_i^1 = \sum_{j=1}^n q_{ij} \times w_j \quad \text{Equation (15)}$$

While the performance index of the *i*th alternative is evaluated using the Weighted Product method given in Equation (16)

$$P_i^2 = \prod_{j=1}^n (q_{ij})^{w_j} \quad \text{Equation (16)}$$

Step 10: Generate the fuzzy performance measurement for each alternative

The S_i^1 and P_i^2 are the results of fuzzy performance measurement for each alternative described by Equations (17).

$$S_i^1 = \frac{1}{3}(S_{i\alpha} + S_{i\beta} + S_{i\gamma}) \text{ and } P_i^2 = \frac{1}{3}(P_{i\alpha} + P_{i\beta} + P_{i\gamma}) \quad \text{Equations (17)}$$

Step 11: Create a WASPAS model for calculating the total relative importance

The integrated utility function value K_i of the WASPAS-fuzzy model for an alternative calculated using Equations (18)

$$K_i = \lambda \sum_{j=1}^m S_{ij} + (1 - \lambda) \sum_{j=1}^m P_{ij}, \lambda = 0, \dots, 1, 0 \leq K_i \leq 1 \quad \text{Equation (18)}$$

Where λ , as shown in Equation (19), is based on the assumption that the total of all alternative WSM weights has to be equal to the total of WPM weights.

$$\lambda = \frac{\sum_{i=1}^m P_i}{\sum_{i=1}^m S_i + \sum_{i=1}^m P_i} \quad \text{Equations (19)}$$

From equation 19, the preference order is ranked, and the optimal alternatives are selected following the highest value of K_i .

4.5.4 Energy Thermal Simulation (ETS) module

This section describes the adopted methodology to integrate the 3D BIM design model with an energy analysis tool to enhance the decision-making and to allow comparison of multiple solutions by using the aforementioned three construction methods. The data input structure used in developing the mentioned methodology consists of three main steps, as illustrated in Figure 4.11.

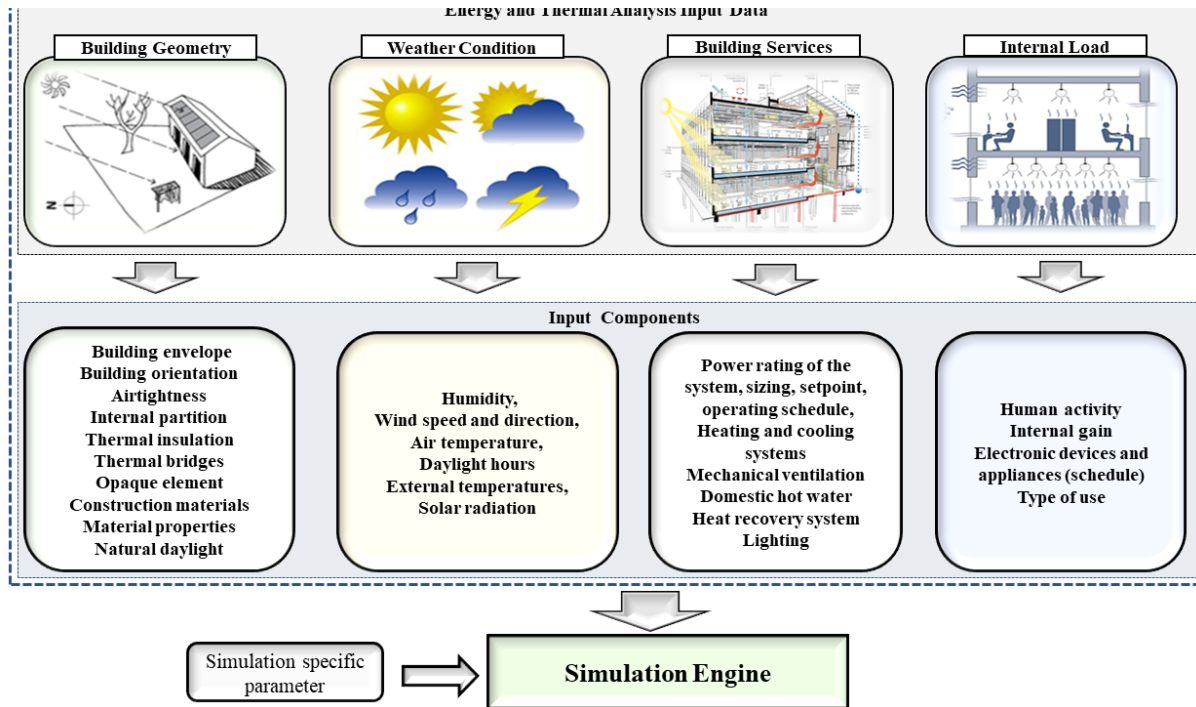


Figure 4.11 - The data input structure for Energy and thermal analysis

Step one focuses on the correctness of the energy simulation, which depends on the adequacy of the entered parameter. Therefore, the 3D BIM design model will serve as the primary input parameter, which will be created by using the materials and design families, including their thermal properties, that will be collected and stored in the external database in line with relevant BIM guidelines to ensure adequate data standards. All the necessary project's specifications and parameters, such as geometry, construction type and materials, project space type, and location, will be defined for each object in the application platform, which will already be in the BIM environment. Figure 4.11 illustrates critical factors and components that directly influence the energy consumption of buildings as the main parameters to enter for the modelling process, which include, building geometry; energy systems; weather conditions; and internal load. However, the building geometry will be automatically extracted from the 3D BIM model by customizing API of Revit. The building geometry includes the building's envelope, orientation and the materials used

for the building envelope, internal partition, airtightness, thermal insulation and bridges, and opaque elements. In the energy simulation models, the living spaces, for instance, rooms and halls, will be referred to as thermal spaces and space boundaries. There will be three applicable criteria for identifying spaces based on ANSI/ASHRAE Standards: 1) altitude below 3,000m (10,000ft); 2) enclosed within the building envelope; and 3) occupants expected to be in space for at least 15 minutes. Next, it will be the energy system that includes the system's power rating, sizing, setpoint, and operating schedule.

The operating schedule will define the peak or off-peak periods in the energy use pattern. Next, the weather data will include climate parameters such as humidity, wind speed, and external temperatures. Finally, the internal loads, electronic devices and appliances, uses, human activities in the building and internal gain will be generally influenced by users' behaviour.

The second step is to evaluate the module's data exchange, owning that BIM tool is somewhat incompatible with the existing energy simulation tool and, therefore, the model conversion always results in information loss and distortion. Thus, the BIM model will be exported into an energy simulation environment through a BIM file schema such as gbXML or IFC. Upon importing the gbXML/IFC file, the model will be reviewed to ensure the correctness and consistency of the data by using a newly created plug-in to resolve the incompatibility between the 3D BIM model and the energy model's file conversion, thereby creating an energy analysis-ready model. At this point, other input information, as illustrated in Figure 4.12, will be fully defined in the data structure, and simulation parameters, such as weather data, internal loads, equipment systems and operating system, which will be corrected and defined here.

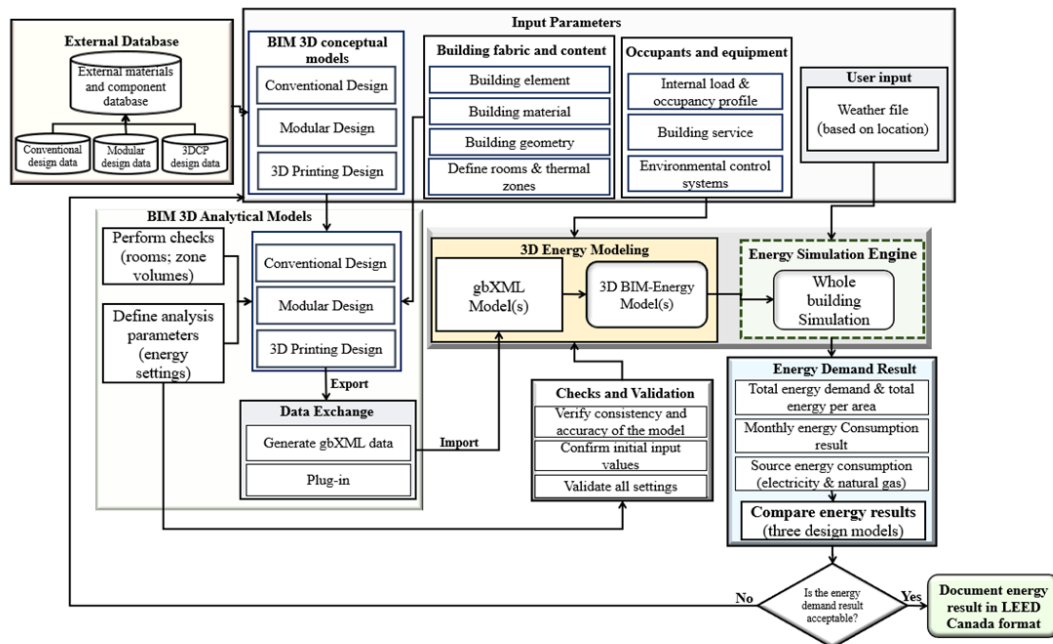


Figure 4.12 - Energy simulation integration process

The final step will involve converting the energy model file to an input data file for the energy simulation tool. This study will adopt one of the four categories of energy simulation tools with their files' compatibility techniques with BIM models' files. Energy simulation graphic user interface such as DesignBuilder to facilitate the energy modelling by providing more graphical interfaces by importing BIM tools files using gbXML inputs model, including improving the geometric model of the building. While energy simulation engines, such as EnergyPlus, will perform energy analysis based on different mathematical tools and thermodynamic equations for energy consumption data.

In the third step, the created energy model will be checked, and its parameters will be modified as required. Then, an energy simulation will be performed by implementing the energy simulation. Detailed energy simulation results are exported and saved in separate text files to be used for other analyses, evaluations, optimizations, and further documentation following Canada's energy modelling compliance guidelines. The output of the BIM-based building energy simulation system

may consist of three parts, including general results (monthly heating and cooling demand; annual heating and cooling demand, and annual total energy demand), optimization results (used to indicate the float of the heat and cooling energy consumption due to the change of window to wall ratio and the building orientation) and detailed results (resulting from sensitivity analysis). Based on the clarifications listed in the study by Queiroz et al., (2020), an adequate energy simulation tool for the early stages of building design should integrate an architectural model, multi-criteria analysis, and rapid responses.

Consequently, the EnergyPlus tool that integrates the features and capabilities of BLAST and DOE-2 and possesses those characteristics will be used as the energy simulation engine for this study. It can perform interdisciplinary assessments (thermal and daylighting performance), its interface allows input data simplification, its programmability for integration with modelling interfaces, and its validation for thermal analysis (Queiroz et al., 2020). Moreover, EnergyPlus adopts integrated and modular algorithms to provide accurate estimations of temperatures in various building zones, which results in better calculations of different design parameters of the energy models, such as its optimized thermal settings. However, EnergyPlus is an energy simulation engine limited to text as its input and cannot directly import BIM files such as gbXML and IFC. Therefore, to support the integration of BIM model's data with IDF (the EnergyPlus native format) model data, the DesignBuilder tool will be used as the simulation graphic user interface (GUI), which uses an analytical engine to assess buildings' energy performance and Radiance's engine for daylighting analysis (Ramaj et al., 2020). Also, DesignBuilder stands out as a robust solution, offering versatile geometry input alongside extensive material libraries and load profiles. Its precise quality control measures ensure result reliability, surpassing standalone EnergyPlus simulations. Hence, DesignBuilder is selected for its capability to conduct detailed,

hourly energy simulations seamlessly within its interface using the integrated functionality of EnergyPlus. Therefore, this study will achieve one of its primary aims by developing plug-ins for DesignBuilder to enhance design analysis, optimization, and input calibration and facilitate complete BIM-energy analysis automation. The development will support the sustainability goals and enable the exploration and selection of various construction alternatives during the conceptual stage.

4.5.5 Circular Economy (CE) module

The CE module will aid in quantifying the material waste, identifying the waste handling equipment, and the costs associated with loading and hauling wastes at the construction and end-of-life stages of building projects. The objective of the integrated model is to incorporate CDW management strategies during the conceptual design stage based on the principles of circular economy by using BIM tool (Autodesk Revit) and Google Maps to enhance the sustainability performance of buildings through the three construction methods (conventional, modular, and 3D concrete printing). The development methodology for the integrated model entails a systematic automated approach to extend design and analysis tools via the development of a plug-in that will seamlessly be integrated with the conceptual design model to enhance its functionality, capabilities, and flexibility in a unified design environment. Achieving flexibility is a vital requirement for the model's development as it ensures that the model is versatile and reliable throughout its lifecycle, allowing designers to incorporate and revise data in a user-friendly manner. The development methodology starts by creating the module's architecture for implementing construction and deconstruction waste (CDW) management strategies, which ensures that the model is flexible and that different parts of the model can work together to access and exchange data reliably and accurately. The four-layered module's architecture encompasses

detailed information and interactions regarding the integration of data schemas between BIM, Google Maps, and CE principles while residing in Autodesk Revit as BIM tool, consisting of: i) input data and information layer; ii) criteria required to initiate and execute analysis; iii) various analysis to be performed directly or via a new plug-in in BIM environment and; iv) output layer consisting of result from the integrated module in the form of an analysis, evaluation or cost reports to support decision making, as shown in Figure 4.13.

Moreover, the module architecture is supported by data flow that focuses on representing how the data is transmitted through the different parts of the layers during the implementation of the integrated module. The process flow shows how data enters and how it exists out of the module and the resulting output generated by the integrated model, as illustrated in Figure 4.14.

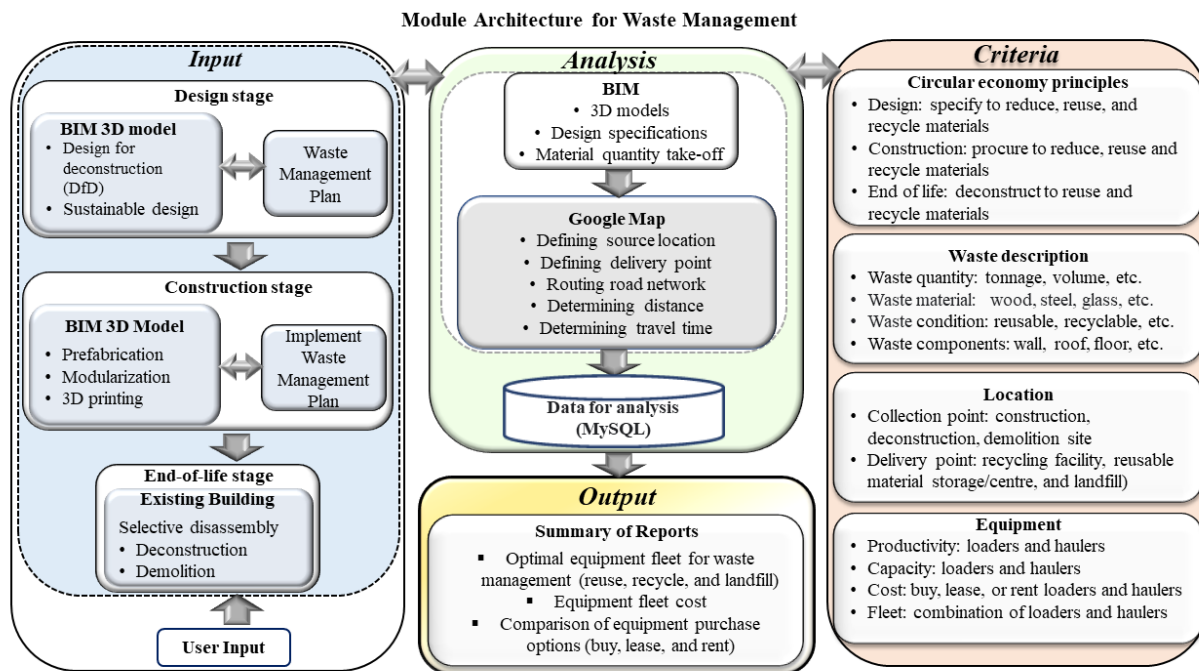


Figure 4.13 - Module's architecture for CDW management

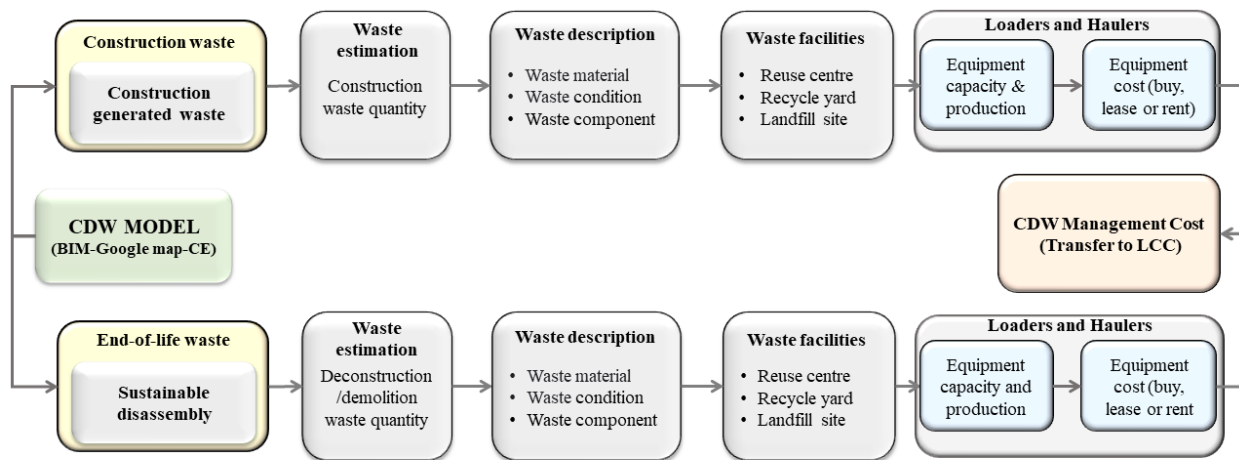


Figure 4.14 - Data flow for implementing CDW management

The data flow consists of a set of processes that convert the input data into output data, connected by flows that indicate how the data is transmitted between the processes. Each data and process in the module represents an operation that requires one or more inputs and produces one or more outputs. Thus, to determine the required equipment, its production rate and associated costs are calculated by a customized plug-in that has been developed for that purpose in Autodesk Revit, which integrates Google Maps services for a combined query utilizing their analysis capabilities. The plug-in uses a combination of data stored in MySQL database, such as location, attributes, quantity, and corresponding features, and data associated with the CE concept, such as reuse and recycling content of a material, to run and complete all the necessary calculations and analyses. The development methodology follows a BIM-leads approach by linking various tools and data to develop the BIM-Google Maps-CE integrated module, which will be implemented through five sequential phases, as shown in Figure 4.15.

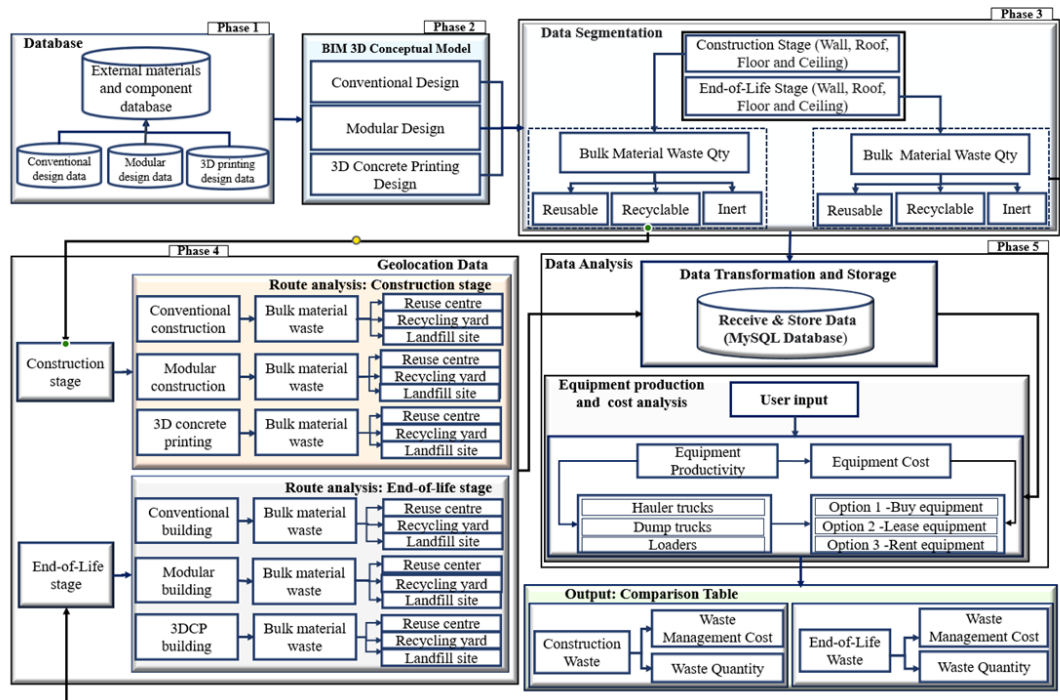


Figure 4.15 - Circular Economy integration process with BIM

Phase one, focuses on the creation of a database for organizing and storing information about the materials and components associated with the three construction methods as an external database with all the necessary data for efficient retrieval, modification, and update. Information about sustainable materials are collected, stored, and used to create new 3D sustainable design families. The storage of the newly created families in BIM tool (i.e., Autodesk Revit) with a file extension of (.rfa) or Revit project (.rvt) file formats (such as door, window, wall, floor, ceiling, roof, etc.) and their associated parameters (such as keynotes, assembly code, specification, and description) for the three abovementioned construction methods is another significant focus of this study. The three databases are integrated with BIM tool through an automated link to aid in evaluating and selecting the material. Hence, developing a separate external database for each design enables the associated families to load upon opening BIM tool and making the components accessible directly from the database during the design process.

Phase two emphasizes creating BIM 3D design model(s) that receive their information from the database to enhance the design, construction, and deconstruction processes using BIM tool (Autodesk Revit). Three identical models will be created separately based on the three construction methods. The modular design will be based on the design for deconstruction (DfD) approach and will be constructed in the form of prefabricated components, the 3D concrete printing design will be based on the specification of the selected printer and its compatible mortar paste, while the conventional design will follow the traditional method of buildings by using wood-frame structure. In addition, BIM tool will be customized by modifying its functionality to suit the flexibility requirements of the module by providing additional detailed information, such as construction specifications, quantity, waste percentage, and material bulk density, to enhance the materials' traceability and waste management analysis. Furthermore, CDW's attributes will be created in BIM tool (Autodesk Revit 2020) by selecting Project Parameters in the Manage tab to add project properties to both the "Project parameter" and "Shared parameter," as shown in Figure 4.16 The additional attributes are essential because the associated parameters of the family are required to identify the waste component of individual material during the quantification of waste. For example, a new material waste attribute called "Bulk density" in the existing "Construction" group parameter is added, as illustrated in Figure 4.16 The figure also shows numerous options for expressing the parameter type in Autodesk Revit, such as number (volume, length, area, distance, rotation angle, pending, time, speed, currency, URL, and material). The parameter selected is "material" to express waste attributes of walls and windows and kg/m^3 was chosen as the unit to express the values, as shown in Figure 4.16.

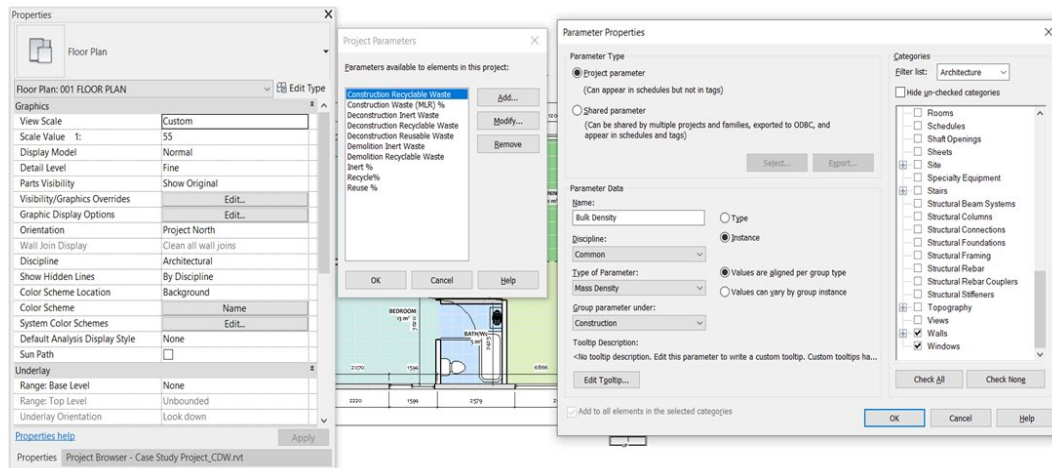


Figure 4.16 - Process of creating waste attributes in BIM tool (Autodesk Revit)

Phase three involves the development of data segmentation to structure the waste of materials into an exclusive data format to aid in an adequate evaluation and efficient decision-making. The process uses the conceptual design model, formally created, of the three design methods (conventional, modular and 3D concrete printing) to formulate various data segregants for easy evaluation. First, into two lifecycle stages: construction and end-of-life; second, the bulk quantity of material waste for each lifecycle stage; and third, into three forms of measurable waste (i.e., reusable, recyclable and inert) based on the circular economy concept. In this study, a BIM-based quantity takeoff (QTO) estimates the wasted materials following the mass balance principle at the construction stage (Guerra et al., 2020) and the total material incorporated in the existing building for the end-of-life stage. The waste generated during the construction stage is considered as the fraction of materials purchased, less the quantity of materials needed to construct a building, by using Equation 20, while the end-of-life waste accounts for all the materials permanently

incorporated into a building. After extracting the materials' quantity takeoff from Autodesk Revit and exporting it to Microsoft Excel, the quantities of waste are further sorted and structured based on the material type, life cycle stage, and the condition of the generated waste.

$$\text{Construction waste} = \text{SUM}_{\text{purchased material}} - \text{SUM}_{\text{needed material}} \quad \text{Equation (20)}$$

Phase four focuses on integrating GoogleMap's tool with BIM tool (Autodesk Revit) to provide the necessary information, such as transportation route, distance, and facilities' location, by defining interconnected lines (edges) and intersections (junctions) representing a path for the travel from one location to another. The dynamic mapping capabilities of Google Maps provide a robust platform for conducting in-depth analyses, including extensive and up-to-date geographic data, making it a valuable tool for spatial analysis, route optimization, and location-based insights. In this study, Google Maps is integrated with a BIM tool to compute and determine the optimal routes from one location to another within a user-defined network, identifying the nearest, shortest, fastest, or safest route between various locations. This integration overlays 3D BIM models accurately onto real-world geographic locations, thereby enhancing spatial awareness and facilitating better decision-making throughout the project lifecycle. Three different locations have been identified in this analysis, which are: location for waste generation (construction/deconstruction/demolition site); location for off-site waste sorting (bulk material waste sorting); location for waste delivery (material reuse centre, recycling facility, storage or landfill) for both construction and end-of-life waste estimation process, as shown in Figure 4.17.

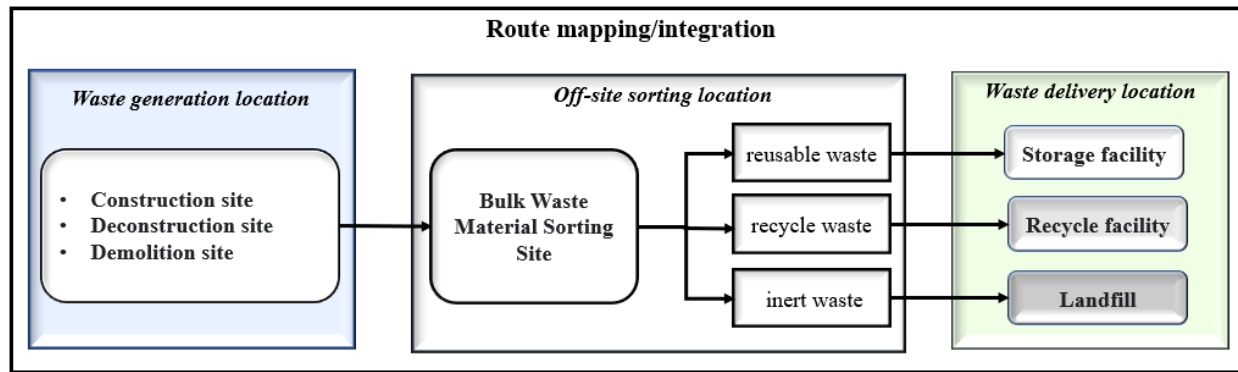


Figure 4.17 - Route definition for network analysis

Phase five concentrates on data analysis by using inputs received from the various module's phases. The initial phase of the analysis involves creating a MySQL-based database management system. This system will be designed to efficiently store the substantial data produced through phases 3 and 4, which will be structured logically to provide versatility within the programming environment to facilitate the automation of data transmission. Hence, MySQL database is the source that hosts detailed data about equipment production analysis and cost estimating for CDW evaluation. Additionally, the scope of work and the equipment requirements are the two primary considerations for waste equipment analysis since the scope of work helps determine the type and capacity of waste handling equipment. Thus, the analysis for waste handling equipment will be carried out by using specifications retrieved from Caterpillar Performance Handbook (Caterpillar, 2018). The primary objective of the analysis is to ascertain the production capacity and cost based on the number of equipment that will be required. This study considered the following waste handling equipment for the evaluation: dump trucks for transporting waste from construction sites to bulk waste sorting sites; loaders and haulers for loading and hauling from bulk waste sorting sites to recycling, reuse centres and landfill sites based on the quantity of waste, equipment capacity, specifications, job description, and location. A waste-handling wheel loader will be used as the loading equipment since they are equipped with the features and protection required in a

demanding waste-handling environment, while the loader and truck production rate will be calculated as weight per hour since construction, demolition and deconstruction waste materials are considered. The steps to determine the various associated factors with the analysis will be adopted from the literature as follows:

1) the material type and the rated heaped-bucket capacity of the loader; 2) the bucket fill factor (*usually from a table*), based on the materials' type; 3) the average cycle time (*usually from a table*), based on the loader's size; 4) the maximum production rate will be determined by using Equation 21:

$$\text{Production rate (LCY/hr)} = \frac{\text{bucket capacity} \times \text{bucket fill factor} \times 60 \text{ mins}}{\text{loader cycle time (min)}} \quad \text{Equation (21)}$$

5) the efficiency factor (usually is 50 minutes of work per hour average); 6) the net production rate in LCY/hour will be determined by using Equation 22:

$$\text{Net production rate} = \text{max. production rate (LC/hr)} \times \text{efficiency factor} \quad \text{Equation (22)}$$

7) the net production rate is converted in tonnage per hour using Equation 23:

$$\text{Net production rate ton/hr} = \frac{\text{Net production rate} \times \text{weight (pounds per LCY)}}{2,000 \text{ pounds per ton}} \quad \text{Equation (23)}$$

Similarly, articulated trucks will be used for waste hauling from construction /deconstruction sites to various locations, as described in Figure 4.15. Articulated trucks will be used in this study for the following reasons: they are versatile, have high maneuverability, work in all weather, and can negotiate poor underfoot conditions. A practical rule of thumb that suggests the use of trucks with a capacity of four times the capacity of the loading equipment bucket will be used in selecting the size of trucks, while the steps that will be used to determine the truck production are: 1) the number of buckets that will load the truck will be determined by Equation 24:

$$\text{Balanced number of bucket} = \frac{\text{hauler capacity (LCY)}}{\text{bucket capacity (LCY)}}, \quad \text{Equation (24)}$$

2) the load time will be measured using Equation 25:

$$\text{Load time} = \text{number of bucket loads} \times \text{loader cycle time}; \quad \text{Equation (25)}$$

the hauling time will be determined by Equation 26:

$$\text{Haul time (hr)} = \frac{\text{haul distance (mil)}}{\text{haul speed (mph)}}; \quad \text{Equation (26)}$$

4) the return time determined by Equation 27:

$$\text{Return time (hr)} = \frac{\text{return distance (mil)}}{\text{return speed (mph)}}; \quad \text{Equation (27)}$$

5) the spot, dump and maneuver time usually is a fixed time element not exceeding 2 minutes as per Nunnally (2007);

6) the truck cycle time is summed up by Equation 28:

$$TCT = L_{Load} + L_{Haul} + L_{Dump} + L_{Return}; \quad \text{Equation (28)}$$

7) the number of trucks required is calculated by Equation 29:

$$\text{Number of hauler required} = \frac{\text{haul unit cycle time}}{\text{loader Time+Dump time}}; \quad \text{Equation (29)}$$

By ensuring the compatibility of the loader and the hauler, the loader will never be kept waiting, but occasionally, a truck can, which is cheaper than a loader sitting idle. Therefore, the maximum number of trips that can be performed by a truck will be determined by the quantity of work to be done using Equation 30:

$$\text{Number of trips} = \frac{\text{Total quantity}}{\text{Truck loading capacity}}; \quad \text{Equation (30)}$$

Furthermore, the equipment cost analysis uses the procedure employed by the construction industry to estimate the hourly operating cost of equipment, such as fuel consumption, tire life, etc. Equipment owning costs will be estimated as follows: 1) depreciation using the straight-line method; 2) investment cost using the value of the average investment over the life of the equipment; 3) insurance, covering for fire, theft, accident, and liability; 4) ownership tax and licenses for the equipment; and 5) cost of rent and maintenance for equipment storage. All the

listed elements of owning cost may be calculated on an annual or hourly basis costs, however, the total owning cost will be expressed as an hourly cost in this study. Operating costs will be incurred while the equipment is in use, hence, costs may vary depending on the equipment usage and job operating conditions. The major elements of the operating cost will include: fuel cost; service cost; repair cost; tire cost; cost of special items; operators' wages, and logistic cost, while the associated cost will be retrieved from historical data or equipment manufacturer recommendations such as Caterpillar Performance Handbook (Caterpillar, 2018). The equipment's detailed estimated cost will include three options (buy, lease and rent), offering users a range of choices and flexibility for efficient decision-making. The evaluation will be applied to the three designs and construction methods (conventional, modular and 3D concrete printing) at the construction and end-of-life stages for the bulk of material waste and the associated forms of waste recycling, reuse and inert to determine the optimal fleet of equipment for the CDW management as shown in Figure 4.18.

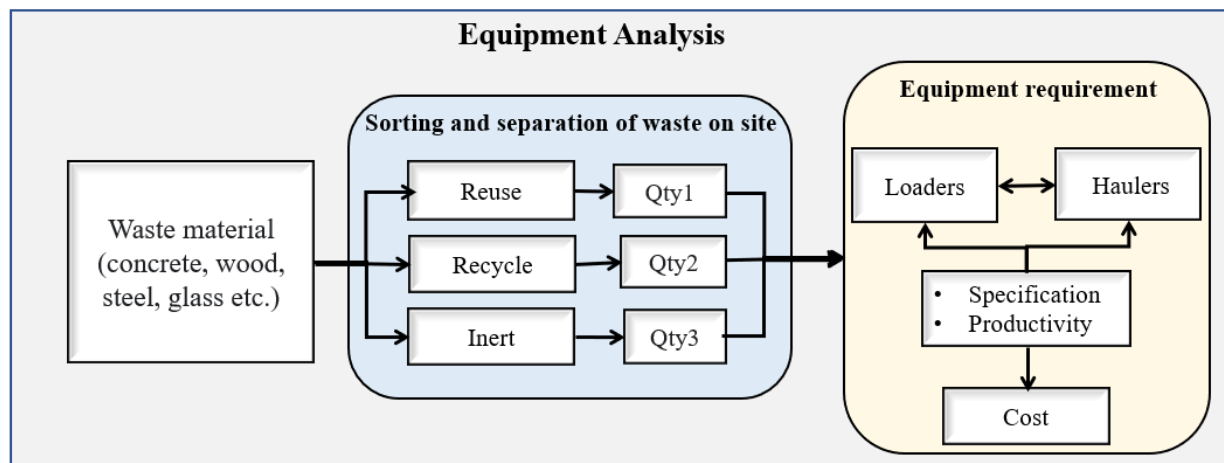


Figure 4.18 - Equipment requirement analysis

4.5.6 Life Cycle Assessment (LCA) module

This module aims to develop a methodology to evaluate the sustainability of building activities over their lifecycle from material production to end-of-life for three construction methods using

an LCA-integrated BIM tool. The objective is to evaluate the environmental impact of buildings within BIM environment and to generate continuous feedback on LCA results to guide the design team to improve the environmental performance of buildings at the early design through the use of Autodesk Revit, LCA tool, and a functional database. The process focuses on the conceptual design of buildings, considering approximate quantities, size, shape, location, orientation, quantity estimation, and energy analysis. The methodological framework for implementing LCA in BIM within the framework of ISO 14040 utilizes four established phases. The module's methodology adheres to the standards' framework and encompasses all the phases, as shown in Figure 4.19.

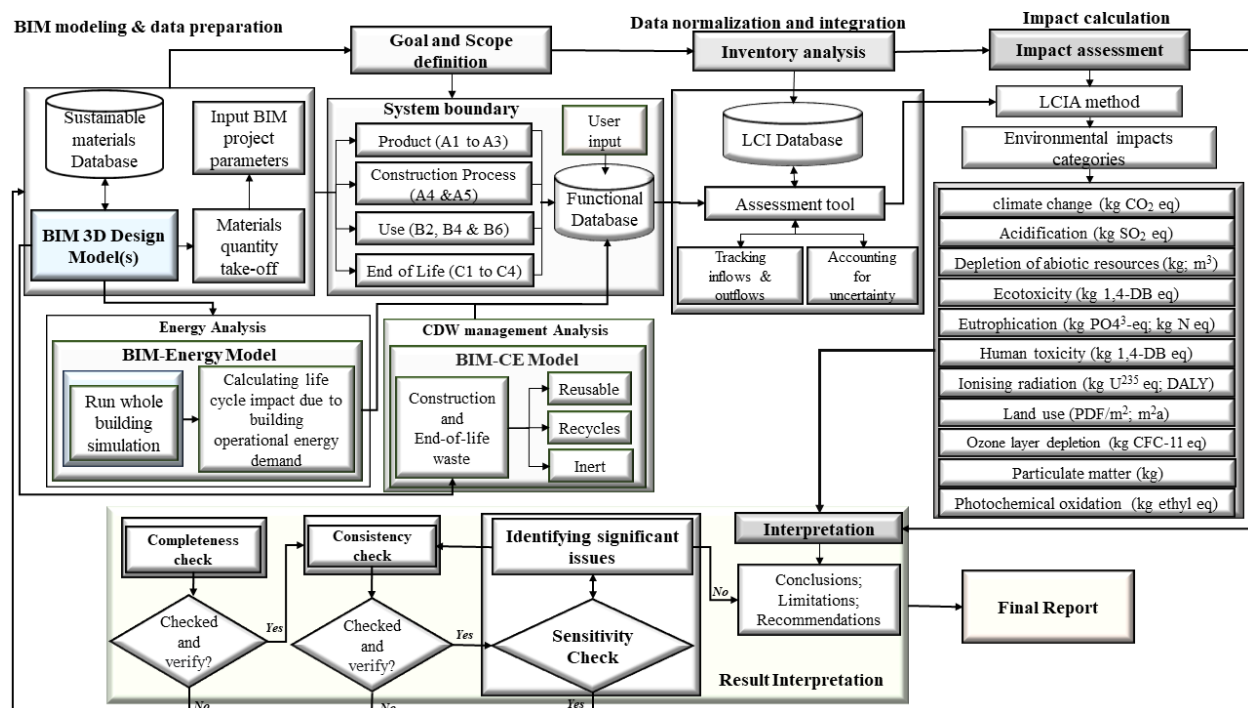


Figure 4.19 - LCA module integration process

4.5.6.1 Goal and scope definition

The study's objective is to establish a methodology to integrate LCA with BIM tools to evaluate the environmental performance of buildings based on the material flows and energy inputs and outputs, as well as to calculate the indicators. The emphasis of the study is on the conceptual design

stage for the three afore listed construction methods over a period of 50 years. The methodology starts by creating a conceptual design model(s). First, the conceptual design model is developed by using the design families stored in BIM tool (Revit) for the three construction methods to create BIM model(s) with their sustainability information. LCA-related information is also integrated into the characteristics of the building's elements', encompassing their physical and functional attributes. Physical properties involve categorizing the elements by type (e.g., wall, floor, roof), specifying their geometric dimensions and volumes, and identifying the construction materials employed (e.g., wood, steel or concrete). The customized BIM model with the other relevant data, utilized for design and construction, are extracted and linked with the Life Cycle Inventory (LCI) for each building design. The LCA module's integration follows a semi-automated approach, while the system boundaries covered in the study are material production, building construction, operation, and end-of-life phases.

The material phase encompasses all the initial processes involved in acquiring the materials used to construct the building. It begins with extracting raw materials from the earth and continues until the products are manufactured and transported from the manufacturer to the building site. The materials examined in this study include wood, concrete, and steel, which are commonly used in building structures. The quantity of each component is determined by analyzing the outputs of the Revit's quantity take-off calculations. However, since this analysis takes place during the early design stage of the building, the impact of this phase is modeled by using a life cycle inventory database. This database contains unit environmental profiles for each relevant material, providing data on the emissions associated with thousands of substances, which are then aggregated into impact categories. The Ecoinvent database was utilized as the life cycle inventory (LCI) reference to analyze energy consumption and transportation in the production processes of these materials.

The environmental impacts associated with the construction phase encompass various factors such as energy consumption, emissions resulting from fuel use in construction machinery, and the transportation of materials and workers based on the chosen construction method. Since the availability of detailed information is limited during the conceptual design stage of the building, the energy demands for these activities are estimated by assuming a uniform probability. However, this study adopted the suggestions of Rezaei et al., (2019) regarding the information from contractors, which proposes that the average electricity and diesel consumption per building area during construction is approximately 60 MJ and 15 MJ, respectively. For additional assessment of the diesel and electricity consumption during the construction phase, the Ecoinvent inventory data is employed.

The operation and maintenance phase comprises the various activities and processes that occur throughout the lifespan of the building. It is considered the most crucial stage in the building's life cycle assessment. The maintenance requirements in this phase are influenced by factors such as the construction type, materials used, machinery utilized, and the frequency of maintenance activities. Therefore, it is vital to accurately consider the sources of environmental impacts associated with this stage. Three major sources contributing to environmental impacts during this phase are energy consumed by household electrical appliances and lighting; heating, ventilation, air-conditioning, and cooling (HVAC) systems; water usage; and the replacement of materials throughout the building's service life. The energy requirements for the operational stage are determined using the DesignBuilder simulation integrated with the BIM tool (Autodesk Revit).

The end-of-life stage includes all the activities related to the deconstruction and dismantling of the building once it reaches the end of its useful service life. During this phase, the environmental impacts are attributed to several factors. These include the use of machinery for building

deconstruction and demolition, loading, hurling and treatment of the wasted materials. The management strategies employed in this stage typically involve options such as reuse, recycling, or disposal in a landfill. In addition, the transportation of materials to the landfill site is considered by assuming a distance of 30 km. On the other hand, recycled materials are transported to the recycling yard, assuming a distance of 25 km. Similarly, reusable materials are transported to a dedicated reusable material centre, with an estimated distance of approximately 40 km.

4.5.6.2 Data extraction and integration

The second step in the methodology of LCA module focuses on the data transmission between BIM and LCA tools. OpenLCA is the assessment tool used to establish a link between lifecycle inventory (LCI) analysis data and BIM data, as per GreenDelta (2020b). The necessary design data will be automatically extracted from the BIM model and integrated into the developed functional database as an input for LCA data. LCI contains the details of the resource flowing into a construction process and the emissions flowing from a process to air, soil, and water. In this process, BIM tool is applied to extract material quantities from the BIM design model(s) comprising various characteristics, is transformed into a detailed bill of quantities (BOQ) and converted into an acceptable unit of measurement supported by the inventory database required to conduct LCA for different building elements of the three construction methods. Next, all the materials listed from the Revit model is linked with a corresponding process obtained from the Ecoinvent database in the functional database. Together with the results from the energy simulation, such as energy consumption and associated emissions during the use and other life cycle stages of buildings as input for the operation energy demand. However, the data integration between Revit and the Ecoinvent database presents difficulties due to the disparity between the specificity and level of detail in Revit's list of materials if compared to their database. Revit's list of materials lacks the same level of specificity, making direct integration challenging. These

associated difficulties will be handled by using RSMMeans database to define the materials' specifications. Following the recommendations derived from a study conducted by Meex et al., (2018) for LCA at the conceptual design stage, this study considers the following building elements: floor, ceilings, doors, windows, exterior walls, interior walls, and roof. An average consumption of 60 MJ of electricity and 15 MJ of diesel per building area during construction will be considered for the construction phase, while the energy consumed in the operation phase will be calculated via DesignBuilder software (using EnergyPlus dynamic simulation engine). End-of-life phases are simplified by obtaining data from the literature.

4.5.6.3 Impact assessment/calculation

In the third step, the life cycle impact assessment (LCIA) is conducted in OpenLCA schema (GreenDelTa, 2019) to translate the findings of the life cycle inventory into the impact categories to enhance comprehension and interpretation of results upon introducing all the required data for all the building's stages, from raw materials extraction to end of life, from the functional database that connects BIM data with LCA data. This study uses the ReCiPe (H) endpoint indicator method with the following categories: damage to human health, damage to ecosystems and damage to resources, as shown in Table 4.3, to assess the potential impacts of the three design types: conventional, modular, and 3D concrete printing, for the following impact categories: climate change, fossil depletion, freshwater ecotoxicity, human toxicity, ionizing radiation, marine eutrophication, metal depletion, particulate matter formation, photochemical oxidant formation, terrestrial acidification and urban land occupation. ReCiPe (H) framework provides a complete and scientifically sound approach to evaluating the sustainability of various activities and focuses on impact assessment methods that are hierarchically organized, considering multiple levels of environmental impact categories. This approach allows for a more detailed understanding of the potential consequences of human activities on the environment, ranging from local to global. Thus,

researchers, policymakers, and businesses can gain valuable insights into the environmental implications of their choices and make informed decisions to promote more sustainable practices and reduce the ecological footprint.

Table 4.3 - ReCiPe (H) endpoint impact categories method (GreenDelTa, 2019)

Impact category group	Name of the impact category	Hierarchist (H)
Acidification	Terrestrial acidification	TAP100 EQ-H
Climate change	Climate change	GWP100 HH-H GWP100 EQ-H
Depletion of abiotic resources	Metal depletion Fossil depletion	MDP100 RD-H FDP100 RD-H
Ecotoxicity	Freshwater ecotoxicity Marine ecotoxicity Terrestrial ecotoxicity	FETP100 EQ-H METP100 EQ-H TETP100 EQ-H
Eutrophication	Freshwater	FEP100 EQ-H
Human toxicity	Human toxicity	HTP100 HH-H
Ionizing radiation	Ionizing radiation	IRP100 HH-H
Land use	Agricultural land occupation Urban land occupation Natural land transformation	ALOP100 EQ-H ULOP100 EQ-H LTP100 EQ-H
Ozone layer depletion	Ozone depletion	ODP100 HH-H
Particulate matter	Particulate matter formation	PMFP100 HH-H
Photochemical oxidation	Photochemical oxidant formation	POFP100 HH-H

Where: H= Hierarchist H; EQ = Ecosystem / RD= Resources / HH= Human Health

The interpretation phase is the final stage of the Life Cycle Assessment (LCA) process. In this phase, the results of the lifecycle impact analysis for the examined activity will be visualized within the design environment of BIM tool. Subsequently, these results will be evaluated and compared with other activities or studies. However, the interpretation process is contingent upon the study's objectives, which can vary. The study concentrates on determining the contribution of each life cycle phase to the overall impact, assessing the impact of different comparing emissions and resource consumption among various alternatives. This methodology focuses on comparing different construction methods, with specific attention given to the impact of the materials' production stage to enhance decision-making at the conceptual design phase.

4.5.7 Life Cycle Cost Analysis (LCCA) module

The objective of this module is to describe the methodology for the development of an integrated BIM-LCCA that will aid designers and investors in assessing the total cost of building ownership, considering all other costs associated with acquiring, operating, and disposing of the building, including the earned revenue. The objective of the development's methodology is to automate the evaluation of the total project costs for all alternatives and to select the design that ensures the building will provide the lowest overall cost of ownership consistent with its overall functionality within BIM tool (Autodesk Revit) environment at the conceptual design stage using the three construction methods. The goal is to identify the most cost-efficient building's design for a construction approach over the life cycle of the building. The methodology will use the capabilities of BIM tool to perform a detailed LCCA that involves establishing design alternatives, determine study period, estimate costs, compute life-cycle costs and analyze results following the construction industry's classification of monetary expenses such as initial costs, running costs (utility, operation, and maintenance), revenues and salvage value to evaluate and justify their initial investments and enables stakeholders making informed decisions by assessing different design alternatives based on long-term financial considerations during the early design stages in a timely manner by following five essential steps as illustrated in Figure 4.20.

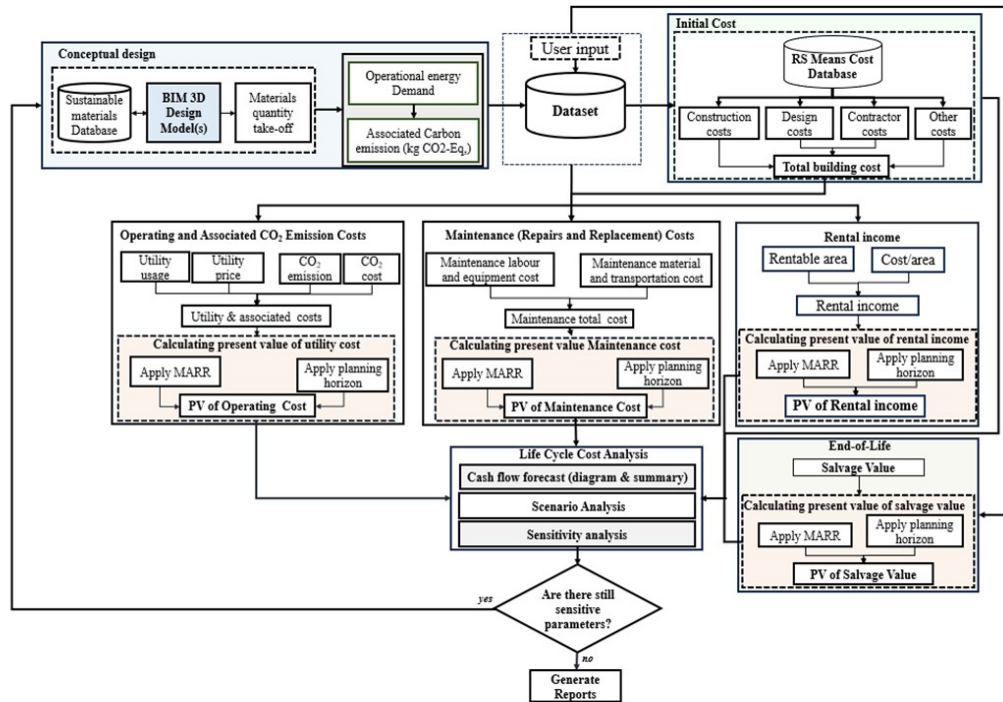


Figure 4.20 - LCCA integration process

The steps of the process involve creating and exploring design options by using conventional construction as the baseline design to compare the other design's alternatives. Subsequent steps involve estimating and analyzing the costs related to the three options, encompassing initial construction cost, operational utility cost, and maintenance costs involving minor repair and major replacement. Table 4.4 provides an overview of the cost components, along with the pertinent information and data sources for facilitating the development and estimation of costs.

Table 4.4 - Cost components and data sources for the LCCA module

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 (DesignBuilder tool)	▪ Industry guidelines (e.g., utility rates)
Carbon Embodied carbon associated with project materials and processes. Operational GHG emissions from utilities	▪ BIM Model (Autodesk Revit) ▪ Energy Simulation result (DesignBuilder tool) ▪ LCA result (openLCA) ▪ 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 for the model's materials will be generated and exported to a functional database to be used in other phases for additional calculations and analysis. Furthermore, BIM tool will be integrated with the energy analysis tool for simulation and to ascertain the operational energy of the building by using the material quantity take-off and building parameters to determine energy consumption for utilities (such as electricity, heating, cooling, and water) at the operation stage. Finally, life cycle analysis (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 Zhang et al., (2022) and integrated within BIM workflow comprising material production, construction, operation, and demolition stages. The created BIM model will be the basis for all the calculations and analysis of results, including the integration with the 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 using the generated QTO and unit costs for conventional and modular building elements retrieved from RSMeans cost database. Existing literature was used to gain insight into the building elements and construction processes related to 3D concrete printing.

Step three, consists of several components of future costs and revenue associated with the operational stage in LCCA. Utility and carbon costs will include energy consumption, which will be analyzed using a BIM-based energy simulation tool (DesignBuilder) to generate the consumption rate as previously mentioned. The associated consumption prices will be collected from sources that are specified in Table 4.4. The obtained 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 as a cost component for the detailed evaluation of the life cycle cost of the building. Furthermore, the CO₂ 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 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 Rezaei et al., (2019), while the associated cost will be estimated by using R.S.Means online 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 where the asset is intended for rental purposes, such as residential buildings and commercial spaces. The expected and estimated rental income 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 end-of-life, the study considers and implements two types of end-of-life salvage. The salvage value represents the estimated worth of an asset at the end of its designated service period. As this study considers different designs, each construction method 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 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 or machinery cost for disassembled building materials for the purpose of reusing, refurbishing, or recycling. Hence, the user has the flexibility to enter those costs as required.

4.5.7.1 Quantifying and normalizing life cycle costs

To calculate the LCC, all annual and one-time costs incurred, along with revenue income at various periods throughout a building's life cycle, are adjusted to current values using the present value

(PV) method, which can be computed by using equation (31), while for uniform annual payments by using equation (32) that considers annual payments associated with constant percentage increases or decreases, whereas equation (33) is used for single occurrences.

$$PV = A \left[\frac{(1+i)^n - 1}{i(1+i)^n} \right] \quad \text{Equation (31)}$$

$$PV = A \left[\frac{1 - (1+j)^n(1+i)^{-n}}{i-j} \right] \quad \text{Equation (32)}$$

$$PV = \frac{F}{(1+i)^n} \quad \text{Equation (33)}$$

Where PV - present value, A - annuity, F - future worth, i - $MARR$, n - analysis period, 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 a 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 net present value (NPV) within a specified time horizon and a discount rate using equation (34).

$$LCCA = \text{initial cost} - \sum(O\&M) + \text{rental income} + \text{salvage value} \quad \text{Equation (34)}$$

Additionally, uncertainty associated with LCCA results will be tackled utilizing the differential sensitivity analysis (DSA) method, as suggested in a study by Perneti et al., (2021), 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.

4.6 Summary

The adopted methodology for the development of the model that integrates BIM and sustainability design was discussed in this chapter. The intent of the research presented in this thesis is to assist users in making efficient decisions related to the suitable type of construction method associated with the selected type of design at the conceptual stage by considering users' interactions and input to facilitate the choice from conventional, modular and 3D printing construction. Furthermore, the model provides users access to reliable and real-time data about sustainable construction materials and associated families for the associated construction methods; and permits them to evaluate the sustainability of the design by using energy analysis, life cycle assessment, and life cycle costing analysis. This is achieved by the successful development and implementation of six modules, which are: database management system (DBMS) module; decision support system (DSS); energy analysis module; circular economy-based CDW management module; life cycle assessment (LCA) module; and life cycle cost analysis (LCCA) module. The six modules are interrelated to each other to make the integrated model unique, flexible, and yet versatile, with a 3D model module at the centre of the integration. Finally, the specific objectives, functionalities, requirements, and workflows of each module were examined, the discussion included the integration automation processes by customizing the application programming interfaces (APIs) of BIM tools for the three construction methods.

CHAPTER 5

Model Development

5.1 Introduction

This chapter discusses the development of the integrated model based on the adopted methodology. The goal is to connect six modules of the integrated model with BIM tool (Autodesk Revit) to support users make quick and informed decisions during the conceptual design stage of buildings. Relevant data from the revealed literature and the structured methodology provided explicit ideas for the skeleton, sequence, and functions needed to develop an integrated model that accurately reflects the design intent and achieves the desired outcomes for sustainability goals. The development procedure enhances collaboration and optimization, allowing for continuous refining of the design and evaluation to maximize its sustainability performance while meeting project's requirements and constraints. The process of developing the entire functionality of the model followed a series of interrelated activities with sustainability tools, integrated either directly by enhancing its existing functionalities through their API or by developing new functions with a user interface within the BIM tool (Autodesk Revit) as plug-ins. Furthermore, the plug-ins developed for this integration are created as a new process tab called COMOTH in Autodesk Revit, which is used to select the construction methods (conventional, modular, 3D concrete printing). The integrated model comprises six modules developed sequentially in the following order: A Database Management System (DBMS) module; A Decision Support System (DSS) module; An Energy and Thermal Simulation (ETS) module; A Circular Economy (CE) module; A Life Cycle Assessment (LCA) module; and A Life Cycle Cost Analysis (LCCA) module.

5.2 Development of the Database Management System (DBMS) module

A Database Management System (DBMS) module is developed to help users manage, store, retrieve, and manipulate data in a database for the three construction methods. This module serves as an interface between the database applications and users, providing mechanisms for creating, updating, querying, and administering the database. The development of this module involved the creation of a plug-in by using the C# programming language. Its aim is to integrate an external database design engine with BIM tool (Autodesk Revit©). This module is structured to collect and organize design data to facilitate efficient storage, retrieval, and management. The data is organized into tables, records, fields, and relationships, representing different entities and their attributes. A new plug-in, COMOTH_DB, is developed to enable designers select and incorporate design data from the database for associated construction methods, as shown in Figure 5.1.

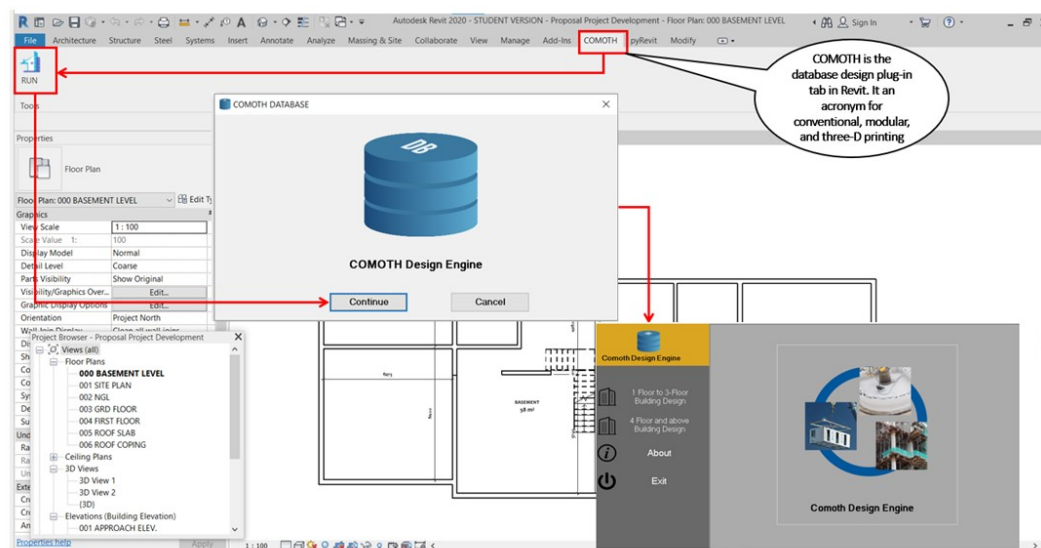


Figure 5.1 - DBMS module development's layout

COMOTH is an acronym for conventional, modular, and 3D concrete printing (3DCP), and the three types of design for the construction of buildings are being considered in this study. Therefore, the database design engine is used to collect materials and design families stored in the associated database, including printer specifications in the case of 3DCP, which is developed for that purpose. This design engine consists of two building design options: 1) 1- floor to 3-floor building design; and 2) 4-floor and above building design; and the two design options use the following three associated databases: i) Conventional Design Database; ii) Modular Design Database; and iii) 3D Concrete Printing Design Database. As shown in Figure 5.2, the user has the option to select a 1- floor to 3-floor or 4-floor and above building design within the database design engine. In addition, choosing either of the two options would enable the database design engine to open the three associate design databases.

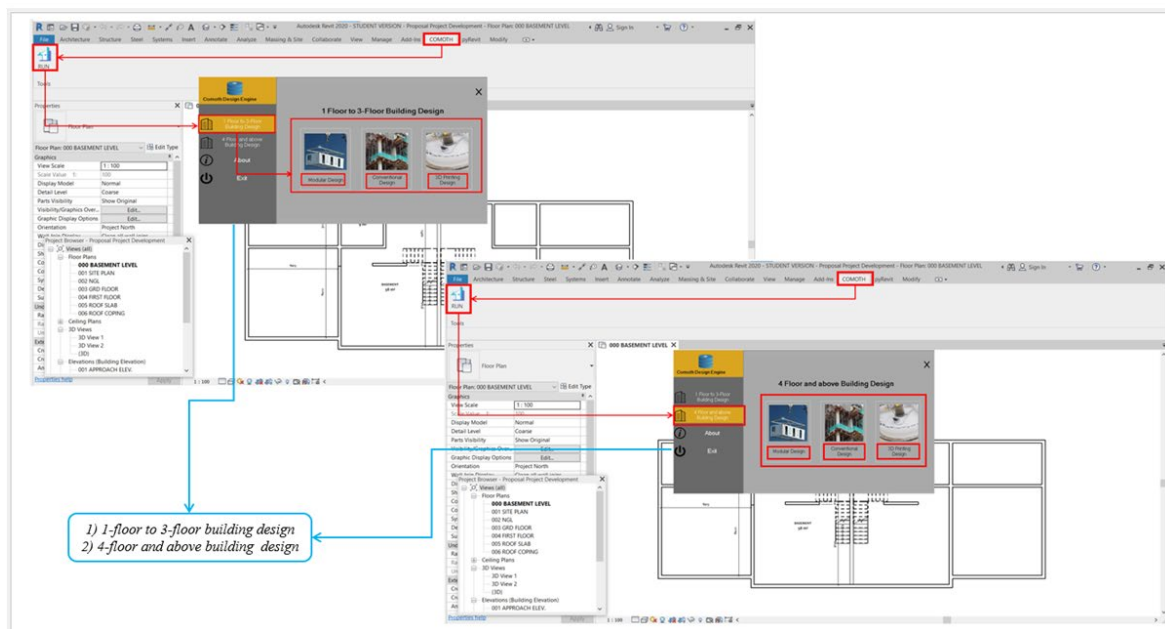


Figure 5.2 - Building design options with the three associated database

The design families such as door, window, wall, floor, and ceiling and their associated parameters, keynotes, assembly code, specification, and description for conventional, modular 3DCP construction methods, are stored in their associated database. So that once the COMOTH_DB plug-in runs, the dialogue for the two building design floor options, information about the design environment, and exit menu opens up. The most important step for the user is to review the options and select the correct design option that is compactable with their intending sustainable design. Then, by selecting the required number of building floors and the design database, the associated database automatically displays all the stored design data. Before importing the design data from an external database to the BIM 3D model, the user can seamlessly open and note component(s) by selecting on it (such as door, window or wall), and its associated family appears for additional review. As shown in 5.3, users will select 1-floor- to 3-floor building design, modular design and door to explore the data collected and stored design data for this purpose.

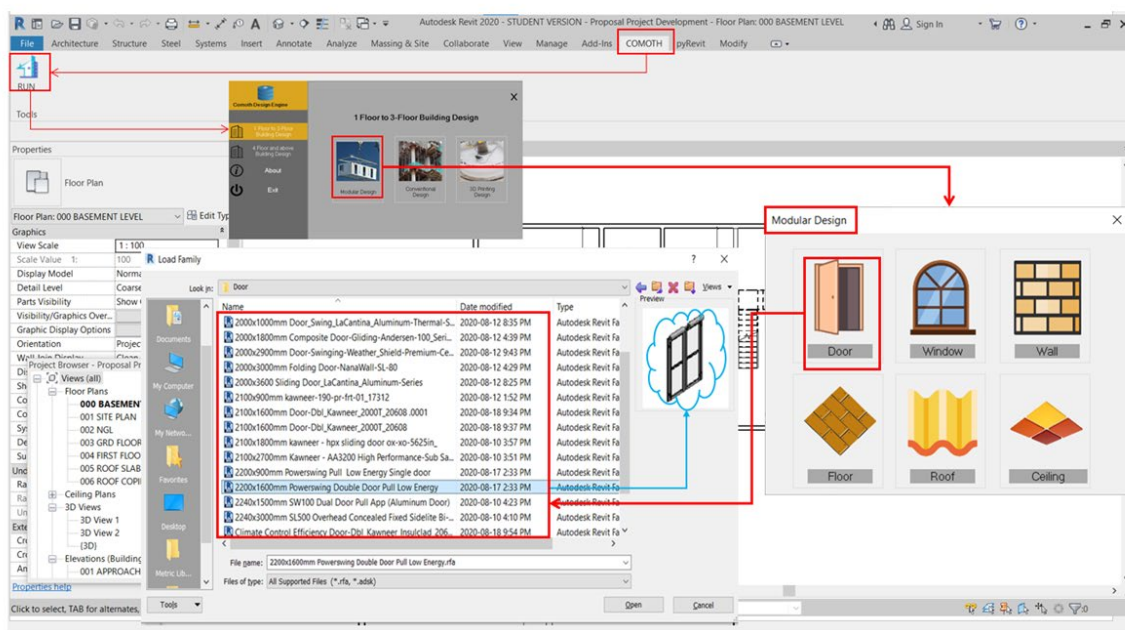


Figure 5.3 - Example of the modular design families of doors

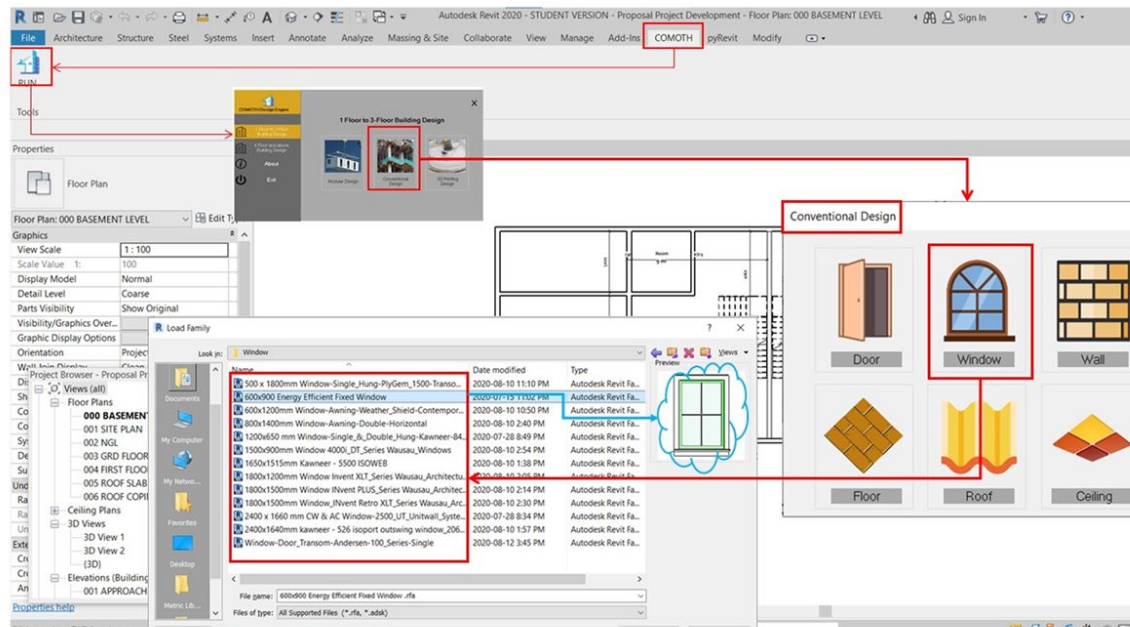


Figure 5.4 - Snapshot of the proposed conventional design window families

Similarly, the selection of 1-floor to 3-floor building design, conventional design and window displays all window design data stored in this section of the external database, as pictured in Figure 5.4. Furthermore, the 3D printing design's option contains information on materials for creating new wall design families and concrete printers' specifications from various manufacturers. The printers' specifications allow designers to review several characteristics of individual 3D printers against the project design objectives from appropriate printer selection, as shown in Figure 5.5. Similarly, selecting 4-floor and above building design options would prompt the design environment to open the three design databases. In this case, the conventional and modular design databases contain the same design data as the 1- floor to 3-floor building design, while the 3D printing database will display a message informing that the building floor option is not yet compatible with that selection. Hence, upon clicking on the 3D printing design database for this design option, the design engine displays a 'not compatible' message, as shown in Figure 5.6.

The development of the DBMS module as part of the integrated model is limited to a three-floor building for 3D printing design. This limitation is the main reason for integrating floor-level design options within the BIM-based database design engine menu to ensure that users do not anticipate a 3D printing building's design that exceeds 3-floors with BIM tool. However, the plug-in is designed to create room for future extensions of the 3D printing building design. Finally, with all the information for a sustainable design and the three building designs of construction methods stored in the COMOTH_DB design engine, the designers can start and complete the creation of their design model streamless and cost-effectively.

5.3 Development of the Decision Support System (DSS) module

In this section, a DSS module is developed in BIM tool to provide users with means and resources that facilitate making effective decisions. This module typically integrates data analysis, modeling techniques, and user interfaces to assist users in evaluating various alternatives and their potential outcomes. The development involves creating a plug-in for the COMOTH tab named DSS in an attempt to facilitate seamless interaction between BIM tool, decision-making models, MATLAB and Excel. Autodesk Revit© serves as the integration platform, while DANP-fuzzy and WASPAS-fuzzy decision models are employed to rate and rank the design components to be selected. MathWorks MATLAB functions as the decision evaluation tool, while Microsoft Excel effectively combines and manipulates data from diverse sources, enhancing the overall decision-making process. The general layout of the module plug-in is shown in Figure 5.7

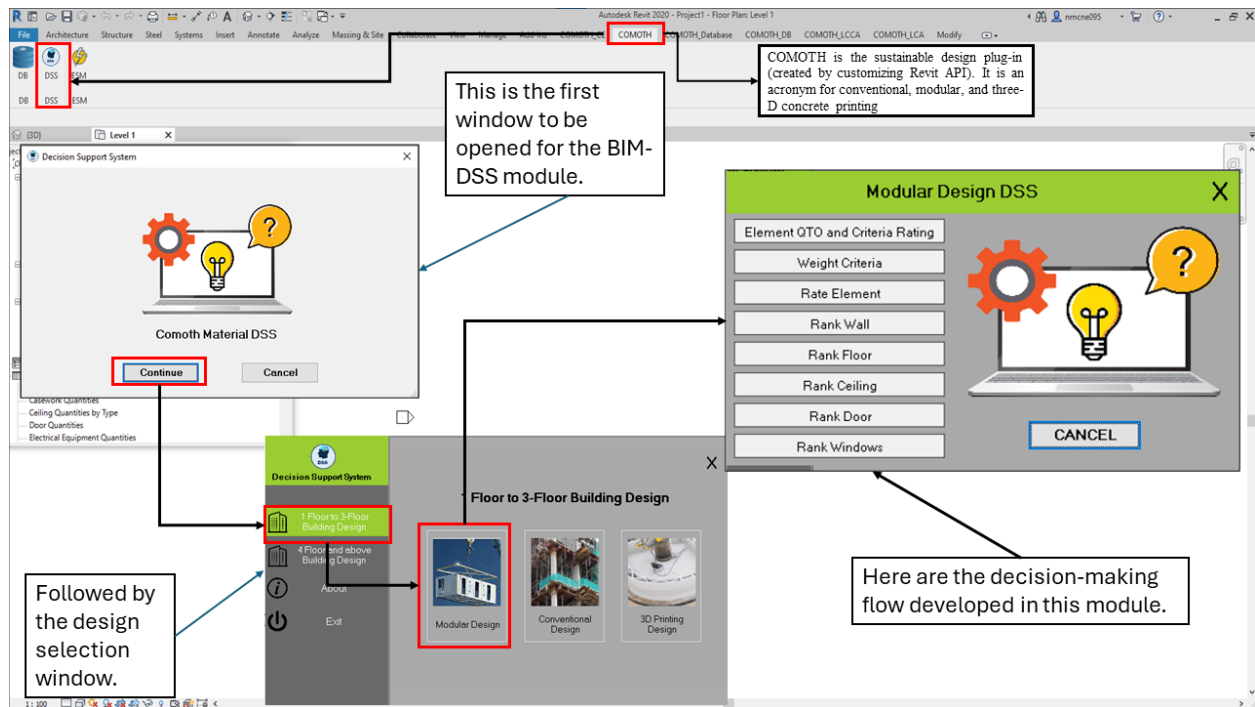


Figure 5.7- Snapshot of DSS module development layout

The process follows a sequential approach comprising four steps for each construction method under consideration: 1) design components were exported from Autodesk Revit© to Excel. These Excel files were created for the 5 design components of the BIM model, such as walls, windows, doors, flooring, and ceiling categories, with each sheet containing individual categories in such a way that components can be identified, connected and exported using the plug-in. This seamlessly developed connection to Autodesk Revit© makes the workflow robust in that once new material is introduced to the model or loaded in the design environment, it's automatically linked and incorporated into the Excel file by just clicking on the plugin. This streamlined process allows experts to assess the design components for rating, perform associated weighting operations using specified category cells, and then save the Excel file for the subsequent process, as shown in Figure 5.8.

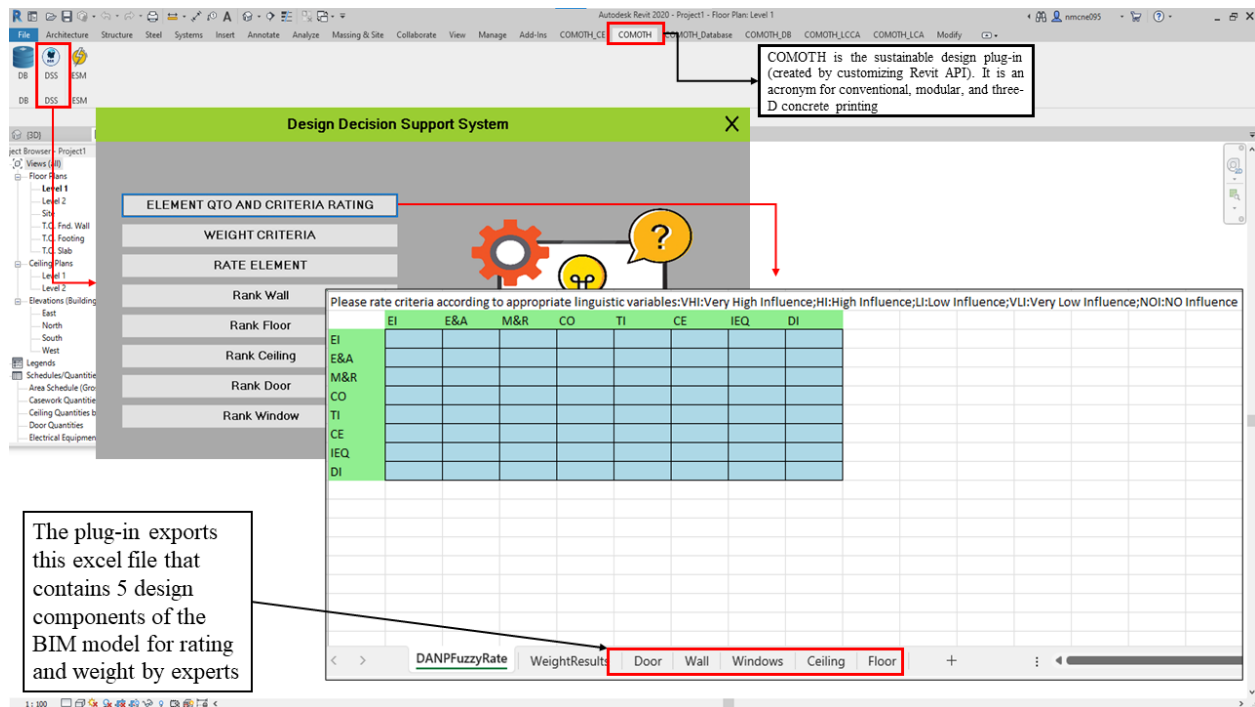


Figure 5.8 - Process of exporting Excel file for rating and weighting

The second step involves creating three broad functions in MATLAB to facilitate decision-making. The first function extracts data from the spreadsheet file. The second function activates the developed DANP-Fuzzy rating and weighting and WASPAS-Fuzzy for ranking and selection. The last function displays the result through MATLAB charts in BIM platform.

The third step involves generating MATLAB dll (Dynamic Link Library) files and compiling MATLAB code using C# programming languages. This process has been adapted to enable the integration of MATLAB functionality into other applications, such as BIM environment. Accordingly, three “dll” files were generated for the 3 associated functions explained in step 3.

In the last step, the “dll” files are utilized to develop dedicated plugins within Autodesk Revit®. As a result, a total of six plugins were created in Revit. The first plugin, for DANP-Fuzzy, assists experts and decision-makers in performing rating design families (components) within Autodesk Revit®. The remaining five plugins are explicitly designed to implement the WASPAS-Fuzzy

model and display results for five building component categories: walls, ceilings, doors, windows and floors. The plugins created for Revit in this development are illustrated in Figure 5.9.

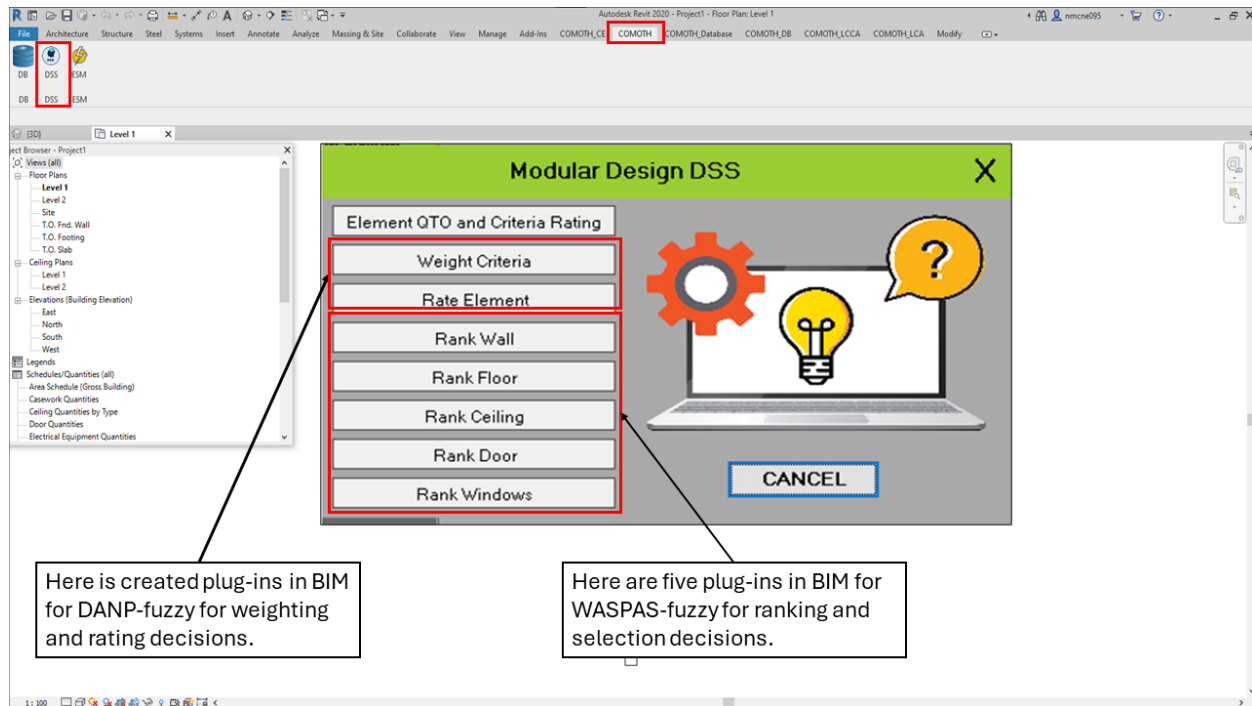


Figure 5.9 - DSS plug-ins for DANP-fuzzy and WASPAS-fuzzy

5.4 Development of the Energy and Thermal Simulation (ETS) module

In this module, a BIM-based building energy simulation model is developed to help designers execute building's performance analysis, such as energy consumption, daylighting, use, and efficiency, to compare and select the building energy demand of their design(s) (i.e., conventional, modular, and 3D concrete printing) by integrating BIM tool and the energy simulation tool. The main objective for developing this module is to assist designers in transferring the building geometry and other associated data from Autodesk Revit© to DesignBuilder and perform energy simulations. DesignBuilder Automation Interface (DB-API) is used in this integration as the tool

to create custom applications to automate and extend the functionality of DesignBuilder within Autodesk Revit API. Since the DB-API is a Component Object Model (COM) based interface, it allows users to access DesignBuilder's functionality using programming languages such as C#, Visual Basic, Python, and others. Hence, to develop this module, C# is used to customize the API(s) in order to automate their associated tasks, such as integration, modifying building models, running simulations, and extracting energy simulation results, while JSON files are used for transmitting and storing structured data between different parts of a program in the form of a plug-in. In developing this module, the first step is to prepare the 3D BIM model by organizing the spaces and zones, adding building components and systems, and defining the thermal zones, including all the fundamentals of construction documentation, corresponding parameters, and performance simulation requirements for the workflow of a Building Energy Modeling (BEM) tools. The newly created plug-in called ESM is assessed through the COMOTH tab in BIM tool (Autodesk Revit©), the general layout of the developed module is shown in Figure 5.10.

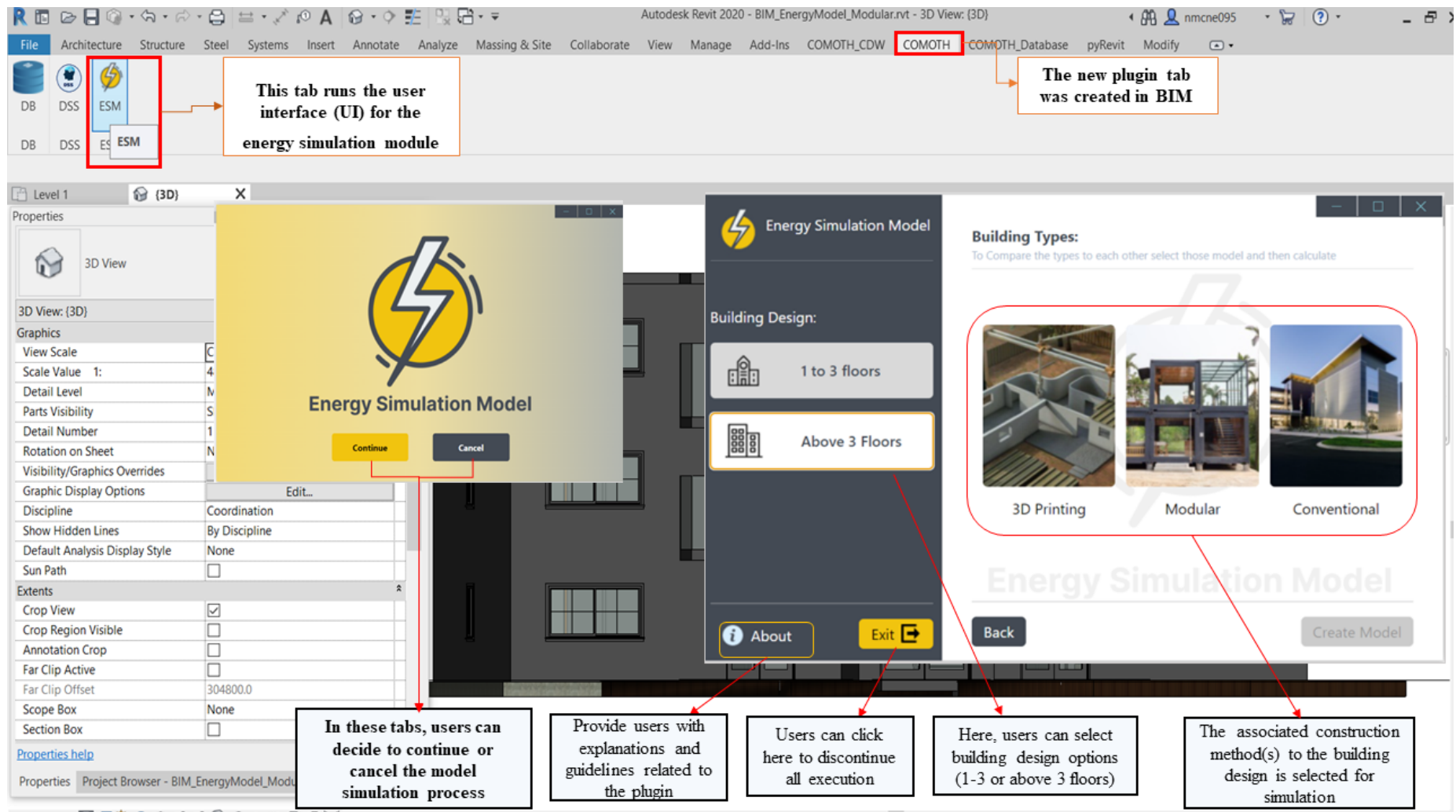


Figure 5.10 - General layout of the developed Energy Simulation module

The development of the Energy Module involves a direct integration of BIM tool with the DesignBuilder using the EnergyPlus engine through a newly created plug-in, which allows users to simulate their design in Autodesk Revit via the back-end automation process and the functionalities of the tools. The plugins export the BIM model to DesignBuilder IDF format to interpret the model's geometry, space, zone and other properties and convert them into an IDF file that EnergyPlus simulation engine can recognize to ensure that the building geometry, materials, constructions, schedules, and other parameters are accurately represented in the IDF file. During the process, users will be prompted to include a weather file of their location to start the analyses, as shown in Figure 5.11. For clarification, a weather file is a digital data file that provides information on outdoor climate conditions, such as temperature, humidity, wind speed and direction, solar radiation, and precipitation for a specific location over a given period of time. These files are essential for the energy simulation programs, as they enable the energy tool to model the building's energy performance under various climate conditions, accounting for the influence of weather on heating, cooling, and lighting loads. Once the simulation is completed, users are also prompted to select a file path to save the results, as shown in Figure 5.11.

It should be noted that the developed model has the ability to extensively execute, complete, measure, and compare energy performance for BIM models for the three construction methods in this study either singularly, differently or simultaneously. Furthermore, codes were developed to generate three input data files (IDF) from the building energy simulation tools, representing each model that was implemented in the energy analysis. The energy simulation tool helps automate the IDF creation process by providing a graphical user interface (GUI) that simplifies data input, thereby making the entire process more user-friendly. Three input Data Files (IDF) are developed for each BIM model, representing conventional, modular, and 3D concrete printing.

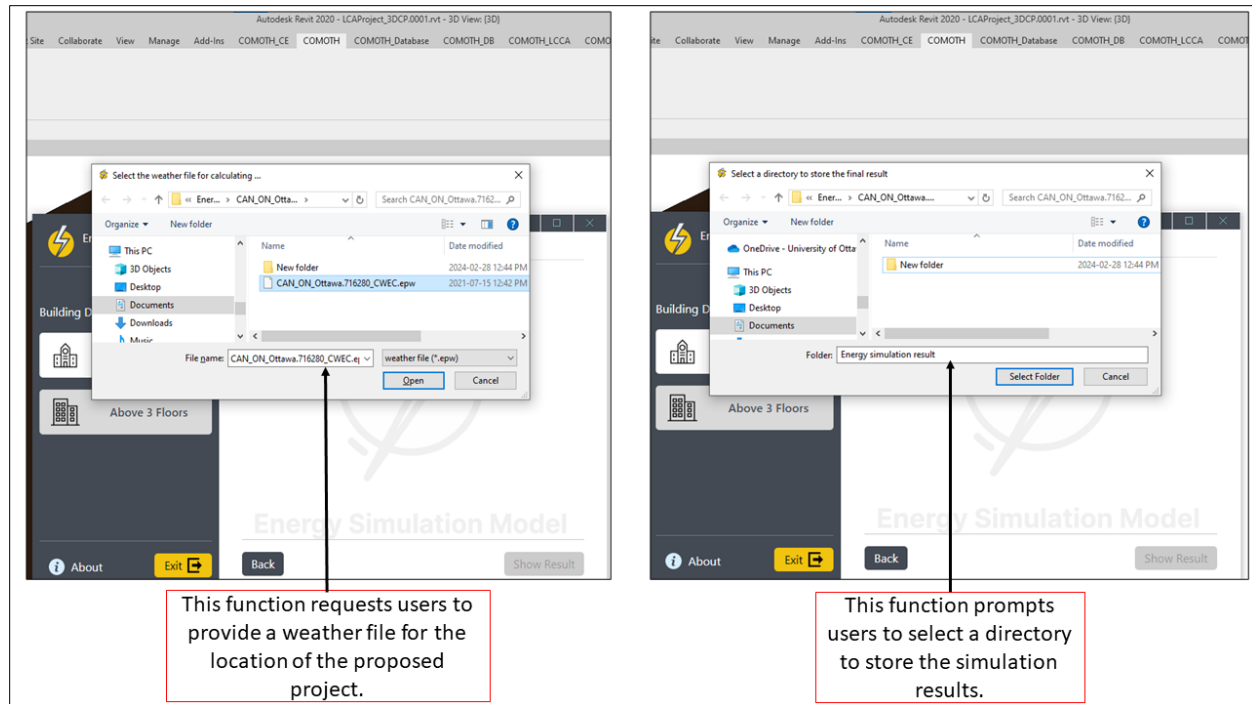


Figure 5.11 - User input for location weather file and path to save results

Another benefit of the newly created plug-in is that it helps overcome the challenges of exporting the model to gbXML format and importing the gbXML file into DesignBuilder, commonly used in BIM and DesignBuilder integration. Thus, the IDF files are generated in DesignBuilder (version 7.02) based on the American Standard Code for Information Interchange (ASCII) standard as an intermediate step before being passed to EnergyPlus (version 9.4) for simulation. Notably, the generated IDF files contain all the information about the building's model, including its geometry, materials, HVAC systems, and schedules to be simulated. Furthermore, the design and development of the user interface (UI) are essential components of development as the UI is an effective way for users to interact with a module within the host application, Autodesk Revit®.

The module is developed with two main design options (1-3 floors and above three-floor building) and implemented to simulate and analyze the three construction methods. However, the 3D concrete printing method only applies to a maximum of three building floors in this study. Users start the clear and intuitive navigation of the plug-in by clicking COMOTH in the top menu bar

and selecting ESM to run the module, the layout and design details make it easy for users to understand and maneuver. In addition, the user interface's command and display panel components allow users to interact with the integrated application easily and efficiently.

After running the plug-in, users will interactively engage with the design platform by selecting the number of floors for the building design and the construction method for the design. One advantage of the plug-in is that it allows users to select the three designs and create their model and simulation all at once. For example, the user clicks on the number floor option, selects the design(s) and simulation command, and is provided feedback on their actions. The module's features ensure quick and smooth instant feedback from user input. For example, it provides Uni Mode, where the user can see the simulation result for a single building design, and Comparing Mode, where the simulation results of the three design construction methods can be compared. Users can then use the analysis results to optimize the design and improve the building's performance.

5.5 Development of the Circular Economy (CE) module

The development of the Circular Economy module aids designers in creating a design that minimizes waste, maximizes building utilization, and simplifies material waste management processes for three construction methods. The evidence supporting the hypothesis for the development of the CE module is derived from existing literature, which identified the needs and informed the data collection and analysis processes. Hence, the development is achieved by customizing and extending the capabilities of the existing BIM tool (Autodesk Revit©) by writing a code that added new functionality to comply with the needs of the BIM-integrate module in order to facilitate communication, data exchange, and interoperability between the different parts of a system in the form of a plug-in in a BIM environment using C# programming language to link to the GoogleMaps tool and other associated data processes as described in the development

methodology. The module enables users to simplify all the processes involved in quantifying the wasted material, selecting the equipment for waste handling and the cost associated with the waste loading and hauling at the various stages of a project through an interactive user interface (UI). Users can access the module interface by clicking on the COMOTH_CE tab in Autodesk Revit© environment to start the waste planning and evaluation processes for their design, as shown in Figure 5.12. Upon clicking on the tab, the first page opens with two prompts, continue and exit, followed by the home page, which contains the basic information for the design platform, such as two options for the number of floors and three associated construction methods, about, exist and reset. The “About” helps users familiarize themselves with the user interface by providing a general introduction and tutorial concerning the plug-in and how to use the module to achieve optimal results.

The integrated model is developed to provide several options with two main design options (1-3 floors and above three floors building) and implemented to evaluate and plan the construction demolition and deconstruction waste (CDW) management strategies for the three construction methods, for the construction and end-of-life stages, except for the 3D concrete printing method, which is until now can only be applied for a maximum of three floors building. First, users will select their construction method to identify the form of waste associated with quantifying wasted materials. By using the module, there are four waste categories, bulk, recyclable, landfill, and reusable, during the construction and end-of-life stages for each construction method, as shown in Figure 5.12.

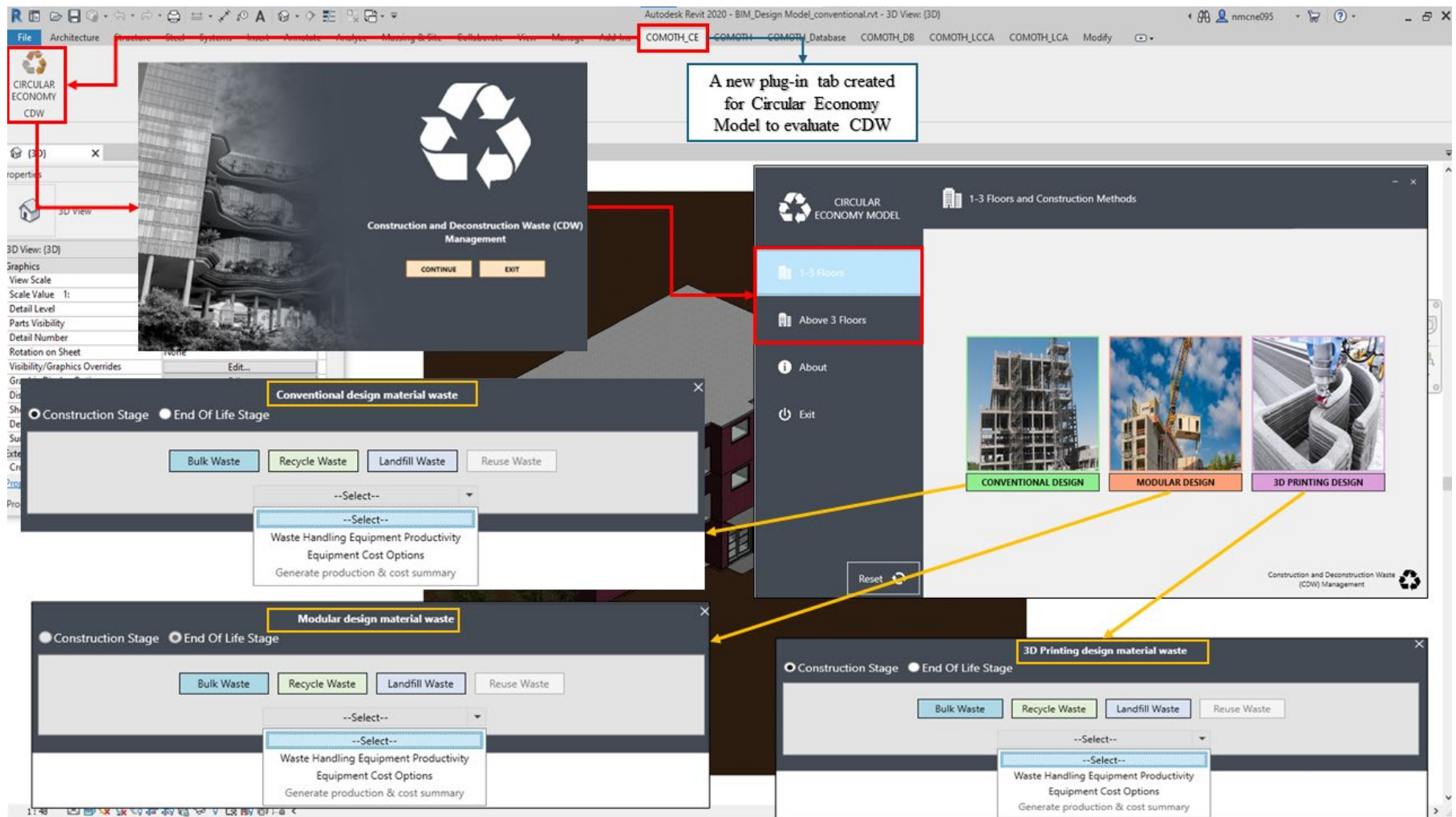


Figure 5.12 - General layout of the developed Circular Economy module

For each of the mentioned waste categories, the module implements three analyses to complete the evaluation of the CDW management process, listed as follows: a) quantify the associated wasted materials; b) estimate the production rate of the equipment required to handle the wasted materials; and c) estimate the cost associated with the equipment handling waste. Users must first select the form of the waste and then click the dropdown to initiate each analysis, starting with estimating the production rate for the equipment, as shown in Figure 5.12. Although the detailed data for the analysis has been predefined and integrated into the module, users must provide some input to suit their specific design needs, two types of information are necessary for calculating the equipment travel distances for their production rate. Upon selecting the type of waste, a second window with a map icon prompts users to choose the destination of the waste facility by name or address. Once users select the type of waste and the equipment from the dropdown, another window opens with the map icon for the destination. In this case, users must select the name or address of the waste facilities where the waste will be transported the waste. Additionally, the second requirement is the quantity of waste, in which the module automatically generates the quantity of waste, streamlining the process for users, as shown in Figure 5.13. In this module, the Google Maps application has been customized to enable users to input a start location or end location and perform a search.

To calculate the associated cost of the waste handling equipment, users must first select the type of waste and the equipment's type (for haulers and loaders) from the dropdown list and then select an option either to buy, lease or rent. In the next window, users must input the fuel cost in dollars/gal for their specific location to calculate individual cost options, as shown in Figure 5.14. One of the main advantages of the developed module is that it provides designers with a more precise calculation when finalizing the evaluation and cost estimation for the selected equipment.

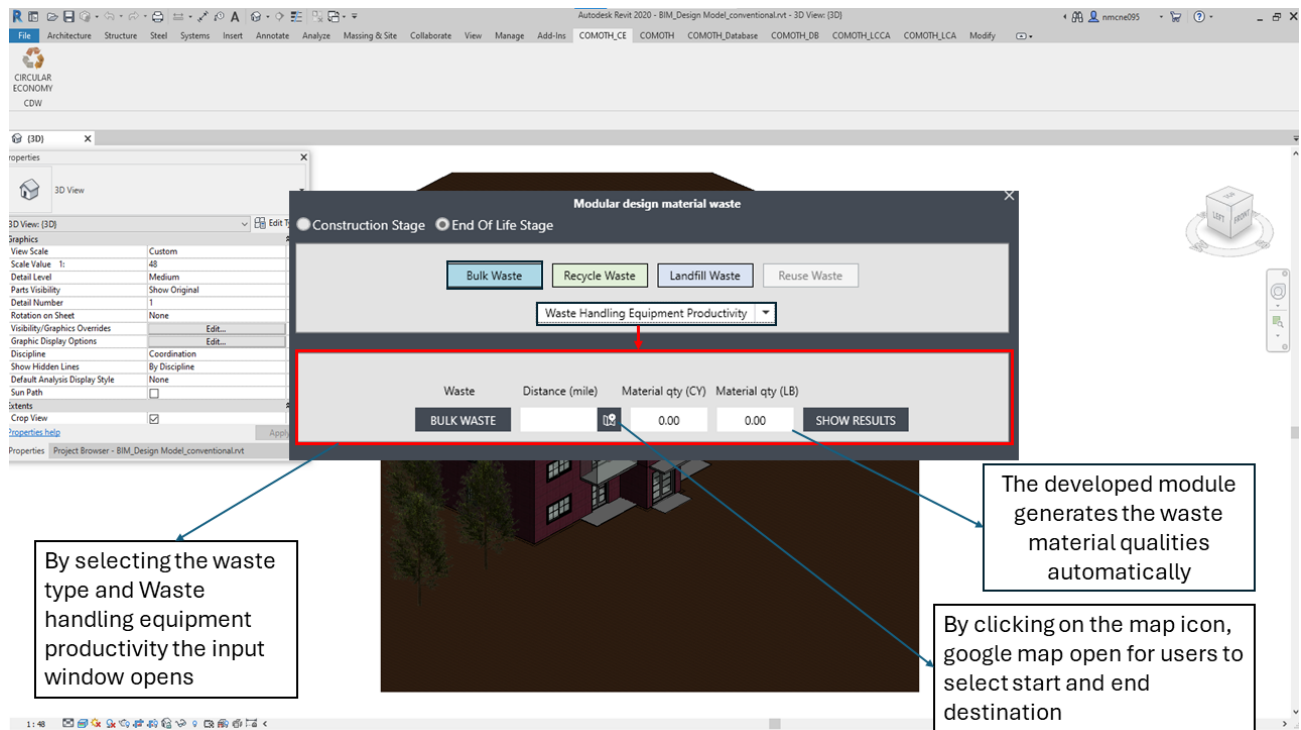


Figure 5.13 - Process to estimate waste handling equipment production rate

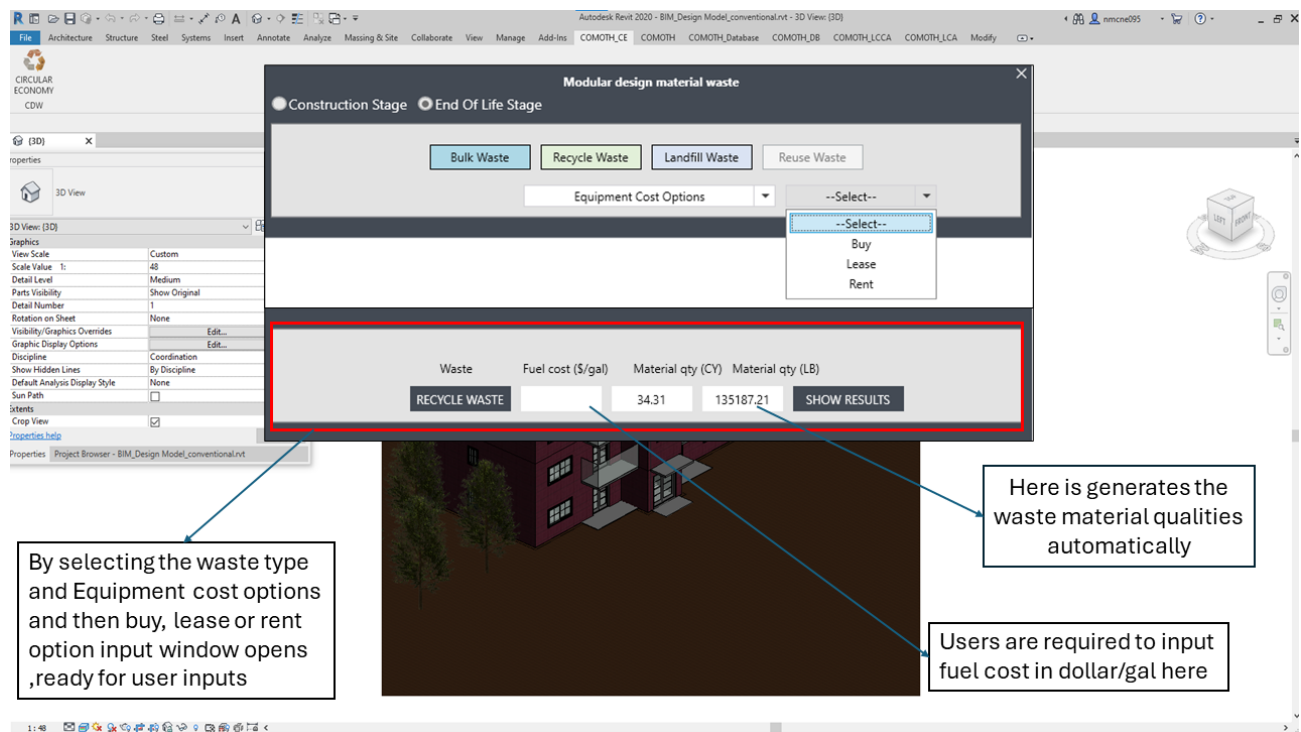


Figure 5.14 - Process to estimate waste equipment cost options

The integrated module is developed and implemented to use a built-in algorithm to select the waste handling equipment and the cost associated with loading and hauling the waste of construction and end-of-life stages based on three options: buy, lease or rent the equipment.

5.6 Development of the Life Cycle Assessment (LCA) module

The LCA module is developed through the creation of a new plug-in that enhances the functionality of existing tools to help users assess the environmental impact of their design options and processes for building projects. This enhancement helps integrate BIM with LCA tools and supports life cycle sustainability evaluation during the design stage. OpenLCA v.1.10.2 from GreenDelta was used as the LCA tool, and Autodesk Revit© as BIM tool. Autodesk Revit is the preferred BIM tool for this development because it empowers users to collaborate and encompasses every aspect of the building's project with the ability to integrate analysis and assessment tools of diverse building elements. However, there is a lack of compatibility between BIM tool and openLCA data. Therefore, to support interoperability with OpenLCA, the developed plug-in is implemented by customizing and extending their existing capabilities by using C# programming languages. Autodesk Revit© APIs are customized to automate all associated integration and modification tasks to aid users in the assessment of the life cycle impact of a building asset by providing a cradle-to-grave approach for assessing the environmental performance of buildings according to EN 15978. The module's development process begins with two primary phases: data construction and user interface design. First, data construction involves automating the extraction of materials quantities into MS Excel sheets for various building elements across the three types of building designs. This step ensures that design data aligns with the requirements of the LCA application. Subsequently, the extracted data is linked with the Life Cycle Inventory (LCI) data source from a functional database corresponding to each building

design. Examples of LCI of material production for the three construction methods from openLCA used for the module data integration and development are shown in Figures 5.15 through 5.17.

Flow	Category	Amount	Unit	Uncertainty	Provider	Description
Fe door, outer, wood-aluminium	251:Manufacture of structural metal products, tanks, reservoirs and...	53.00000	m2	none	P market for door, outer, wood-aluminium door, ...	Doors
Fe glass fibre	231:Manufacture of glass and glass products/2310:Manufacture of ...	4531.00000	kg	none	P market for glass fibre glass fibre Cutoff, U - GLO	roof - 50%insulation batt
Fe glazing, double, U<1.1 W/m2K	231:Manufacture of glass and glass products/2310:Manufacture of ...	144.00000	m2	none	P market for glazing, double, U<1.1 W/m2K glazin...	External door and window
Fe gypsum plasterboard	239:Manufacture of non-metallic mineral products n.e.c./2395:Ma...	2.0985064	kg	none	P market for gypsum plasterboard gypsum plaster...	Gypsum Board
Fe joist, engineered wood	162:Manufacture of products of wood, cork, straw and plating ma...	7720.00000	m	none	P engineered wood joist production joist, engine...	Wood Joist - 50mm x 200
Fe light clay brick	239:Manufacture of non-metallic mineral products n.e.c./2392:Ma...	1728.00000	kg	none	P market for light clay brick light clay brick Cutoff...	Thin bricks
Fe mastic asphalt	239:Manufacture of non-metallic mineral products n.e.c./2399:Ma...	3000.00000	kg	none	P market for mastic asphalt mastic asphalt Cutoff...	for roof - 50%
Fe packaging film, low density polyethylene	222:Manufacture of plastics products/2220:Manufacture of plastics...	1.00000	kg	none	P market for packaging film, low density polyethy...	polyethylene sheet (Vapc
Fe polystyrene foam slab for perimeter insulati...	222:Manufacture of plastics products/2220:Manufacture of plastics...	902.00000	kg	none	P market for polystyrene foam slab for perimeter in...	Blanket insulation for flo
Fe residual wood, dry	162:Manufacture of products of wood, cork, straw and plating ma...	24.00000	m3	none	P fibreboard production, soft, from wet & dry proc...	Sheathing and flooring
Fe transport, freight, lorry > 32 metric ton, EURO3	492:Other land transport/4923:Freight transport by road	4.3727464	t*km	none	P market for transport, freight, lorry > 32 metric ton...	material transport to con
Fe window frame, aluminium, U=1.6 W/m2K	251:Manufacture of structural metal products, tanks, reservoirs and...	91.00000	m2	none	P market for window frame, aluminium, U=1.6 W/...	Windows

Figure 5.15 - LCIA of the material production process for conventional construction

Flow	Category	Amount	Unit	Uncertainty	Provider	Description
Fe bisphenol A epoxy based vinyl ester resin	201:Manufacture of basic chemicals, fertilizers and nitrogen compounds, ...	1124.00000	kg	none	P market for bisphenol A epoxy based vinyl ester resi...	flooring @ 50%
Fe door, outer, wood-aluminium	251:Manufacture of structural metal products, tanks, reservoirs and stea...	53.00000	m2	none	P market for door, outer, wood-aluminium door, ou...	Doors
Fe forging, steel	241:Manufacture of basic iron and steel/2410:Manufacture of basic iron a...	1.9515064	kg	none	P forging, steel, large open die forging, steel Cutoff...	joist and studs
Fe glazing, double, U<1.1 W/m2K	231:Manufacture of glass and glass products/2310:Manufacture of glass a...	144.00000	m2	none	P market for glazing, double, U<1.1 W/m2K glazing, ...	External door and w
Fe gypsum plasterboard	239:Manufacture of non-metallic mineral products n.e.c./2395:Manufact...	2.9985064	kg	none	P market for gypsum plasterboard gypsum plasterb...	Gypsum Board
Fe polystyrene foam slab for perimeter insulati...	222:Manufacture of plastics products/2220:Manufacture of plastics produ...	5018.00000	kg	none	P market for polystyrene foam slab for perimeter insu...	Blanket insulation
Fe polyvinylfluoride, film	222:Manufacture of plastics products/2220:Manufacture of plastics produ...	1124.00000	kg	none	P market for polyvinylfluoride, film polyvinylfluoride...	flooring @50%
Fe residual wood, dry	162:Manufacture of products of wood, cork, straw and plating materials/...	8.64000	m3	none	P fibreboard production, soft, from wet & dry process...	Sheathing
Fe tin plated chromium steel sheet, 2 mm	241:Manufacture of basic iron and steel/2410:Manufacture of basic iron a...	2020.00000	m2	none	P market for tin plated chromium steel sheet, 2 mm ...	ALL Sheets
Fe transport, freight, lorry, unspecified	492:Other land transport/4923:Freight transport by road	4.1322064	t*km	none	P market for transport, freight, lorry, unspecified tra...	Transportation for
Fe window frame, aluminium, U=1.6 W/m2K	251:Manufacture of structural metal products, tanks, reservoirs and stea...	91.00000	m2	none	P market for window frame, aluminium, U=1.6 W/m2...	Windows

Figure 5.16 - LCIA of the material production process for modular construction

Flow	Category	Amount	Unit	Uncertainty	Provider	Description
F ₂ bisphenol A epoxy based vinyl ester resin	201:Manufacture of basic chemicals, fertilizers and nitrogen compound...	1124.00000	kg	none	P market for bisphenol A epoxy based viny...	flooring @ 50%
F ₂ cement, pozzolana and fly ash 11-35%, non-...	239:Manufacture of non-metallic mineral products n.e.c./2394:Manufac...	4.28420E4	kg	none	P cement production, pozzolana and fly as...	Cement, flyash and s...
F ₂ door, outer, wood-aluminium	251:Manufacture of structural metal products, tanks, reservoirs and stea...	53.00000	m2	none	P market for door, outer, wood-aluminium...	Doors
F ₂ glass fibre	231:Manufacture of glass and glass products/2310:Manufacture of glass...	4531.00000	kg	none	P market for glass fibre glass fibre Cutoff...	roof -50% insulation...
F ₂ glazing, double, U<1.1 W/m2K	231:Manufacture of glass and glass products/2310:Manufacture of glass...	144.00000	m2	none	P market for glazing, double, U<1.1 W/m2...	External door and wi...
F ₂ gravel, crushed	081:Quarrying of stone, sand and clay/0810:Quarrying of stone, sand an...	9.05880E4	kg	none	P gravel production, crushed gravel, crus...	Gravel
F ₂ gypsum plasterboard	239:Manufacture of non-metallic mineral products n.e.c./2395:Manufac...	4618.00000	kg	none	P market for gypsum plasterboard gypsu...	Gypsum Board
F ₂ joist, engineered wood	162:Manufacture of products of wood, cork, straw and plaiting material...	712.00000	m	none	P engineered wood joist production joist, ...	Wood Joist - 50mm ...
F ₂ mastic asphalt	239:Manufacture of non-metallic mineral products n.e.c./2399:Manufac...	1500.00000	kg	none	P market for mastic asphalt mastic asphal...	for roof - 50%
F ₂ plasticiser, for concrete, based on sulfonate...	201:Manufacture of basic chemicals, fertilizers and nitrogen compound...	458.00000	kg	none	P market for plasticiser, for concrete, based...	admixture for concr...
F ₂ polystyrene foam slab for perimeter insulati...	222:Manufacture of plastics products/2220:Manufacture of plastics pro...	3289.00000	kg	none	P market for polystyrene foam slab for peri...	insulation for all
F ₂ polyvinylfluoride, film	222:Manufacture of plastics products/2220:Manufacture of plastics pro...	1124.00000	kg	none	P market for polyvinylfluoride, film polyvi...	flooring @50%
F ₂ reinforcing steel	241:Manufacture of basic iron and steel/2410:Manufacture of basic iron ...	3456.00000	kg	none	P market for reinforcing steel reinforcing ...	Steel bars
F ₂ residual wood, dry	162:Manufacture of products of wood, cork, straw and plaiting material...	5.00000	m3	none	P fibreboard production, soft, from wet & ...	Sheathing
F ₂ sand	081:Quarrying of stone, sand and clay/0810:Quarrying of stone, sand an...	6.08570E4	kg	none	P market for sand sand Cutoff, U - GLO	Sand (0-2mm)
F ₂ window frame, aluminium, U=1.6 W/m2K	251:Manufacture of structural metal products, tanks, reservoirs and stea...	91.00000	m2	none	P window frame production, aluminium, U...	Windows

Figure 5.17 - LCIA of the material production process for 3D concrete printing

The third phase involves designing and developing the user interface by utilizing C# programming language alongside the Windows Presentation Foundation (WPF). WPF, an integral part of the .NET framework supported by Visual Studio, offers a robust graphical user interface (UI) framework. The utilization of WPF aims to provide a robust platform for creating interactive and dynamic user interfaces. It facilitates the segregation of the visual presentation and behaviour of an application's UI from its underlying logic, thereby streamlining the creation of sophisticated and visually appealing applications. Additionally, C# is employed to script the backend application code, encompassing the logic, functionality, and integration rules governing the application's behaviour. This included the development of a new tab within Autodesk Revit© named COMMTH_LCA, as shown in Figure 5.18.

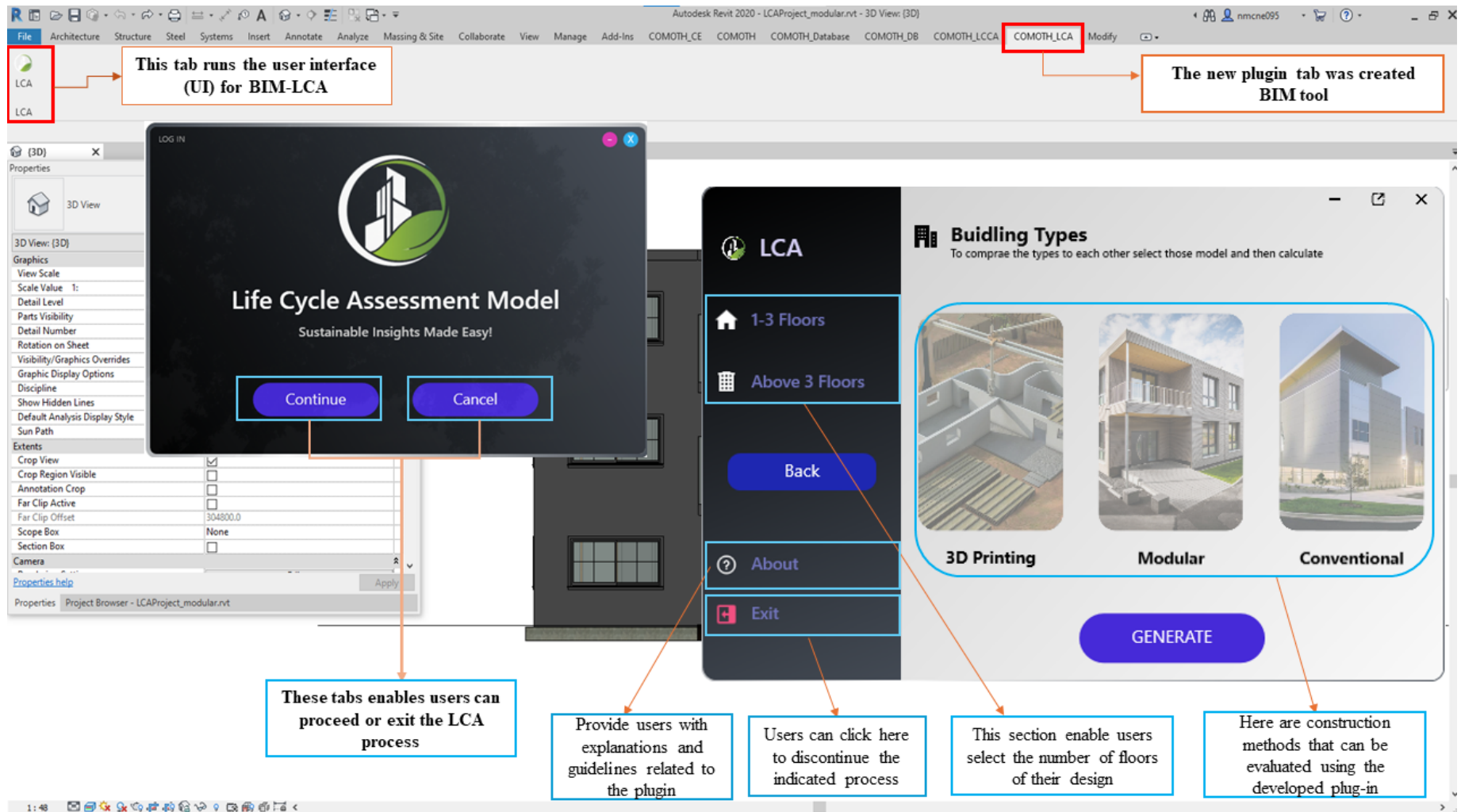


Figure 5.18 - Screenshot of the plug-in user interface LCA module

The detailed module's development involves the creation of wireframes and mockups of the graphical user interfaces for the intro window, main window, combo box window, and presentation window using extensible application markup language. The design aimed for a smart and visual appealing interface, considering sustainability themes and ease of use. The development process begins with a thorough analysis of users' requirements for the LCA module within the COMOTH process and with an understanding of the plug-in's goals, functionalities, and needs. Thus, requirements included a COMOTH_LCA tab, LCA run button, building type selection, design option (s), LCA stages, data visualization (tables and charts), saving functionality, and intuitive user interfaces. Figure 5.19 shows the LCA system boundaries and associated reports in graphical and tabulated formats of the developed LCA module.

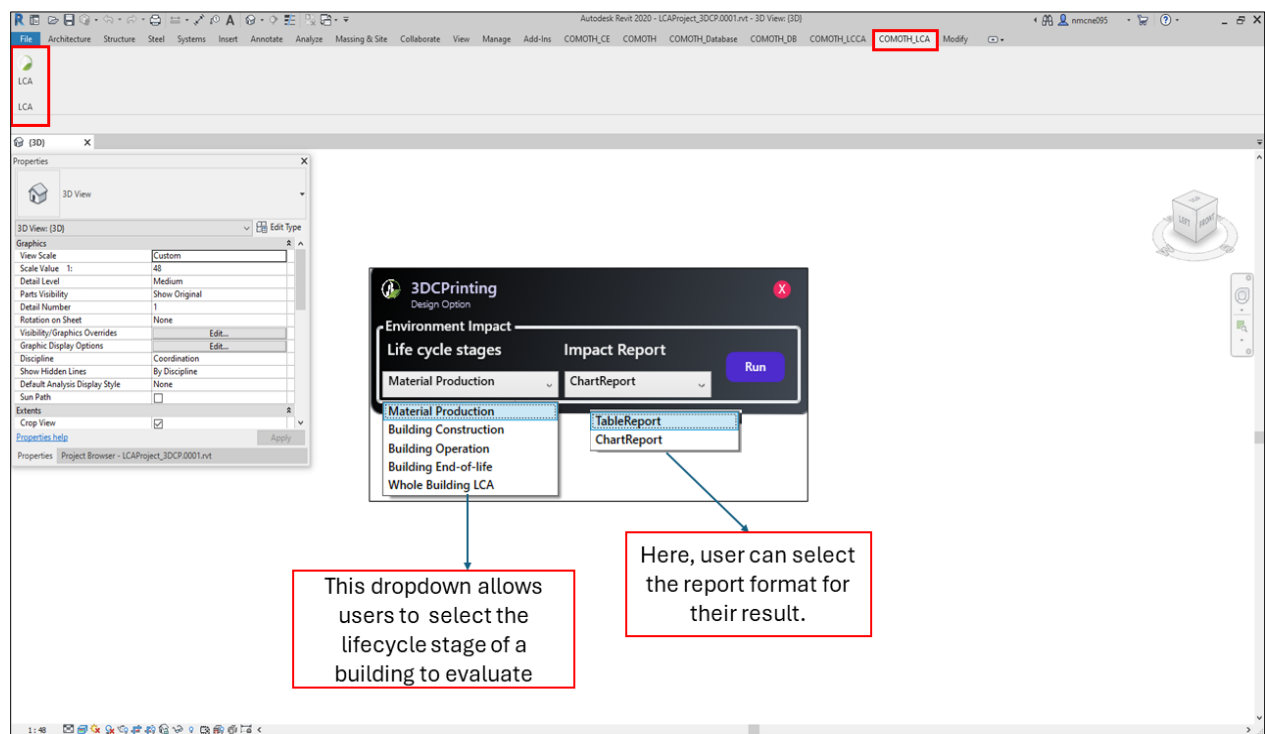


Figure 5.19 - LCA system boundaries and associated report form

Figure 5.19 shows the scope of the assessment of the LCA module by representing the processes and activities that are included in the analysis. System boundaries are critical because they determine the extensiveness and reliability of the LCA results. In this study, cradle-to-grave system boundaries are considered and used for the module's development. This boundary encompasses all stages of the product or system life cycle, from raw material extraction (cradle) to disposal or recycling (grave). It includes the extraction of raw materials, manufacturing, transportation, use phase, maintenance, and end-of-life treatment (e.g., recycling, landfilling, or reuse).

The developed LCA module consists of the other functionality and operational buttons: building design options, 1-3 floors building and above 3 floors building. However, the 3D concrete printing design option is not compatible with the above 3 floors, hence users must only select 1-3 floor option for 3DCPrint design; (ii) three construction methods, namely conventional, modular and 3D concrete printing; (iii) generate button, which opens the presentation window for the selection of lifecycle stages (tables and charts), the LCA process will not be activated unless the building design option and construction method are both selected; (iv) back button terminates the ongoing processes in the main window and returns to the intro window; (v) about button provides users with a general introduction, background information to get them to familiarize with the plug-in and interface sections; (vi) exit button terminates the program; and (vii) control buttons provides the options to maximize, minimize, or close the user interface (UI). For example, users can assess the environmental impact of the 3D Concrete printing construction method's lifecycle stages by selecting the 1-3 floor design, 3DCPrinting method, and generate button.

5.7 Development of the Life Cycle Cost Analysis (LCCA) module

The five phases representing the integrated LCCA module, described in Figure 4.20 of the methodology chapter, are developed by customizing and extending the capabilities of the existing BIM tool's APIs using the software development kits, which serve as the building blocks for software applications. These tools allow writing additional programming code to create new functionality to fulfill the needs of the module'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 overpassed 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 module 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 module, as shown in Figure 5.20. The module is designed with two main design options (1 to 3 floors and above 3-floors building), three construction methods (namely conventional, modular and 3D concrete printing) and developed to execute various actions for life-cycle costing using the embedded data and associated commands both cost evaluation and result simulations. Figure 5.21 shows the detailed layout of the developed module. The module permits users to access individual buildings' LCC information through various sections such as general information, cost and revenue (initial, operation, maintenance, rental income and salvage value) and analysis (LCC cashflow, scenario and sensitivity) as shown in Figure 5.21.

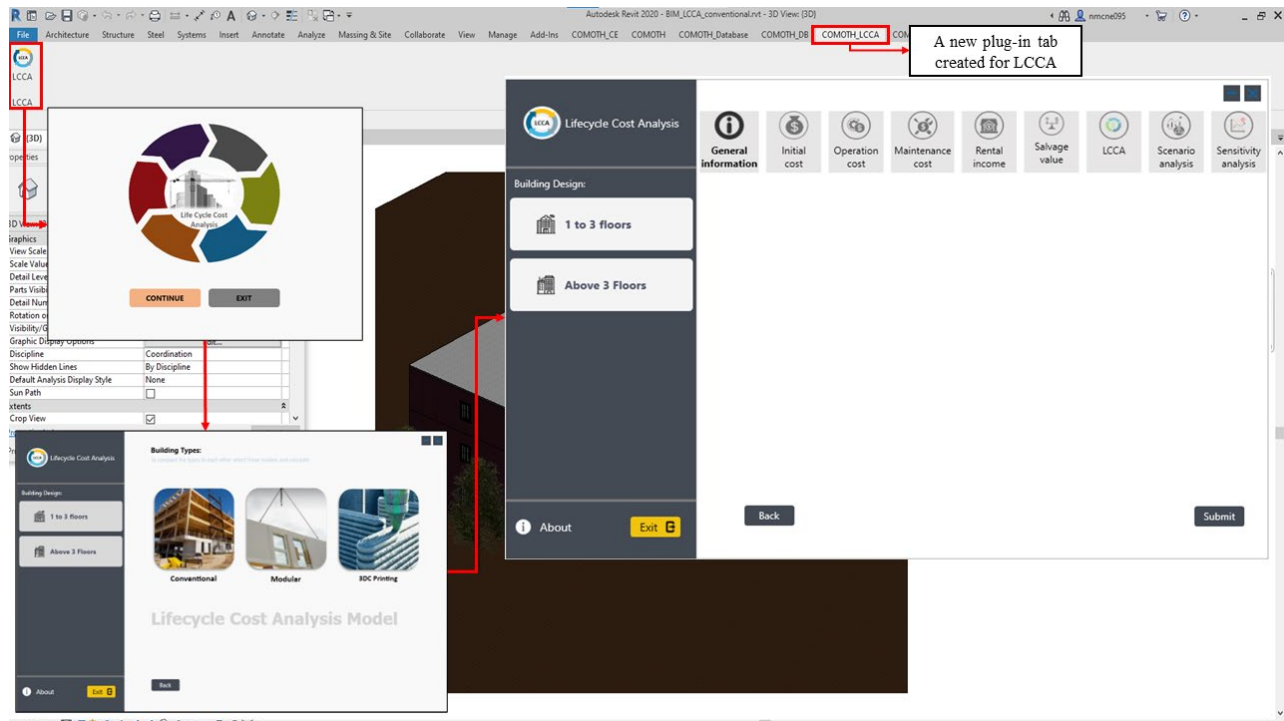


Figure 5.20 - Snapshot of the developed LCCA module design

Users are required to enter specific information that are essential for conducting the LCCA within the 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 module identifies any missing information in the data entry process, it will trigger a warning to enter the missing information, and the user is prevented from moving forward with the process; hence, the submission of values from that section into the functional database will be disabled until all required fields are appropriately populated. The module prompts users first to choose a floor design option (1-3 floors and above three floors) and one of the three construction methods (conventional, modular, and 3D concrete printing).

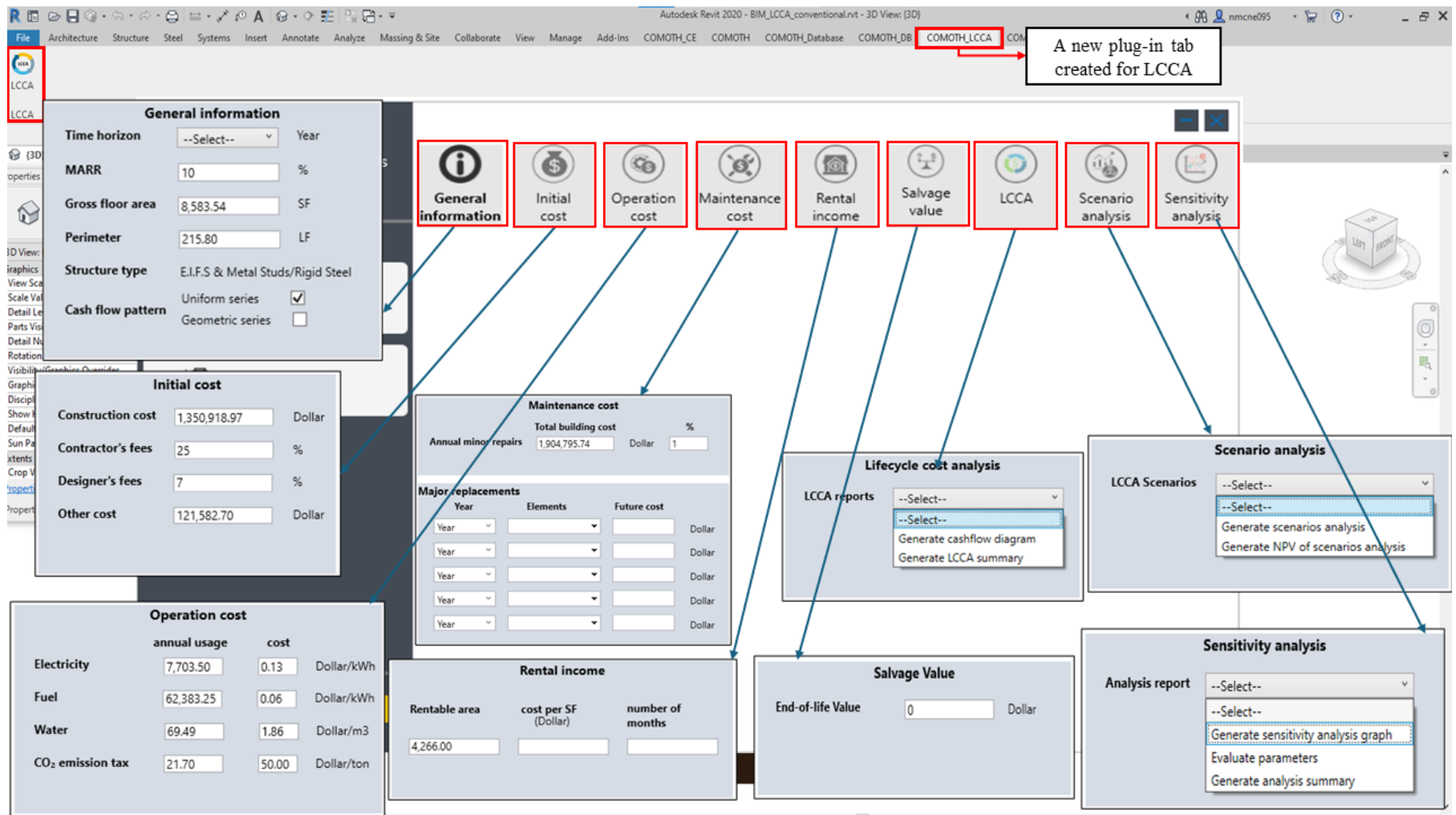


Figure 5.21 - LCCA module general information, cost, revenue analysis structure

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 was estimated by generating and exporting the material quantities take-off from the BIM 3D design model. This data was then integrated with RSMeans 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 existing studies (Batikha et al., 2022). Users are expected to input the contractor's fees as a percentage of the construction cost and other necessary costs, as shown in Figure 5.21.

The operation cost consists of the building's annual energy usage cost for electricity, fuel, and water consumption, as well as the associated carbon emission tax. Energy costs are calculated through the integration of the DesignBuilder 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 to fulfill the requirements for 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 DesignBuilder within BIM environment for review and simulation, as shown in Figure 5.22. The analysis results, consisting of the annual energy consumption, monthly electricity and natural gas usage, and prices, are all integrated into the LCCA module as the operating cost in the specified cells, as shown in the module's general information.

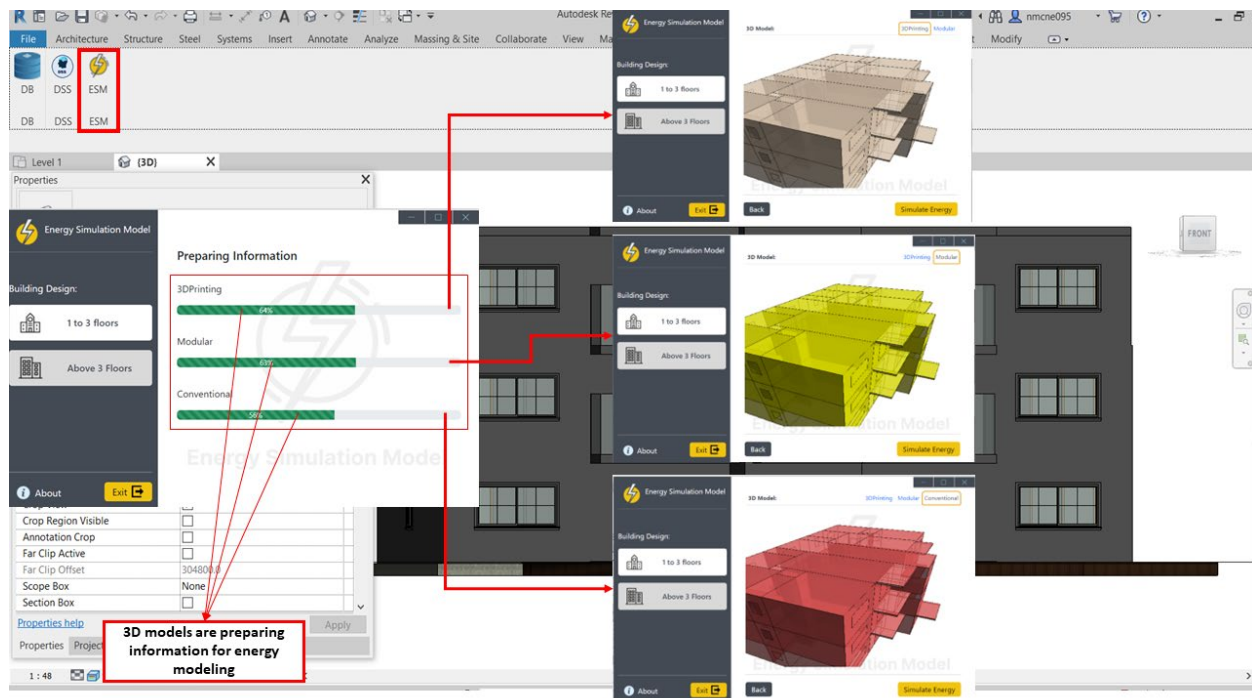


Figure 5.22 - Operational energy analysis for LCCA

The carbon emissions tax linked to the building operation phase is calculated by using the emission estimation approach outlined in the methodology and expressed as “emissions = activity data × emission factor.” The annual usage data is derived from the energy demand simulations and multiplied by the regional emission factors for Ontario for the computation. CO₂ per cubic meter of natural gas to CO₂ per kilowatt-hour (kWh) is converted by using a conversion as 1m³ gas = 10.55kWh factor. Emission results were brought to the same unit of measurement and multiplied by the regional carbon tax rate. Furthermore, the residential price of electricity is considered as being 8.7 cents per kWh (Rad et al., 2021), domestic natural gas is 16.15 cents per cubic metre (converted to kilowatt hours by using 1m³ = 10.55 kWh), the cost of the domestic water usage is taken as \$1.86 per cubic metre, and the CO₂ emission price is calculated at \$50 per tonne. The annual increases in the cost is set at 3% for operation and maintenance costs and 2.5% for rental

income following Ontario rent increase guidelines. To develop 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 module 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 components of the building, 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 calculated using RSMeans online cost data, which is connected to the LCCA module from the functional database. This cost is then adjusted to base-year values for the time of its future occurrence, following the recommendations of Fuller (2016).

In computing the rental income, the integrated module automatically generates the rentable area from the design model, the generated value is then multiplied by the cost per rentable area and the total number of months, as illustrated in Figure 5.21. 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 (Rad et al., 2021). After entering each cost, users must click the submit button to transmit the provided information and to complete all the associated analyses. The module computes the lifecycle costs at the back end to generate various analyses and reports for users, as shown in Figure 5.21: 1) LCC report - cashflow diagram and LCCA summary; 2) LCCA scenarios - scenario analysis and NPV of scenario; and 3) Sensitivity analysis - sensitivity graph, sensitive parameters, and sensitivity summary.

5.8 Summary

The focus of this chapter was the development of the integrated model to automate the evaluation and selection of associated construction methods (i.e., conventional, modular, and 3D printing) at the conceptual design stage. The model was developed through three distinct approaches: 1) utilizing the built-in functions within both BIM (i.e., Autodesk Revit©) and other sustainability design tools (such as DesignBuilder, openLCA, MATLAB, Google Maps, etc.); 2) employing set of rules and protocols for the applications to establish interaction via their APIs; and 3) creating new functionalities as plugins and integrating them with the corresponding tools. The model is implemented in a modular format, where the 3D BIM design model acts as the central hub for the whole integration and evaluation. The six modules developed in this chapter include 1) a database management system (DBMS) module; 2) a decision support system (DSS) module; 3) an energy and thermal simulation module; 4) a circular economy (CE) for construction and demolition waste management module; 5) a lifecycle assessment (LCA) module; and 6) the lifecycle cost analysis (LCCA) module. Moreover, the workflow employed in the development confirms that the integrated modules remain adaptable, allowing modifications and expansion to incorporate additional functions to handle various tasks associated with comparing and selecting associated construction methods at the conceptual design stage of buildings. The sequential procedures for developing the six modules were explained in detail in each section, utilizing a combination of tables and figures to provide a more profound illustration. The developed model provides users with several functionalities to assist them with the design and associated design evaluation by offering a data-rich environment with extensive sustainability analysis capabilities. It presents a variety of feedback and outputs in graphical and tabular formats to support and facilitate the decision-making process for designers and owners throughout the design process.

CHAPTER 6

Model Testing and Verification

6.1 Introduction

This chapter concentrates on testing and validating the functionalities and capabilities of the developed model through its integrated modules for evaluating and selecting construction methods (e.i., conventional, modular, and 3D printing) during the conceptual design stage. Each module is presented in a manner that clearly demonstrates its capabilities, functions, and outcomes. The three identical 3D BIM design models for three-story residential buildings were created at LOD 300 using Autodesk Revit 2020, as shown in Figure 6.1. It is important to note that while conceptual design models are typically created at LOD 100, this case project's model was upscaled to LOD 300 to define the building's layers and textures for the required calculations, analysis, and simulations. These case projects aim to test and verify the workability, functions, and performance of various modules integrated into the model. The buildings are intended to be constructed in Ottawa, ON, Canada, with a total gross area of 8,584 ft² and a perimeter of 216 LF, 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. The design element layers of a building component consist of different materials and properties that contribute to the overall performance and appearance of the component. In Revit, these are typically modeled as a single layer containing multiple materials. Figure 5.7a illustrates the layering of materials for each construction method and their associated thermal transmittance, providing a reliable representation of the construction process.

Finally, this study assumes that the three designs have a similar foundation; therefore, it excluded all substructural elements and associated materials for works below the floor slab.

6.2 3D BIM design model(s) for testing and verification

This section provides a broad description of the three identical 3D BIM design models that will be created in Autodesk Revit®. These models are intended to be used for testing and verifying the six developed modules of the integrated model.

The conventional design of the case project 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, 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 details of the material layers for the construction and summary QTO are shown in Figure 6.1a and Figure 6.1b.

The modular prefabrication design consists of metal studs/rigid steel frame structure designed using CFS, following BS 5950-1:2000 guidelines and the process outlined in (CISC, 2016). The floor slab configuration is assumed to be a composite steel corrugated deck, supported by purlins spaced at 1 metre centre-to-centre, 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/m², as suggested by Batikha et al., (2022), for low-rise steel buildings within two to six stories. The details of the material layers for the construction and summary QTO are shown in Figure 6.1a and Figure 6.1c. The 3D concrete printing method adopted in this study follows the approach proposed by Shrestha et al., (2022). 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. The details of the material layers for the construction and summary QTO are shown in Figure 6.1a and Figure 6.1d.

Finally, the scope testing and verification focuses on evaluating and justifying environmental and economic sustainability indicators, associated criteria, and various sub-criteria across the three described construction methods. These include environmental impact, waste management, lifecycle cost analysis, building operational energy demand, and thermal comfort. These indicators and criteria are essential for addressing multiple aspects of sustainability in a building.

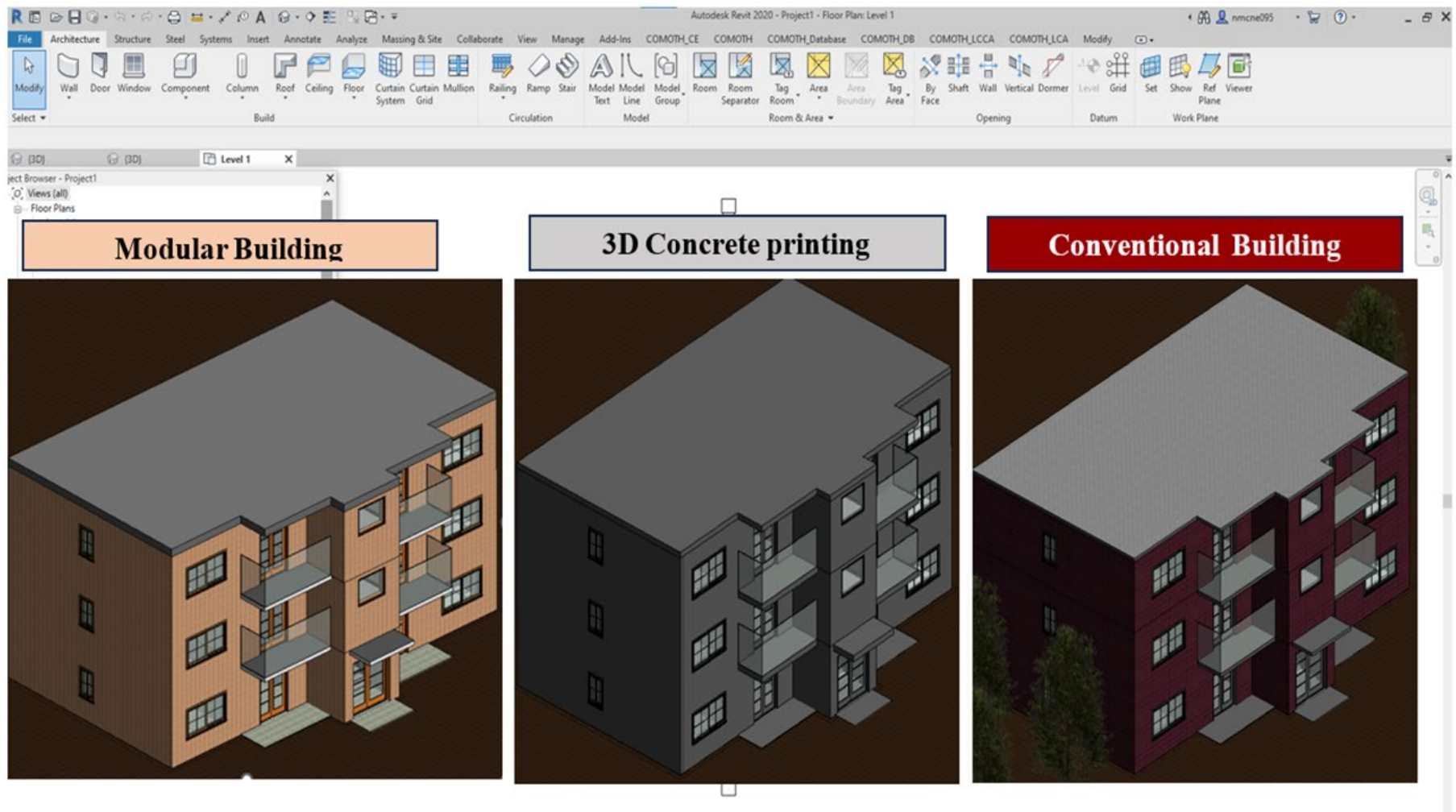


Figure 6.1 - 3D BIM design model(s) used for testing

Family Category	Conventional Construction			Modular Construction			3D Concrete Printing		
	Material	Thickness	U-value (W/m ² K)	Material	Thickness	U-value (W/m ² K)	Material	Thickness	U-value (W/m ² K)
FLOOR	Wood floor		0.448	Steel Bar Joist modular floor		0.328	Precast concrete floor slabs		0.338
	Wooden Flooring tiles	15mm		Vinyl Composition Tile	15mm		Floor finish	15mm	
	Sheathing - OSB -Subflooring	15mm		Wood - Sheathing - plywood	15mm		Precast concrete slab	100mm	
	Batt Insulation	50mm		Rigid Board insulation	50mm				
	Wood Joist/Rafter - 2"x 8"	50mm		Steel Bar Joist Layer	100mm				
WALL	Brick Veneer wall on wood		0.341	Sandwich Panel on Mtl. Stud		0.268	3D Printing Exterior Wall (150mm)		0.361
	Brick Veneer -Masonry outer layer	20mm		Metal - Aluminium - part of panel	2.5mm		Printed concrete wall	50mm	
	Wall Sheathing - Particleboard/ OSB	15mm		Rigid insulation - part of panel	80mm		Spray form insulation	50mm	
	Air gap	10mm		Metal - Stud Layer	100mm		Printed concrete wall	25mm	
	insulation	100mm		Metal - Aluminium - part of panel	2.5mm		Printed concrete wall	25mm	
	Wood - Stud 2"x4"	100mm	0.25	Gypsum Wall Board	15mm	0.227			0.361
	Gypsum, Board	15mm		Modular sandwich panels			3D Printing Interior Wall (75mm)		
	Interior wall			Gypsum Wall Board	12mm		Printed Concrete Wall	25mm	
	Gypsum, Board	12mm		Metal - Stud Layer	25mm		Spray form Insulation	25mm	
	Wood - Stud Layer @ 400 mm O.C	50mm		Semi-rigid insulation	25mm		Printed Concrete Wall	25mm	
OPENING	Fiberglass Batt	20mm	1.45	Gypsum Board	12mm	1.45	Windows in aluminium frame		1.45
	Gypsum, Board	12mm		Windows in aluminium frame			Outer layer- low-E glazing	6mm	
	Windows in aluminium frame			Outer layer- low-E glazing	6mm		Filled gap - argon	13mm	
	Outer layer- low-E glazing	6mm	1.45	Filled gap - argon	13mm	1.45	Inner layer- low-E glazing	6mm	1.45
	Inner layer- low-E glazing	6mm		Inner layer- low-E glazing	6mm		Door: Exterior		
	Door: Exterior			Door: Exterior			Outer layer- low-E glazing	6mm	
	Outer layer- low-E glazing	6mm		Outer layer- low-E glazing	6mm		Filled gap - argon	13mm	
ROOF	Filled gap - argon	13mm	0.213	Filled gap - argon	13mm	0.37	Inner layer- low-E glazing	6mm	0.213
	Inner layer- low-E glazing	6mm		Inner layer- low-E glazing	6mm		Interior door: Wooden		
	Interior door: Wooden			Interior door: Wooden					
	Asphalt Shingle on wood rafters		0.213	Steel Truss on metal standing seam		0.37	Asphalt Shingle on wood rafters		0.213
	Rigid Board -Insulation	100mm		Metal - Sheet / Flashing	50mm		Rigid Board	100mm	
	Wood Joist/Rafter	50mm		Rigid insulation	50mm		Wood Joist/Rafter	50mm	
	Sheathing - particleboard/ OSB	15mm		Structure, stainless Steel	50mm		Sheathing - particleboard/ OSB	15mm	
	Water/vapor Barrier	6mm		Steel siding	50mm		Water/vapor Barrier	6mm	
	Asphalt Shingle	3mm		Roofing - Metal Standing Seam	25mm		Asphalt Shingle	3mm	
				Vapor / Moisture Barriers - felt	20mm				

Figure 6.1a - Construction material and layers details

Conventional materials QTO						
Assembly Description	Family and Type	Material: Description	Material: Name	Material: Manufacturer	Material: Area (m²)	Material: Volume (m³)
Floor Construction	Floor: Floor-- Wood joist 300mm - Vinyl finish	Flooring, vinyl tile, solid colors, 300 mm x 300 mm x 12 mm	Flooring vinyl tiles	Armstrong	576	8.64
		12 mm Sheathing CDX particleboard/OSB, subfloor	Particleboard/ OSB	West Fraser		8.64
		Blanket insulation for floors/ceilings, fiberglass, paper or foil backing, 1 side, 89 mm thick, 2.2m2.K/W, incl. spring type wire fasteners	Batt Insulation	Owens Corning		28.8
		50mm x 100mm wood joist, framing horizontal and vertical	Wood Joist	Century Mill Lumber		2.13
		Headers - (100mm x 200mm)	Wood Headers	Century Mill Lumber		1.8
		Gypsum ceiling Board, weatherproof, 15mm thick	Gypsum Board	Arbec forest product		6.912
Exterior Walls	Basic Wall: Exterior Wall-- Brick veneer on wood stud	Thin brick veneer, norman, 68 mm x 16 mm x 200 mm, on masonry/plaster back-up, includes 3% brick and 25% mortar waste, excludes scaffolding, grout and reinforcing	Brick Veneer - Masonry	Brampton brick	540	10.8
		Sheathing, OSB on roof, CDX, 15mm thick	Particleboard/ OSB	Arbec forest product		8.1
		Modified bituminous sheet air barrier, SBS modified sheet laminated to polyethylene sheet, 40 mils thick, 100 mm wide	Air gap	W. R. Meadows, Inc.		0.54
		Wall insulation, rigid, fiberglass, unfaced, 38mm thick, 1.1m2.K/W, 24kg/m3	Insulation	Plasti.Fab.		54
		Wood framing, partitions, standard & better lumber, 50 mm x 100 mm studs, 300 mm OC, 2400mm high, includes a single bottom plate and double top plate, excludes waste	Wood Stud Layer mm O.C	Century Mill Lumber		72.93
		Gypsum sheathing, Fire-Rated Type X 12mm thick	Gypsum Board	CGC Inc.		6.48
Partitions	Basic Wall: Interior Partition-- 75mm drywall partition (1-hr)	Gypsum sheathing, Fire-Rated Type X 12mm thick	Gypsum Board Wall	CGC Inc.	750.96	9.01
		Wood framing, partitions, standard & better lumber, 50 mm x 100 mm studs, 300 mm OC, 2400mm high, includes a single bottom plate and double top plate, excludes waste	Wood Stud Layer	Century Mill Lumber		16.91
		Blanket insulation, for walls or ceilings, mineral wool batts, 88 mm thick, 2.1 m2.K/W	Mineral Wool Batt R30	Owens Corning		15.02
		Gypsum sheathing, Fire-Rated Type X 12mm thick	Gypsum Board Wall	CGC Inc.		9.01
Roof	Basic Roof: Roof-- Wood rafter 200mm - Asphalt Shingles	Framing, roofs, fascia boards, 50mm x 200mm on roof	Wood Joist-Rafter	Nordic Structures	200	0.96
			Particleboard/ OSB	Arbec forest product		4.23
		Vapor retarders, building paper, aluminum and kraft laminated, foil 2 sides	Vapor Barrier	W. R. Meadows, Inc.		1.69
		Modified bituminous sheet air barrier, SBS modified sheet laminated to polyethylene sheet, 40 mils thick, 100 mm wide	Air gap	W. R. Meadows, Inc.		28.20
		Asphalt shingles, standard strip, inorganic, class A, 25 year	Asphalt Shingle	GAF		1.41

Figure 6.1b - Summary of material QTO for conventional construction

Modular materials QTO						
Assembly Description	Family and Type	Material: Description	Material: Name	Material: Manufacturer	Material : Area (m²)	Material: Volume (m³)
Floor Construction	Floor: Floor-- Prefabricated Steel Bar Joist floor panel	Flooring, vinyl tile, solid colors, 300 mm x 300 mm x 5 mm	Vinyl Composition Tile	Armstrong	576	2.88
		Wood - Sheathing - 15 mm CDX plywood, subfloor	Plywood	West Fraser		8.64
		Blanket insulation for floors/ceilings, fiberglass, paper or foil backing, 1 side, 89 mm thick, 2.2m2.K/W, incl. spring type wire fasteners	Rigid Board insulation	Owens Cornings		28.80
		Steel Bar Joist Layer 100mm	Steel Bar Joist Layer	Bailey Metal Products		0.26
		Steel Bar Joist Layer 100mm	Steel Headers	Bailey Metal Products		0.02
		Gypsum sheathing, with embedded glass mats, 13 mm thick	Gypsum ceiling Board	CGC Inc.		6.91
Exterior Walls	Basic Wall: Exterior Wall--Prefabricated metal wall panels	Aluminum siding, on steel construction, natural, standard type, 0.48mm thick	Aluminium sheet- part of panel	VicWest Steel	540	0.98
		Furring Channel 2.75 inch x 12 ft. Galvanized Steel	Metal furring	Bailey Metal Products		0.01
		Aluminum siding, on steel construction, natural, standard type, 0.48mm thick	Aluminium sheet - part of panel	VicWest Steel		0.98
		Wall insulation, rigid, extruded polystyrene, 172kPa compressive strength, 75mm thick, 2.64m2.K/W	Rigid insulation - part of panel	Owens Cornings		81.00
		Aluminum siding, on steel construction, natural, standard type, 0.48mm thick	Aluminium sheet - part of panel	VicWest Steel	576	0.98
		Steel Bar Joist Layer 100mm	Steel Bar Joist Layer	Bailey Metal Products		1.33
		Gypsum sheathing, with embedded glass mats, 13 mm thick	Gypsum ceiling Board	CGC Inc.		6.48
Interior Wall	Basic Wall: Interior Wall--Prefabricated metal wall panels	Gypsum sheathing, with embedded glass mats, 13 mm thick	Gypsum Wall Board	CGC Inc.	750.96	9.01
		Galvanized studs, 18 ga x 63 mm W studs 400 mm OC x 2.4 m H, incl galvanized top & bottom track, excl openings, headers, beams, bracing & bridging	Stud Layer with bracing strap	Bailey Metal Prod		0.82
		Wall insulation, rigid, extruded polystyrene, 172kPa compressive strength, 75mm thick, Gypsum sheathing, with embedded glass mats, 13 mm thick	Rigid insulation - part of panel	Owens Cornings		18.77
			Gypsum Wall Board	CGC Inc.		9.01
Roof	Basic Roof: Roof Materials-- Prefabricated metal standing seam roofing system	Boxed roof ridge beam, for CF metal rafters, w/ galvanized joist & track, double, 18 ga x 200 mm D	Structure - stainless Steel	Bailey Metal Products	200	0.03
		Metal roof decking, steel, open type B wide rib, galvanized, under 465 m2, 38 mm D, 22 gauge	Steel sheet	VicWest Steel		0.17
		Vapor retarders, building paper, polyethylene vapor barrier, standard, 0.05mm thick	Vapor - Moisture Barriers	W. R. Meadows,		1.69
		Extruded polystyrene insulation, for roof decks, 50mm thick, 1.8m2.K/W, 103kPa compressive strength, fastening excluded	Rigid insulation	Dow Corning		28.20
		Membrane layer	Membrane	Dow Corning		0.02
		Aluminum roof panels, corrugated or ribbed, natural, 0.4mm thick	Metal Standing Seam	VicWest Steel		0.17

Table 6.1c - Summary of material QTO for modular construction

3D Concrete Printing QTO						
Assembly Description	Family and Type	Material: Description	Material: Name	Material: Manufacturer	Material : Area (m²)	Material : Volume (m³)
Floor Construction	Floor: Floor Materials -Prefabricate insulated concrete floor	Flooring, vinyl tile, solid colors, 300 mm x 300 mm x 3 mm	Flooring vinyl tiles	Armstrong	576	8.64
		Precast concrete slab 100mm thick	Precast concrete slab	M CON Products	576	43.2
		Blanket insulation for floors/ceilings, fiberglass, paper or foil backing, 1 side, 89 mm thick, 2.2m2.K/W, incl. spring type wire fasteners	Rigid Board insulation	Owens Corning	576	28.8
		Gypsum sheathing, with embedded glass mats, 13 mm thick	Gypsum ceiling Board	CGC Inc.	576	6.91
Exterior Walls	Basic Wall: 3D Printing Concrete Exterior (150mm) Wall - double wall with a cavity	Gantry-style printer, 3D printing concrete wall,printing with a speed of 40 to 50 cm/sec and rebars	3D concrete printed wall	COBOD2 wall	540	27
		Insulation, polyurethane foam, 32kg/m3 density, 50mm thick, 2.28m2.K/W, sprayed	Spray form insulation	John Manville	540	27
		Gantry-style printer, 3D printing concrete wall,printing with a speed of 40 to 50 cm/sec and rebars	3D concrete printed wall	COBOD2 wall	540	27
		Paints & coatings, walls, concrete masonry units (CMU), rough surface, second coat, latex, brushwork	Exterior wall painting	Cloverdale paint	540	10.8
Internal Walls	Basic Wall: 3D Printing Concrete Exterior (150mm) Wall - double wall with a cavity	Gantry-style printer, 3D printing concrete wall,printing with a speed of 40 to 50 cm/sec and rebars	3D concrete printed wall	COBOD2 wall	750.96	18.8
		Insulation, polyurethane foam, 32kg/m3 density, 50mm thick, 2.28m2.K/W, sprayed	Spray form insulation	John Manville	750.96	18.8
		Gantry-style printer, 3D printing concrete wall,printing with a speed of 40 to 50 cm/sec and rebars	3D concrete printed wall	COBOD2 wall	750.96	18.8
Roof	Basic Roof: Roof-Wood rafter 200mm - Asphalt Shingles	Framing, roofs, fascia boards, 50mm x 200mm	Wood Joist-Rafter	Nordic Structures	200	0.96
		Sheathing, oriented strand board, 15 mm thick, on roof	Particleboard-OSB	Arbec forest product	200	4.23
		Vapor retarders, building paper, aluminum and kraft laminated, foil 2 sides	Vapor Barrier	W. R. Meadows, Inc	200	1.69
		Modified bituminous sheet air barrier, SBS modified sheet laminated to polyethylene sheet, 40 mils thick, 100 mm wide	Air gap	W. R. Meadows, Inc	200	28.20
		Asphalt shingles, standard strip, inorganic, class A, 25 year	Asphalt Shingle	GAF	200	1.41

Figure 6.1d - Summary of material QTO for 3D concrete printing construction

6.3 Testing and verifying the developed DBMS module

Once a design is initiated, the users run the module by using COMOTH_DB in Autodesk Revit, which opens the database with a form requesting to select an option related to the number of floors. There are two building design options for this design engine: 1) 1- floor to 3-floor building design; and 2) 4-floor and above building design. Selecting a 1-floor to 3-floor building design instructs the design engine to open the three building construction methods, as shown in Figure 6.2.

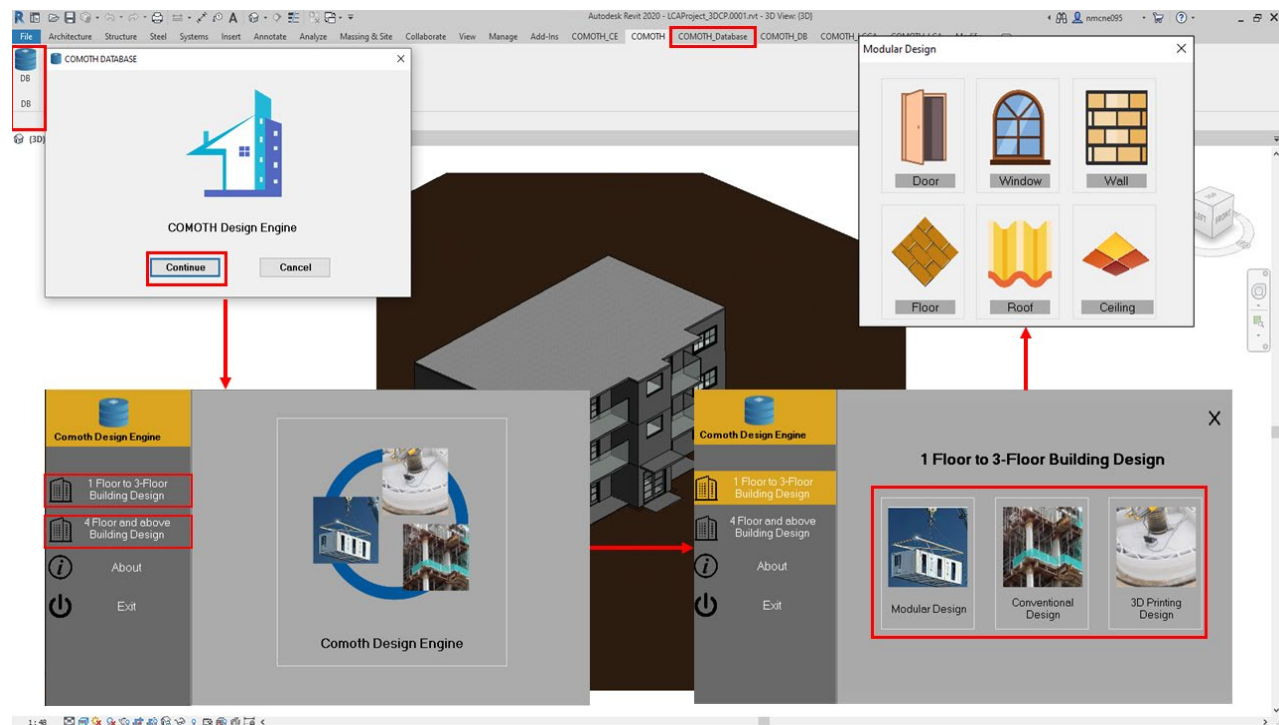


Figure 6.2 - Options and processes of the DBMS module

The design parameters for conventional and modular prefabricated building construction methods such as door, window, wall, floor, ceiling, roof and column and slab stored in the database with their associated information (keynotes, assembly code, specification, and description) are ready for use, while 3D printing design option has information about the materials (for wall design) and 3D printers' specifications. Similarly, selecting a 4-floor and above building design would instruct

the system to open three design options; however, only the conventional and modular designs are compatible with that selection. The 3D printing design option will show a ‘not compatible’ message as this study is part of an ongoing research; the developed model is limited to 3D printing design for three floors for now. However, the DBMS module is designed to be expended for future extensions of the 3D printing building design. With all the information for incorporating sustainability in the design of various building construction methods stored in the COMOTH design engine, users can commence and achieve their design in a streamless and cost-effective manner.

Using the 3D BIM model, users can begin to select and import suitable design families to be incorporated into their design using the DBMS module to access the external database where all design data have been stored by clicking the COMOTH_DB tab to run the developed module and, on the DB loader push button, to start the data retrieval from the database engine into Autodesk Revit© library to be used in the design environment. By using this process, all the loadable families, such as windows and doors, are automatically loaded in the project via the developed plug-in and ready for designers to use directly. Figure 6.3 shows Autodesk Revit© project browser with only the generic design families before using the developed plug-in, while Figure 6.4 shows the loaded families from the external database after the design families were loaded using the COMOTH_DB developed tool. Notably, the system families for the design, such as walls, roofs, and floors, which are not loadable from an external database, were created and transferred as an Autodesk Revit© project into the design platform using the functions in Autodesk Revit©.

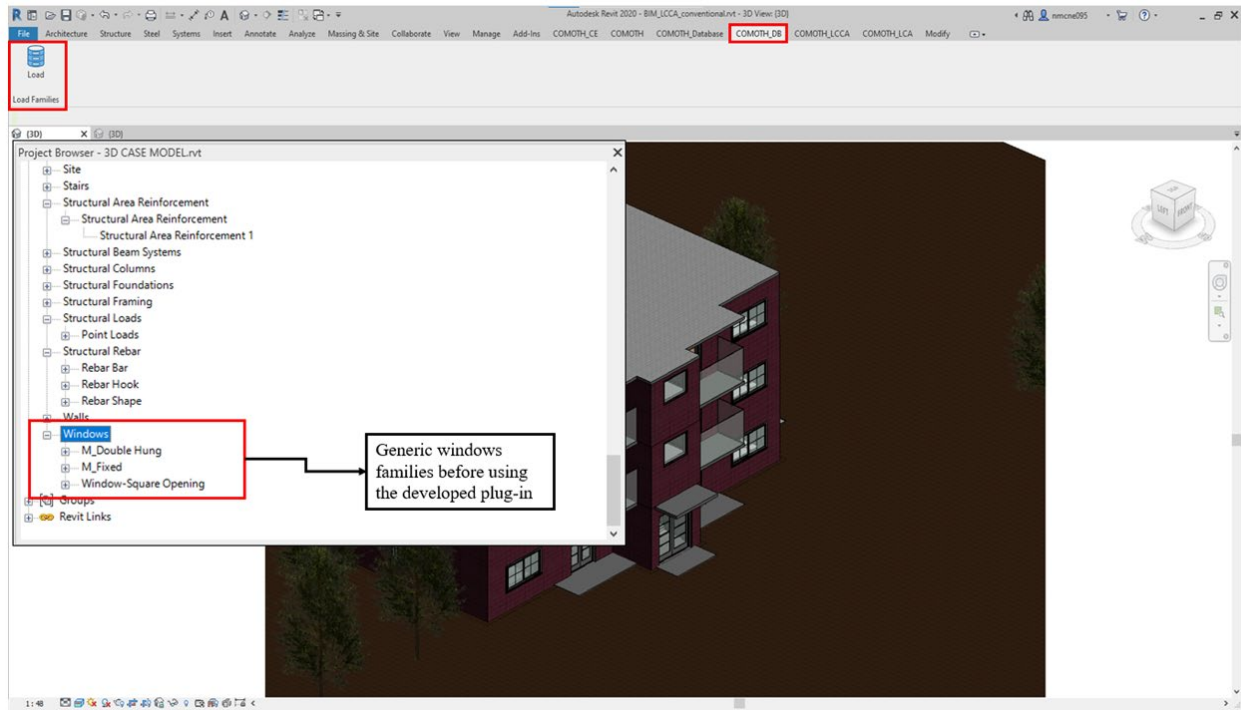


Figure 6.3 - Snapshot of Revit project generic window families

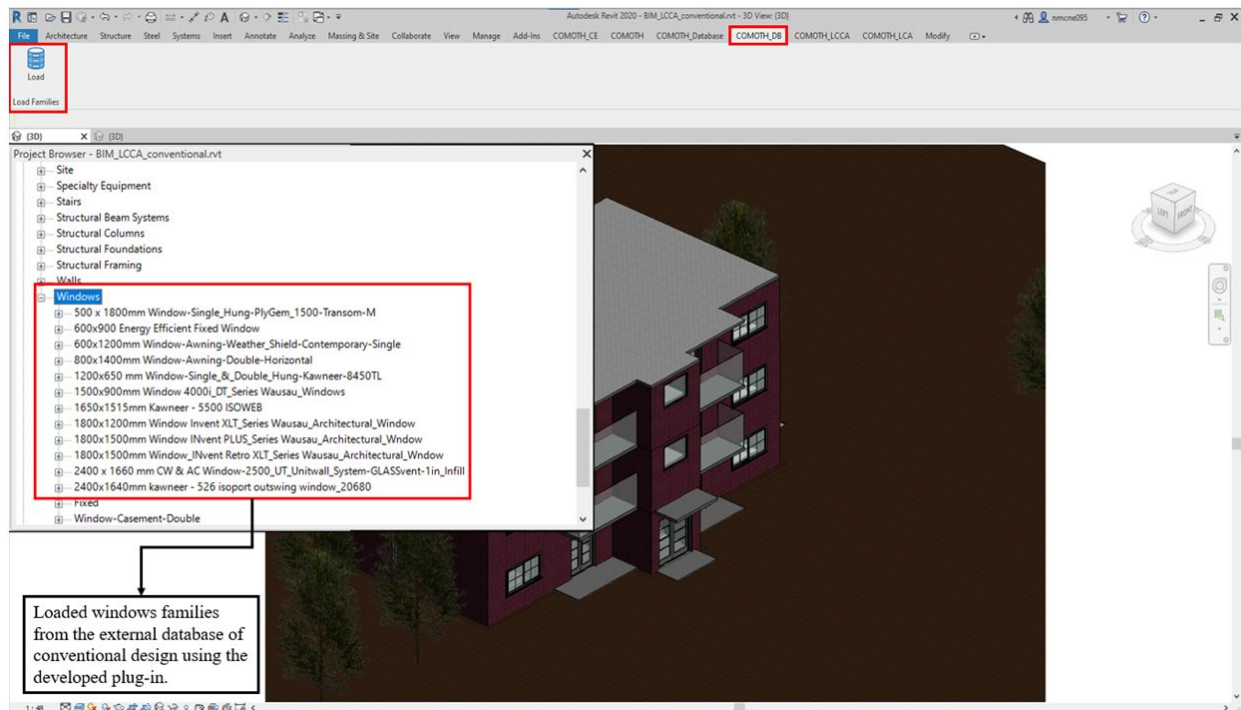


Figure 6.4 - Snapshot of loaded window families from the external database

6.4 Testing and verifying the developed Decision Support System module

Following the use of the DBMS module for storing and importing 3D design families into the Revit design platform, the DSS module assists users in selecting appropriate design components that meet the defined sustainability objective for buildings in each construction method (i.e., conversational, modular, and 3D concrete printing). The developed DSS module is an integrated expert model employing DANP-fuzzy for rating and WASPAS-fuzzy for ranking components in decision-making that guides users through the process of selecting and incorporating the appropriate design components, as shown in Figure 6.5.

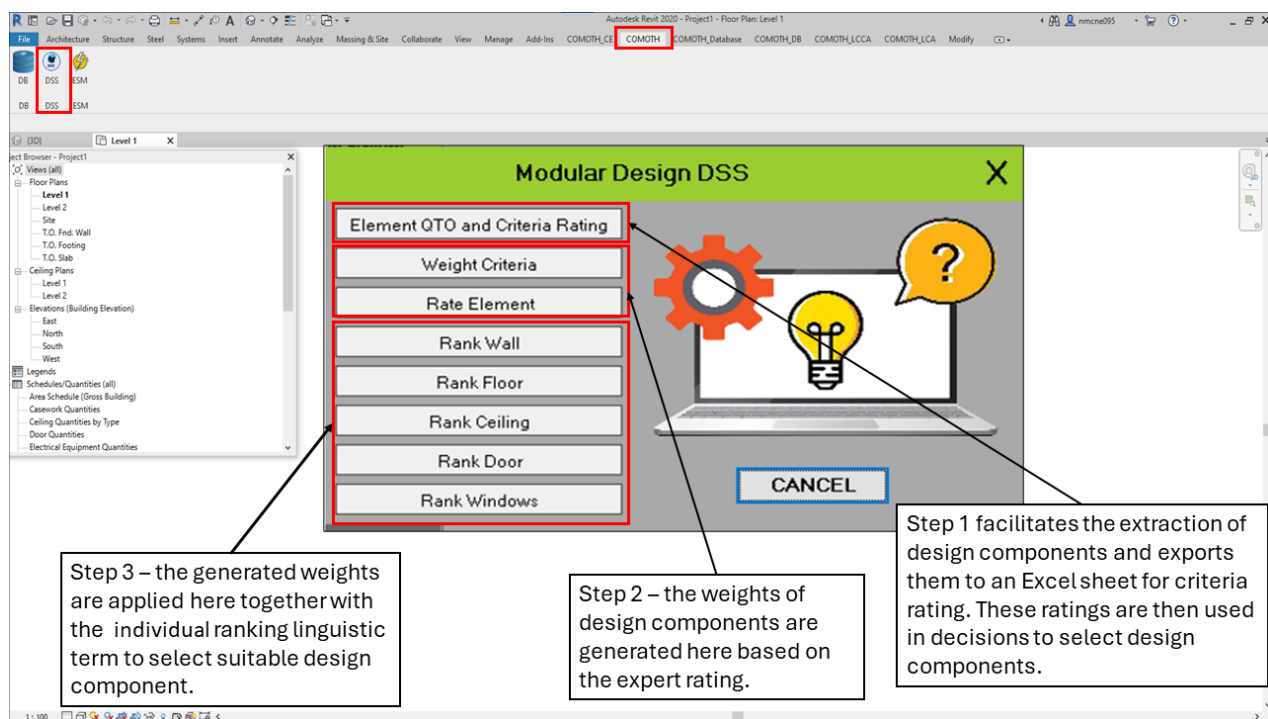


Figure 6.5 - Processes and steps in the DSS module

As explained earlier, once the designer runs the COMOTH_DB, the next step is to select the number of floors and the construction method. The first step is extracting the design components by clicking “Element QTO and Criteria Rating.” The eight criteria in consideration for this study are Environmental Impacts (EI); Energy and Atmosphere (E&A); Material and Resources (M&R); Cost (CO); Time (TI); Circular Economy (CE); Indoor Environmental Quality (IEQ); and Design

and Innovation (DI). At this stage, an Excel file automates the implementation of the DANP fuzzy link to the five components of the 3D design model, and eight decision criteria open in another window, which are ready for the rating process from start to completion. Once completed, the user must save and close the Excel file, as shown in Figure 6.6.

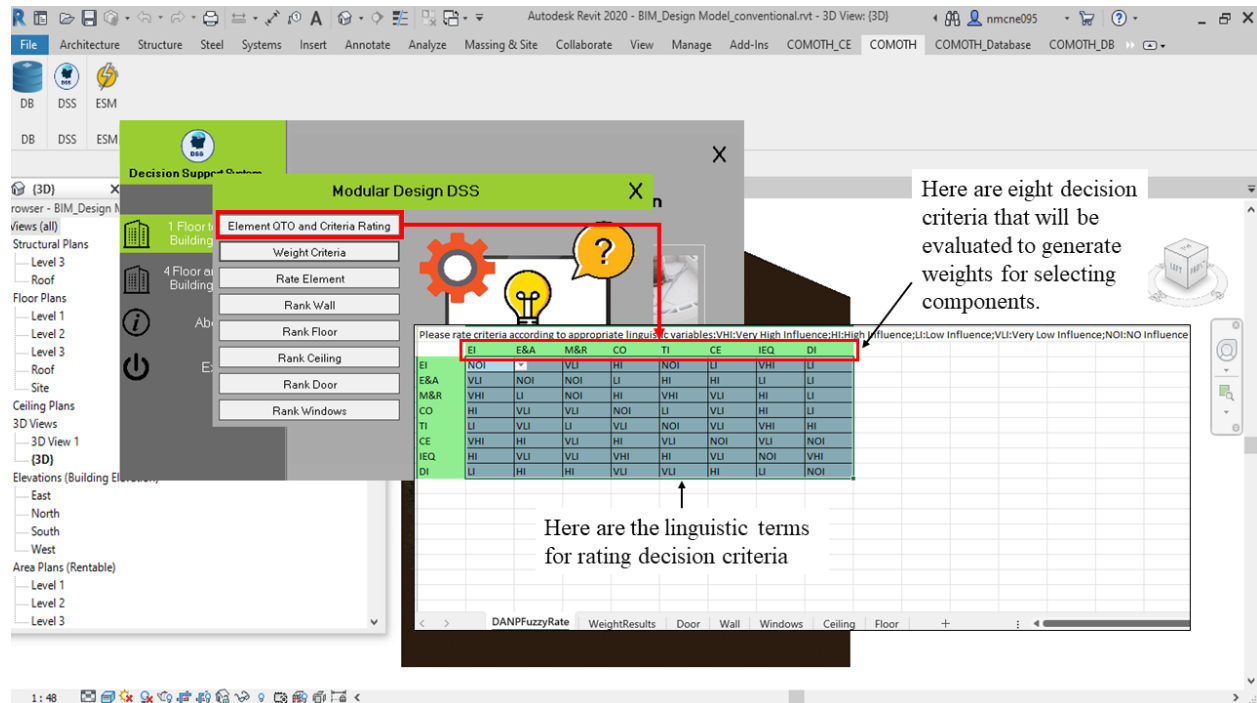


Figure 6.6 - Criteria Rating process for the DSS module

The user can see the resulting weights using the weight criteria button in step 2. The DANP fuzzy is linked and manipulated in the MATLAB tool in the background to aid all computations, from translating sustainability criteria rating on the DANP fuzzy cell into a scale of number intervals (Table 6.1) for forming a matrix, then resolving and normalizing matrices (Table 6.2), including further evaluation for direct and indirect relationships (Table 6.3), associated with the eight sustainability criteria and finally a cause-effect relation of criteria.

Table 6.1 - Implementation of fuzzy numbers

	EI	E&A	M&R	CO	TI	CE	IEQ	DI
EI	(0,0,0.25)	(0.75,1,1)	(0.5,0.75,1)	(0.5,0.75,1)	(0,0.25,0.5)	(0.5,0.75,1)	(0,0.25,0.5)	(0.25,0.5,0.75)
E&A	(0.75,1,1)	(0,0,0.25)	(0.5,0.75,1)	(0.25,0.5,0.75)	(0.25,0.5,0.75)	(0.25,0.5,0.75)	(0.25,0.5,0.75)	(0.25,0.5,0.75)
M&R	(0.25,0.5,0.75)	(0.5,0.75,1)	(0,0,0.25)	(0.75,1,1)	(0.5,0.75,1)	(0.5,0.75,1)	(0,0.25,0.5)	(0.25,0.5,0.75)
CO	(0.5,0.75,1)	(0.25,0.5,0.75)	(0.5,0.75,1)	(0,0,0.25)	(0,0.25,0.5)	(0.5,0.75,1)	(0.25,0.5,0.75)	(0,0.25,0.5)
TI	(0.25,0.5,0.75)	(0.25,0.5,0.75)	(0,0.25,0.5)	(0.5,0.75,1)	(0,0,0.25)	(0.5,0.75,1)	(0.25,0.5,0.75)	(0.5,0.75,1)
CE	(0.5,0.75,1)	(0.25,0.5,0.75)	(0.75,1,1)	(0.75,1,1)	(0.25,0.5,0.75)	(0,0,0.25)	(0,0.25,0.5)	(0.25,0.5,0.75)
IEQ	(0.5,0.75,1)	(0.25,0.5,0.75)	(0.5,0.75,1)	(0.25,0.5,0.75)	(0,0.25,0.5)	(0.5,0.75,1)	(0,0,0.25)	(0.75,1,1)
DI	(0.25,0.5,0.75)	(0,0.25,0.5)	(0.5,0.75,1)	(0.5,0.75,1)	(0.25,0.5,0.75)	(0.5,0.75,1)	(0.75,1,1)	(0,0,0.25)

Table 6.2 - Normalized matrix

	EI	E&A	M&R	CO	TI	CE	IEQ	DI
EI	(0,0,0.03)	(0.1,0.14,0.14)	(0.07,0.1,0.14)	(0.07,0.1,0.14)	(0,0.03,0.07)	(0.07,0.1,0.14)	(0,0.03,0.07)	(0.03,0.07,0.1)
E&A	(0.1,0.14,0.14)	(0,0,0.03)	(0.07,0.1,0.14)	(0.03,0.07,0.1)	(0.03,0.07,0.1)	(0.03,0.07,0.1)	(0.03,0.07,0.1)	(0.03,0.07,0.1)
M&R	(0.03,0.07,0.1)	(0.07,0.1,0.14)	(0,0,0.03)	(0.1,0.14,0.14)	(0.07,0.1,0.14)	(0.07,0.1,0.14)	(0,0.03,0.07)	(0.03,0.07,0.1)
CO	(0.07,0.1,0.14)	(0.03,0.07,0.1)	(0.07,0.1,0.14)	(0,0,0.03)	(0,0.03,0.07)	(0.07,0.1,0.14)	(0.03,0.07,0.1)	(0,0.03,0.07)
TI	(0.03,0.07,0.1)	(0.03,0.07,0.1)	(0,0.03,0.07)	(0.07,0.1,0.14)	(0,0,0.03)	(0.07,0.1,0.14)	(0.03,0.07,0.1)	(0.07,0.1,0.14)
CE	(0.07,0.1,0.14)	(0.03,0.07,0.1)	(0.1,0.14,0.14)	(0.1,0.14,0.14)	(0.03,0.07,0.1)	(0,0,0.03)	(0,0.03,0.07)	(0.03,0.07,0.1)
IEQ	(0.07,0.1,0.14)	(0.03,0.07,0.1)	(0.07,0.1,0.14)	(0.03,0.07,0.1)	(0,0.03,0.07)	(0.07,0.1,0.14)	(0,0,0.03)	(0.1,0.14,0.14)
DI	(0.03,0.07,0.1)	(0,0.03,0.07)	(0.07,0.1,0.14)	(0.07,0.1,0.14)	(0.03,0.07,0.1)	(0.07,0.1,0.14)	(0.1,0.14,0.14)	(0,0,0.03)

Table 6.3 - Total-relation matrix

	EI	E&A	M&R	CO	TI	CE	IEQ	DI
EI	0.317905	0.391817	0.419703	0.419658	0.266704	0.420553	0.260699	0.324877
E&A	0.423851	0.286038	0.417924	0.389606	0.297367	0.392239	0.292755	0.329365
M&R	0.384707	0.379648	0.341961	0.453457	0.337799	0.434458	0.271111	0.336583
CO	0.387634	0.327492	0.402494	0.316164	0.253894	0.404812	0.278143	0.282538
TI	0.368598	0.332283	0.352357	0.414941	0.237023	0.418546	0.294351	0.357141
CE	0.40503	0.343173	0.441315	0.445686	0.299529	0.338921	0.26218	0.327437
IEQ	0.416512	0.35087	0.435501	0.405329	0.276717	0.438148	0.249949	0.393382
DI	0.385052	0.318371	0.432859	0.434761	0.306308	0.438486	0.35674	0.286734

One significant highlight of this module is using causal relationship diagrams to determine and illustrate the impact relationships amongst criteria, which is calculated by the sum of the criteria of each column (D) and those of the column (R) of the total relation matrix. The cause and effect diagram is plotted using (D+R) and (D-R) as shown in Table 6.4, where D+R (horizontal axis) represents effects among criteria, with a higher value indicating a more significant effect, and D-R (vertical axis) reflects the cause among the criteria. A positive value means that the criteria is the cause of other criteria, and a negative value indicates that the criteria are affected by other criteria. Hence, the degree of influence of design criteria for material selection is interpreted based on the relationship zones in which they fall, as illustrated in Figure 6.7.

Table 6.4 - The cause-effect relation of criteria

	D	R	D-R	D+R
EI	1.129424	1.126462	0.002962	2.255886
E&A	1.127813	1.057503	0.07031	2.185316
M&R	1.106316	1.179588	-0.07327	2.285904
CO	0.97487	1.176792	-0.20192	2.151662
TI	1.07051	0.790445	0.280065	1.860955
CE	1.084136	1.162279	-0.07814	2.246416
IEQ	0.64333	0.606689	0.036642	1.250019
DI	0.643474	0.680116	-0.03664	1.32359

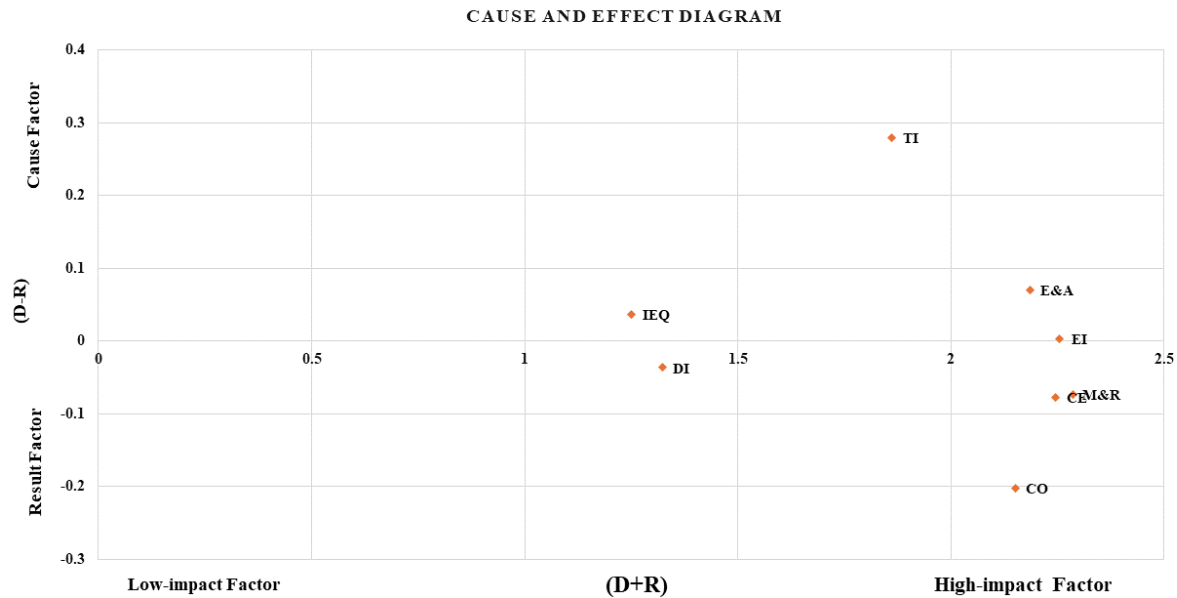


Figure 6.7 - Causal diagram among criteria for material selection

As shown in Figure 6.7, Time (TI) is located at the highest point for D-R, meaning that Time (TI) has the highest cause on other criteria, followed by Energy and Atmosphere (E&A); Indoor Environmental Quality (IEQ); and Environmental Impacts (EI). On the other hand, the relationship map indicates that both Material and Resources (M&R) and Environmental Impacts (EI), which were strongly overlapped by Circular Economy (CE), and are located on the right side of the diagram, have the highest (D + R) value, being the strongest effect in relation to other criteria, should be selected as the main factors for decision making. The result from the causal diagram of the relation among criteria for material selection demonstrates consistency with LEED-based credits consideration for material selection of environmentally responsible materials by encouraging the use of materials that promote regional economies, materials with high recycled content, rapid renewable cycle, and low-emitting contaminant and can reduce environmental impact and indoor air quality of buildings (Florez and Castro-Lacouture, 2013). Furthermore,

Table 6.5 explains the relationship between criteria driven by the threshold value (0.356378). Hence, the value of 1 means that the criteria have a relationship with its related criteria, while (0) zero implies that the criteria have no relationship with their corresponding criteria.

Table 6.5 - Evaluation of the criteria relationship

	EI	E&A	M&R	CO	TI	CE	IEQ	DI
EI	0	1	1	1	0	1	0	0
E&A	1	0	1	1	0	1	0	0
M&R	1	1	0	1	0	1	0	0
CO	1	0	1	0	0	1	0	0
TI	1	0	1	1	0	1	0	1
CE	1	0	1	1	0	0	0	0
IEQ	1	1	1	1	0	1	0	1
DI	1	0	1	1	0	1	1	0

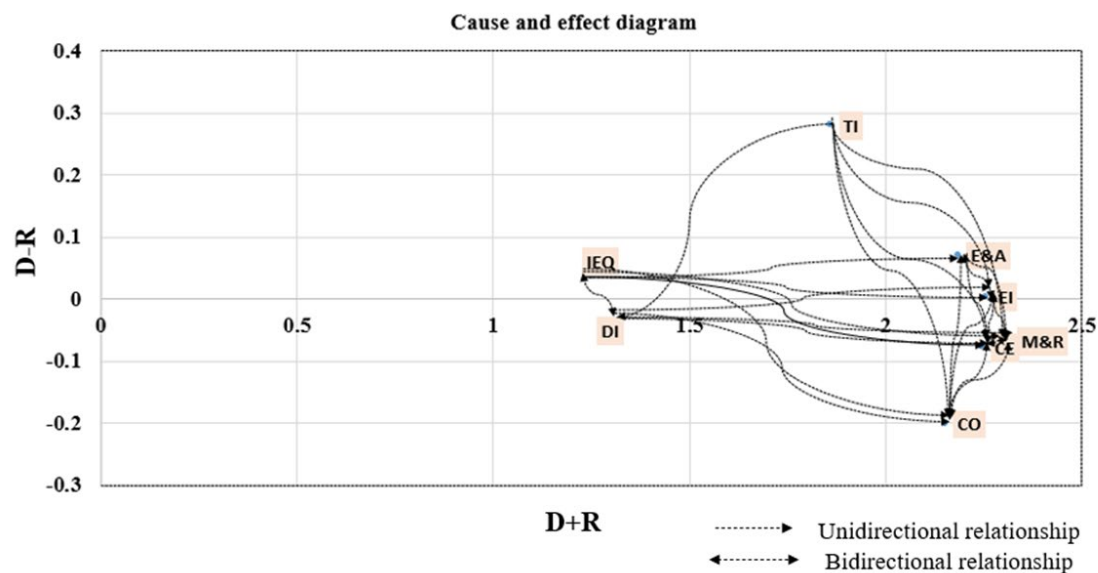


Figure 6.8 - Impact relation map for criteria

In Figure 6.8, the diagram uses arrow connections to determine and illustrate the relationship between criteria based on the results from Table 6.5. The unidirectional and bidirectional relationships demonstrate how sustainable selection criteria influence each other more precisely.

For example, IEO and DI are bidirectional, while CO and DI are unidirectional. The first decision supermatrix is derived by comparing all criteria on the second and third levels and their total-relation matrices. After that, the resulting unweighted supermatrix is normalized and transformed into a weighted supermatrix, as shown in Table 6.6.

Table 6.6 - Weighted supermatrix

	EI	E&A	M&R	CO	TI	CE	IEQ	DI
EI	0.222336	0.395214	0.38245	0.41489	0.183195	0.401915	0.367444	0.632556
E&A	0.42249	0.197456	0.380054	0.371664	0.266408	0.361928	0.465963	0.534037
M&R	0.351583	0.388857	0.25956	0.393797	0.266479	0.339724	0.375303	0.624697
CO	0.355978	0.27276	0.371262	0.287247	0.203568	0.509185	0.566832	0.433168
TI	0.372406	0.328351	0.299242	0.427223	0.15184	0.420937	0.423532	0.576468
CE	0.336897	0.26272	0.400384	0.490092	0.25743	0.252478	0.36767	0.63233
IEQ	0.354512	0.269474	0.376014	0.373907	0.191128	0.434966	0.28746	0.71254
DI	0.337669	0.231488	0.430842	0.386471	0.232586	0.380943	0.655755	0.344245

Subsequently, criteria weights are computed from the weighted supermatrix through exponentiation of the matrix and multiplying with the normalized supermatrix until all numbers in each matrix column reach convergence. In this study, all calculations were automated and executed using the integrated BIM-MATLAB tool, which enhanced swiftness and correctness. Hence, a weight convergence occurred by weighted supermatrix raising to the power of $2K + 1$ (only six times), which is equivalent to half the time employed in other studies (Mavi & Standing 2018; Mirhosseini et al. 2020). For the final results, users only need a single click on the “weight criteria” button to generate the evaluated weight summary of each criterion, as shown in Figure 6.9 and illustrated in Table 6.7

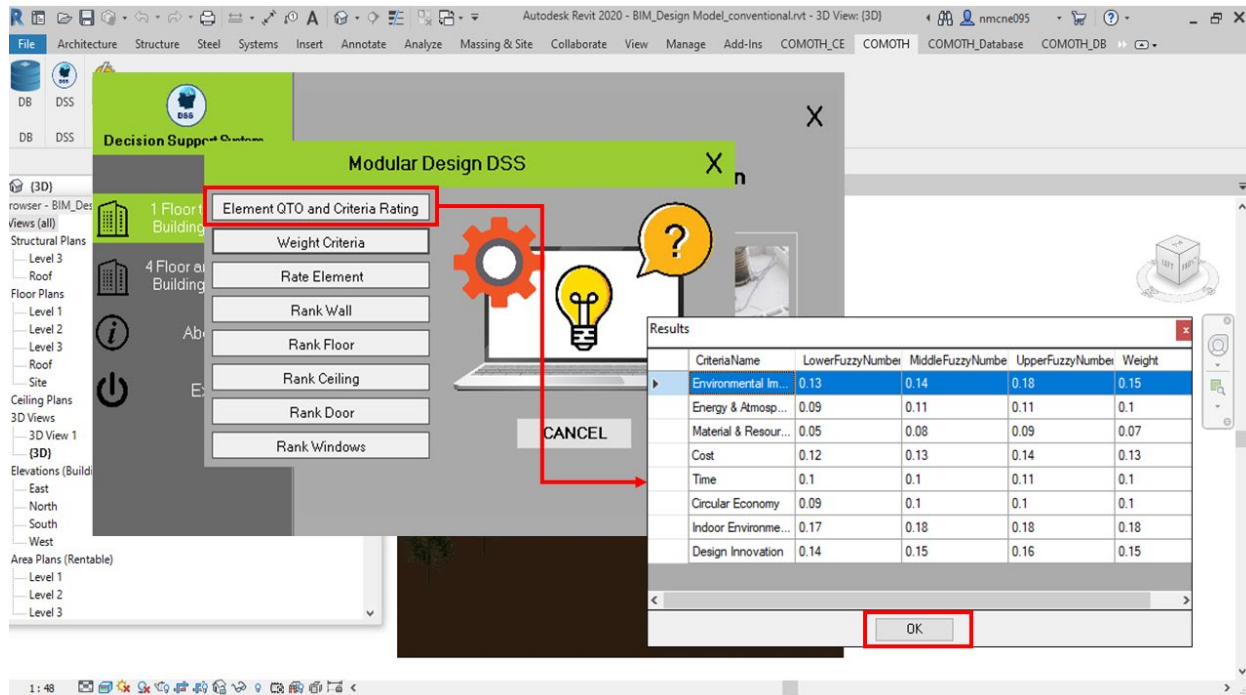


Figure 6.9 - Results (weights) of criteria rating process

Table 6.7 - Criteria weights interpretation

	Lower Fuzzy Number	Middle Fuzzy Number	Upper Fuzzy Number	Weight of Criteria	Weight Rank
EI	0.128012	0.143385	0.179566	0.150321	2
E&A	0.09435	0.108815	0.113468	0.105544	5
M&R	0.050164	0.076306	0.089436	0.071969	8
CO	0.12141	0.129991	0.14046	0.13062	4
TI	0.096147	0.101726	0.106256	0.101376	6
CE	0.087473	0.096788	0.10325	0.095837	7
IEQ	0.174255	0.17956	0.182168	0.178661	1
DI	0.141913	0.148946	0.15666	0.149173	3

Furthermore, users can assess the complete evaluation executed by the DSS module by clicking “ok” on the summary window, as highlighted in Figure 6.10, which automatically opens an Excel spreadsheet containing all the analyses.

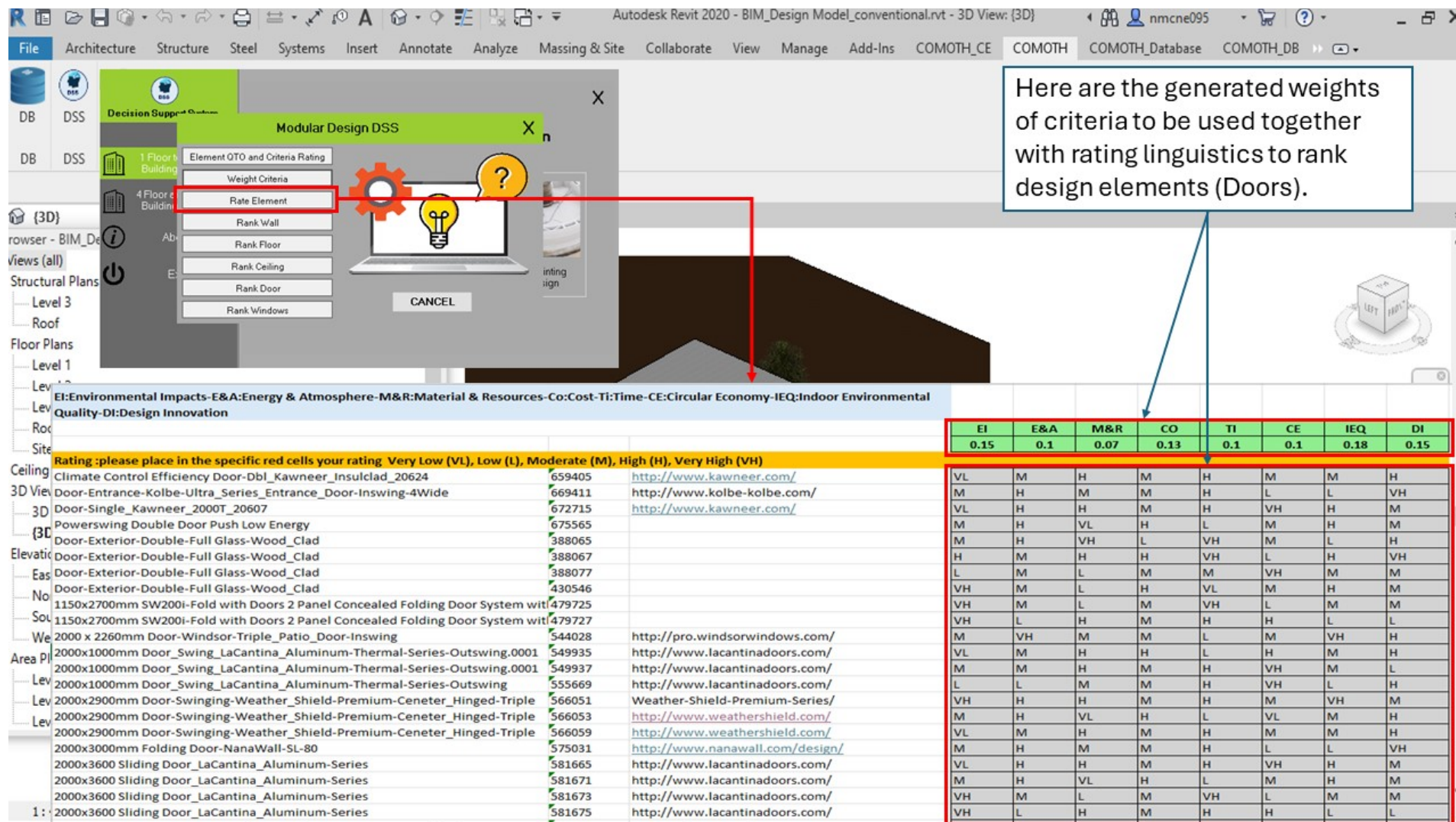


Figure 6.10 - Rating element of design components using the DSS module

At this stage, the rating and weighting are complete, and generated weights are ready to be applied for rating individual elements of categories of components of the 3D BIM design model. Next, the generated weights from rated criteria are applied together with the individual rating linguistic term to rank suitable design components. Users must select one component category after another as listed in the Excel sheet and rate all or selected materials they wish to use for their design using the linguistic term in the designated cell, as shown in Figure 6.10.

Users are required to complete the rating process for all five components, following the example illustrated in Figure 6.6. Subsequently, they should save and exit the Excel sheet to generate the results. Users can rank all the elements within the DSS module interface by clicking "Rank Wall," "Rank Floor," etc. The associated elements will then be ranked, and the result will be published. Users can save the generated result and rank the next component until all elements across all components are ranked. The alternatives with the highest K closeness coefficient value determine the best alternatives among all elements. Thus, the rank with the highest K values is considered the optimal element that users can select for the sustainable design, followed by the subsequent alternatives in descending order, as demonstrated in Figures 6.11 through 6.15. It should be noted that the described testing process applies to the three construction methods considered in this study.

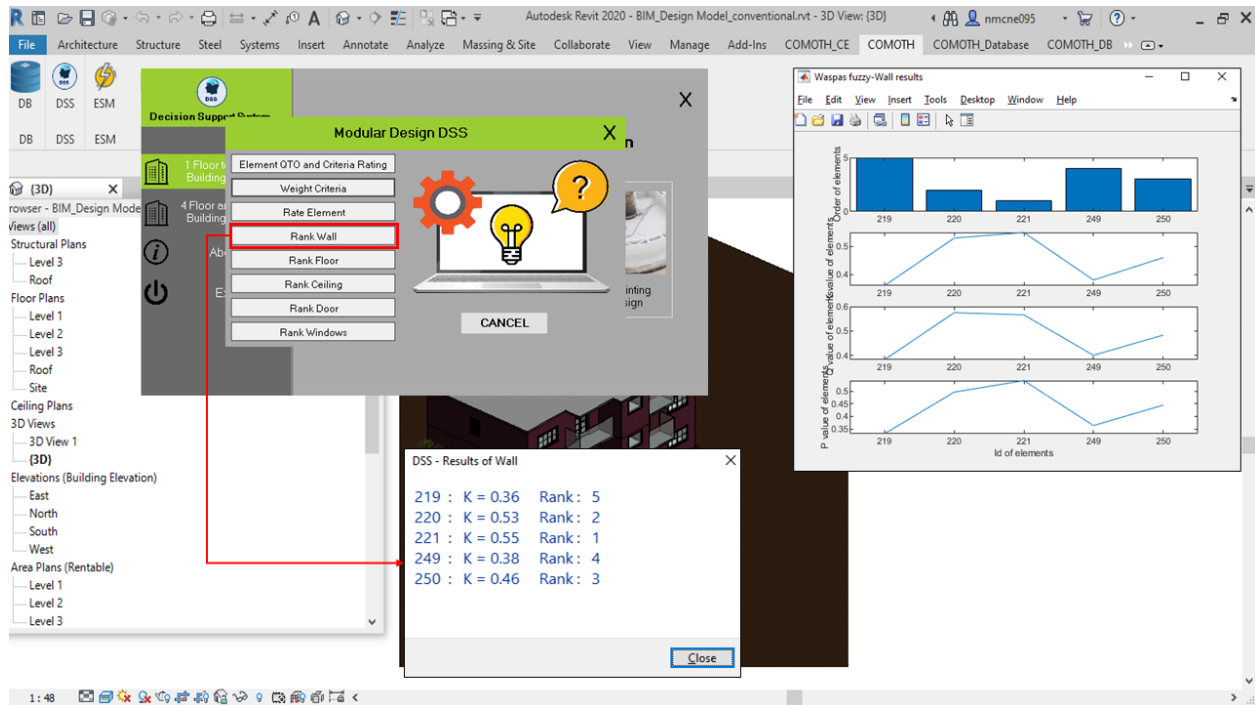


Figure 6.11 - Results of the Wall ranking process

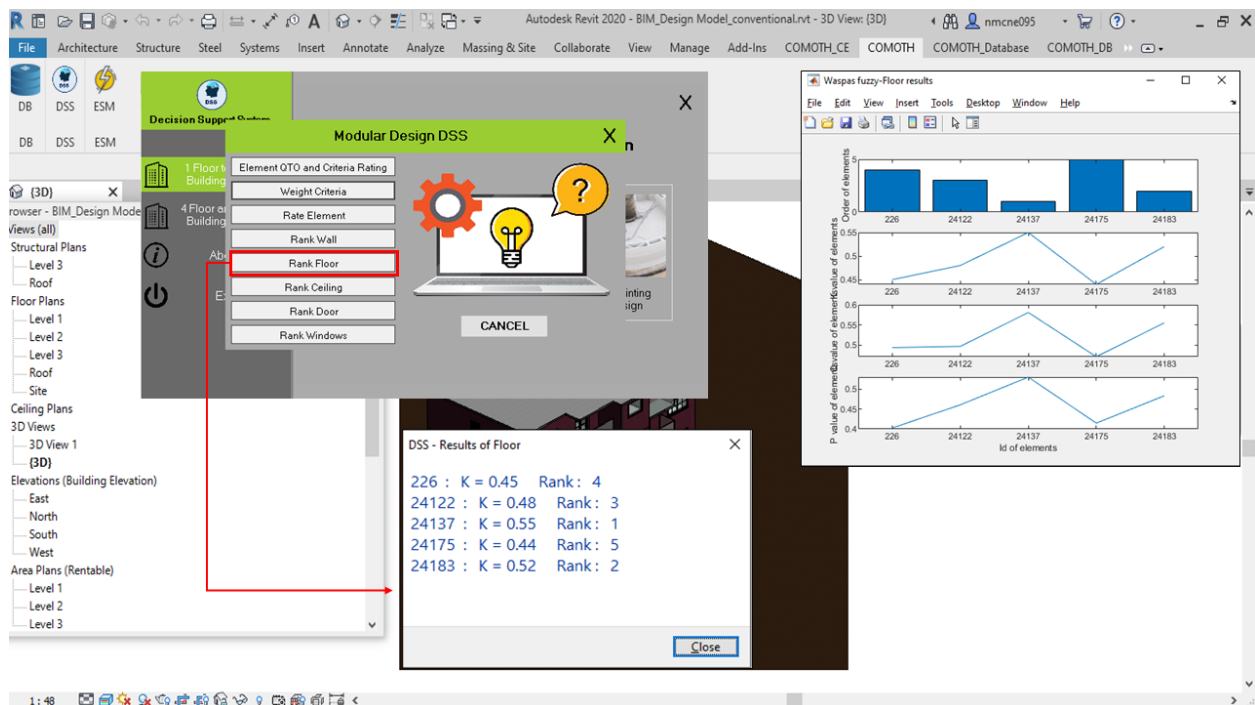


Figure 6.12 - Results of the Floor ranking process

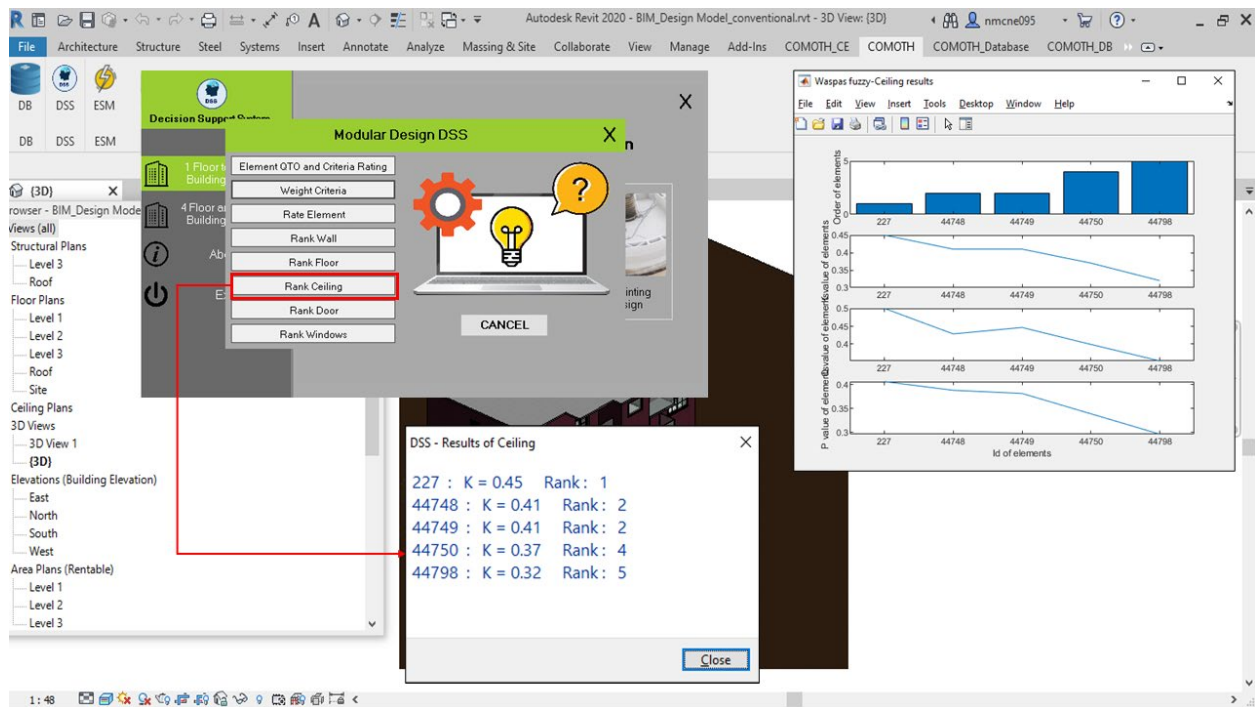


Figure 6.13 - Results of the Ceiling ranking process

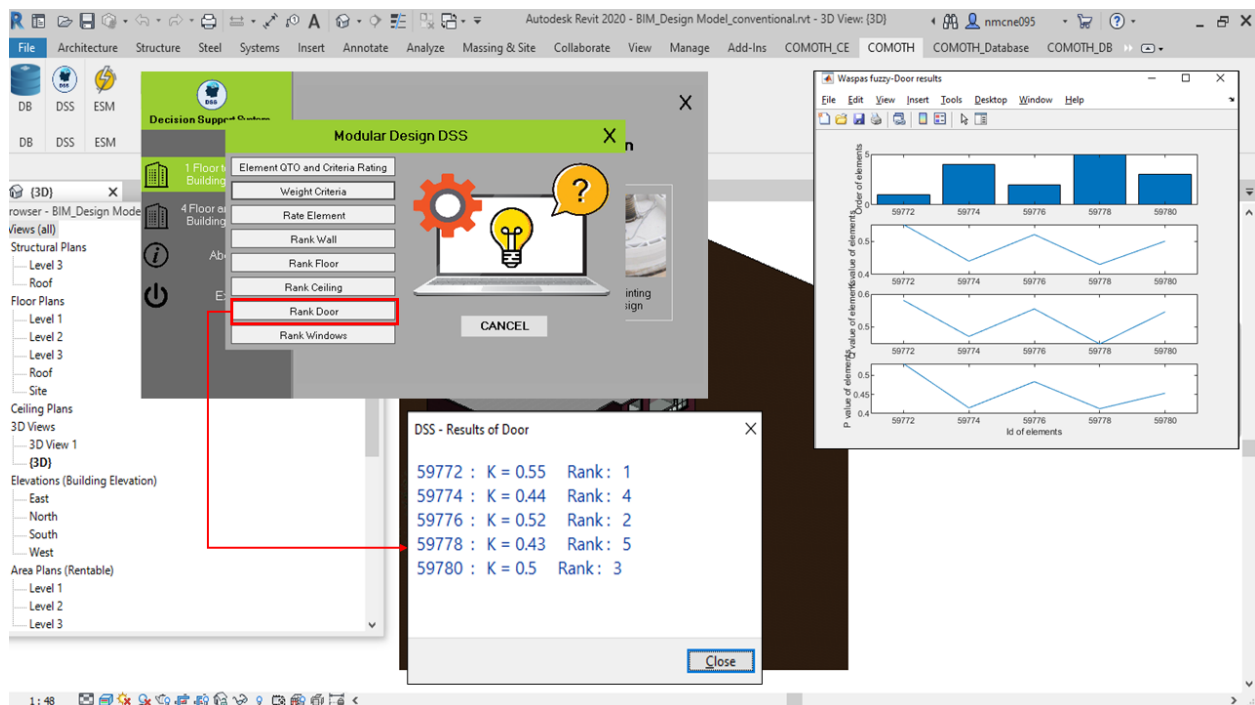


Figure 6.14 - Results of the Door ranking process

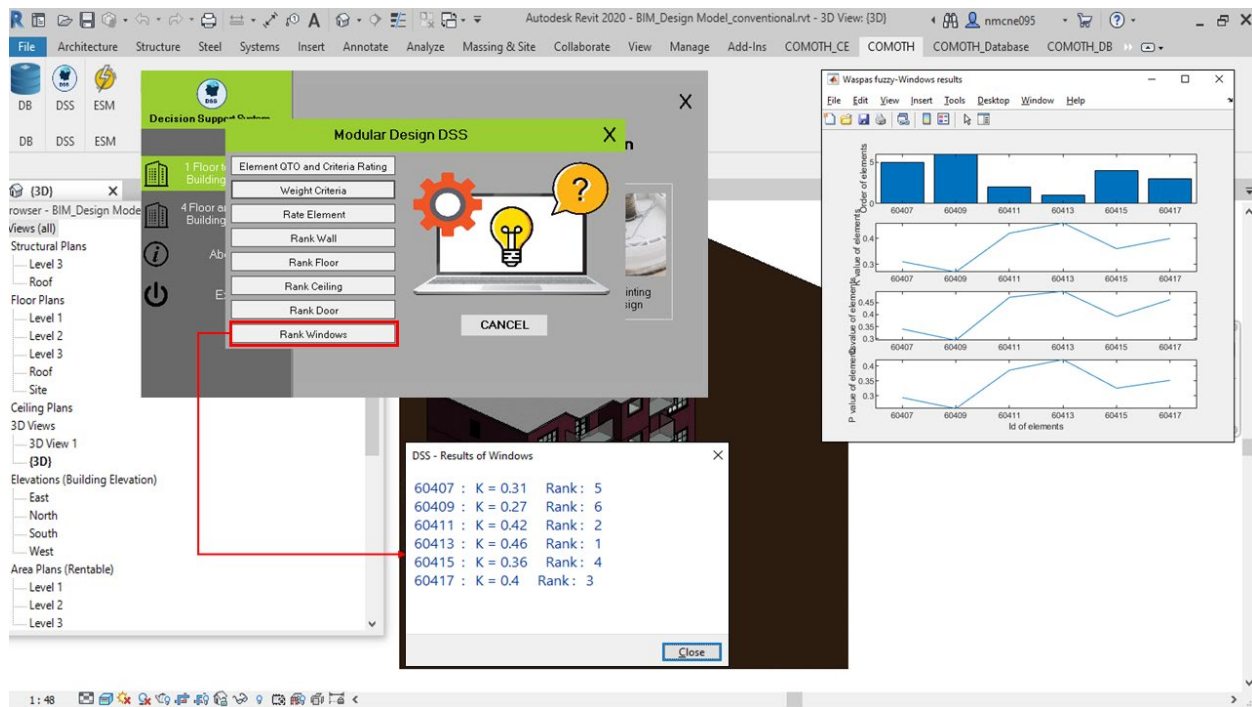


Figure 6.15 - Results of the Window ranking process

6.5 Testing and verifying the developed Energy Simulation module

Having all the suitable design elements selected and incorporated into the conceptual 3D BIM model by using the DSS module, the developed energy simulation module is then tested for its functionality and adequacy for input, criteria, analysis, and generated output to verify the capability, workability and flexibility of the module for meeting an energy performance target, demand and consumption, optimization of comfort conditions among others. The BIM design models outlined referenced in Figure 6.1 were employed for testing together with material QTO in Figures 6.1b to 6.1d, which outlines the detailed information used for the case buildings, while Figure 6.1a details the specific construction components and materials layers utilized for each construction method undergoing testing. Additional configurations for the energy analysis include electricity as the primary energy source for building power and an HVAC system regulating temperatures across all zones for heating and cooling purposes, as shown in Table 6.8.

Table 6.8 - General information description for the Energy Simulation module

General description	Conventional	Modular	3D concrete printing
Building type (residential)	Multi-family	Multi-family	Multi-family
Gross floor area (m²)	798	798	798
Number of thermal zones	39	39	39
Window to wall	30%	30%	30%
Building envelope (U-value)			
Floor	0.448 W/(m ² k)	0.328 W/(m ² k)	0.339 W/(m ² k)
External Wall	0.341 W/(m ² k)	0.268 W/(m ² k)	0.361 W/(m ² k)
Internal Wall	0.250 W/(m ² k)	0.227 W/(m ² k)	0.361 W/(m ² k)
Window (double-glazed with air gaps)	1.45 W/(m ² k)	1.45 W/(m ² k)	1.45 W/(m ² k)
Roof	0.213 W/(m ² k)	0.370 W/(m ² k)	0.213 W/(m ² k)
HVAC	• Heating and cooling calculations using zones met by zone equipment. • Natural gas for heating, and electricity from the grid for cooling Domestic Hot Water (DHW) use for bathrooms and kitchens. • Natural ventilation used for all zones with choosing the min fresh air		
Activity	Dwell_DomBed_Occ was selected for the general schedule of bedrooms in the building.		

Heating is done by natural gas, while cooling is by electricity from the grid. Natural ventilation is used in all zones, and domestic hot water (DHW) is be supplied for bathrooms and kitchens. Heating temperatures in heated areas is maintained at 25°C, with heating activating automatically when the external temperature falls below 10°C. Consequently, users can initiate the energy simulation process by utilizing the developed module and selecting COMOTH and ESM to run and initiate the associated processes, starting with "continue" or "cancel, followed by the design options and the construction method. Users can simultaneously select one, two or three construction methods to create a data-ready simulation model, as shown in Figure 6.16.

Depending on the selection, the data for building construction methods is generated and ready to create the energy analysis data, by clicking on the “create model” button, the module automatically generates all the energy files of the BIM design model. All input information is prepared in the background, and a sample model is created, as shown in Figure 6.17. It is important to note that

users can use the same process to create one, two or three energy models simply by doing a selection from the construction method(s).

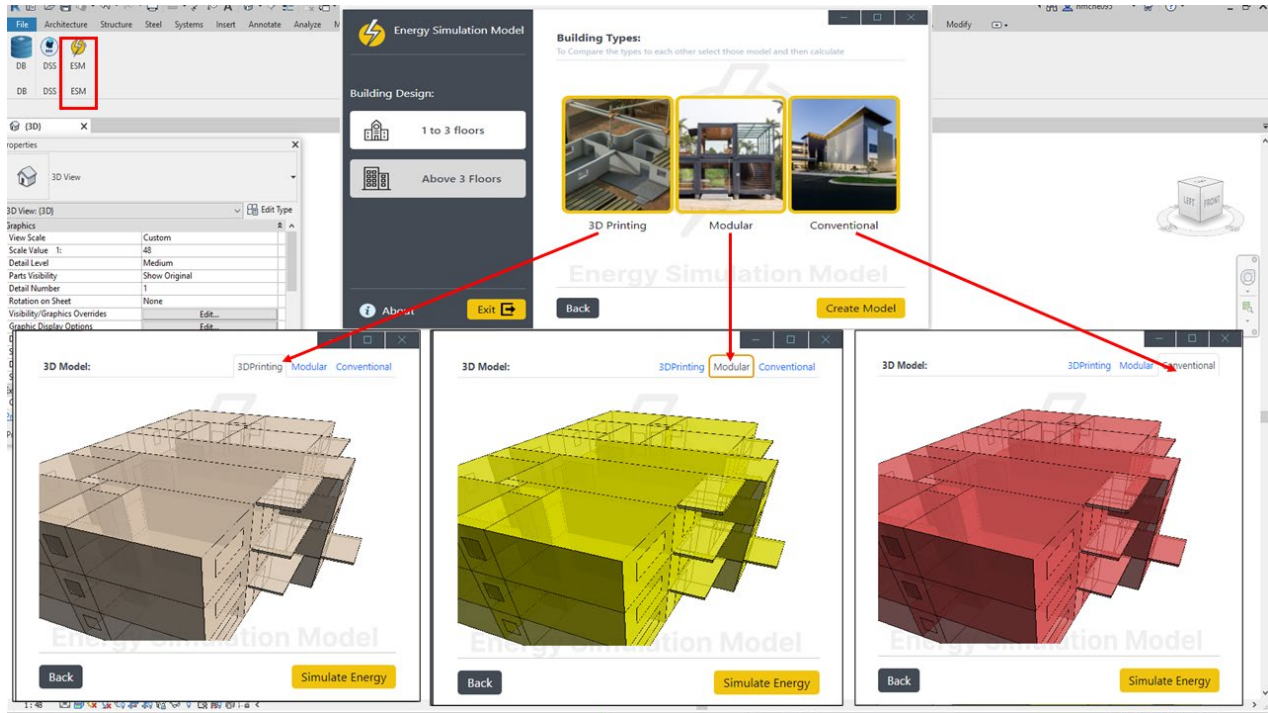


Figure 6.16 - Extracting and exporting the model's data and files

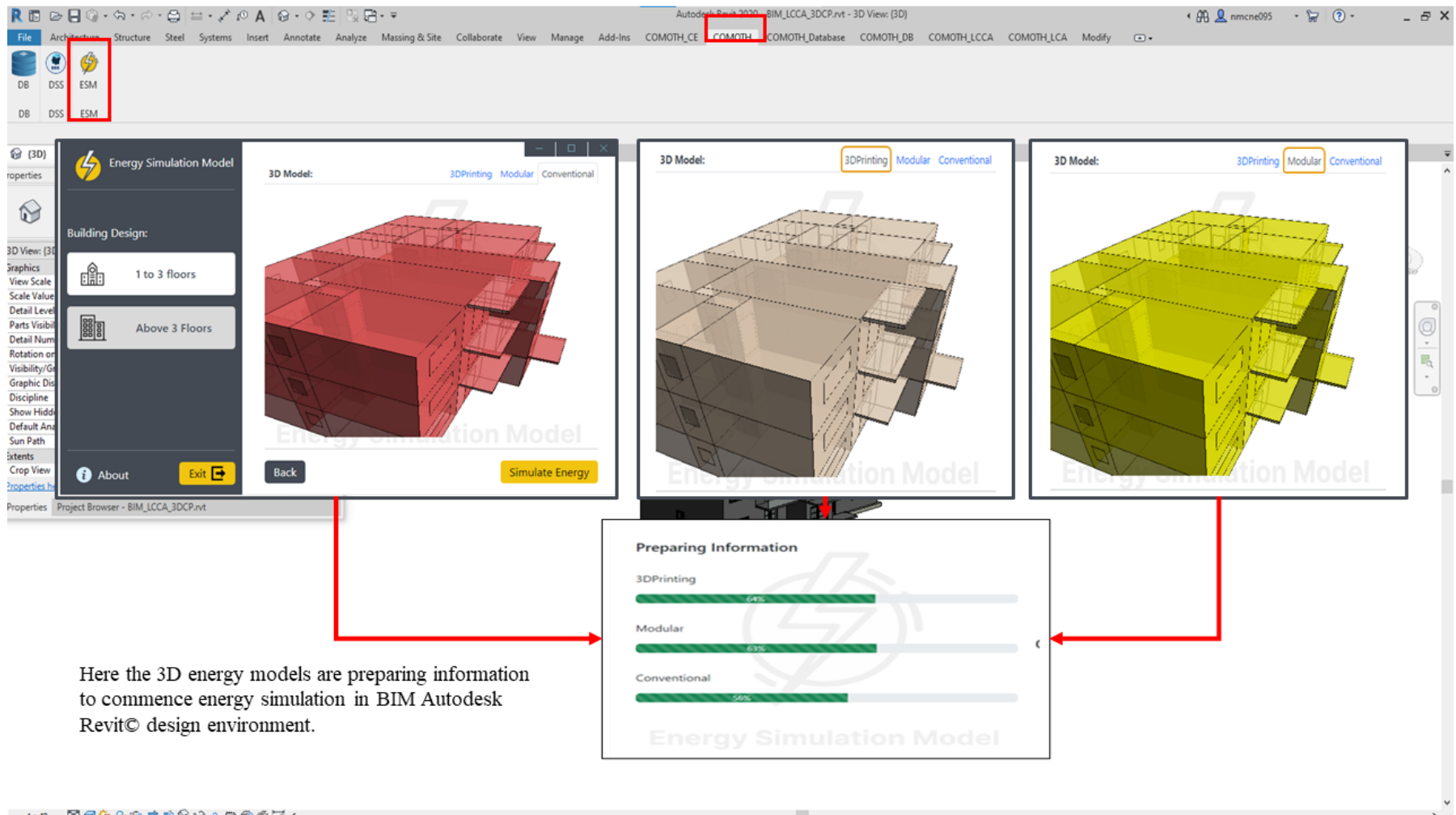


Figure 6.17 - Processing energy model(s) data for simulation

Once the files of the Revit model are exported to IDF format, the created plugins help to interpret the Revit model geometry and properties and convert them into an EnergyPlus IDF file simulation. The next step is for users to click on the “simulate energy” button, and the module will request for a weather file to be uploaded for the building energy calculations. Users must provide and use a weather file for their specific location as they are critical for accurately predicting the building’s energy performance. For this model’s testing, the EnergyPlusWeather (EPW) file format of Ottawa weather was selected and used for the energy analysis (CAN_ON_Ottawa.716280_CWEC.epw). The process of uploading the EnergyPlusWeather is illustrated in Figure 6.18.

Next, users are prompted to select a folder location in their document to store the energy result, as shown in Figure 6.19.

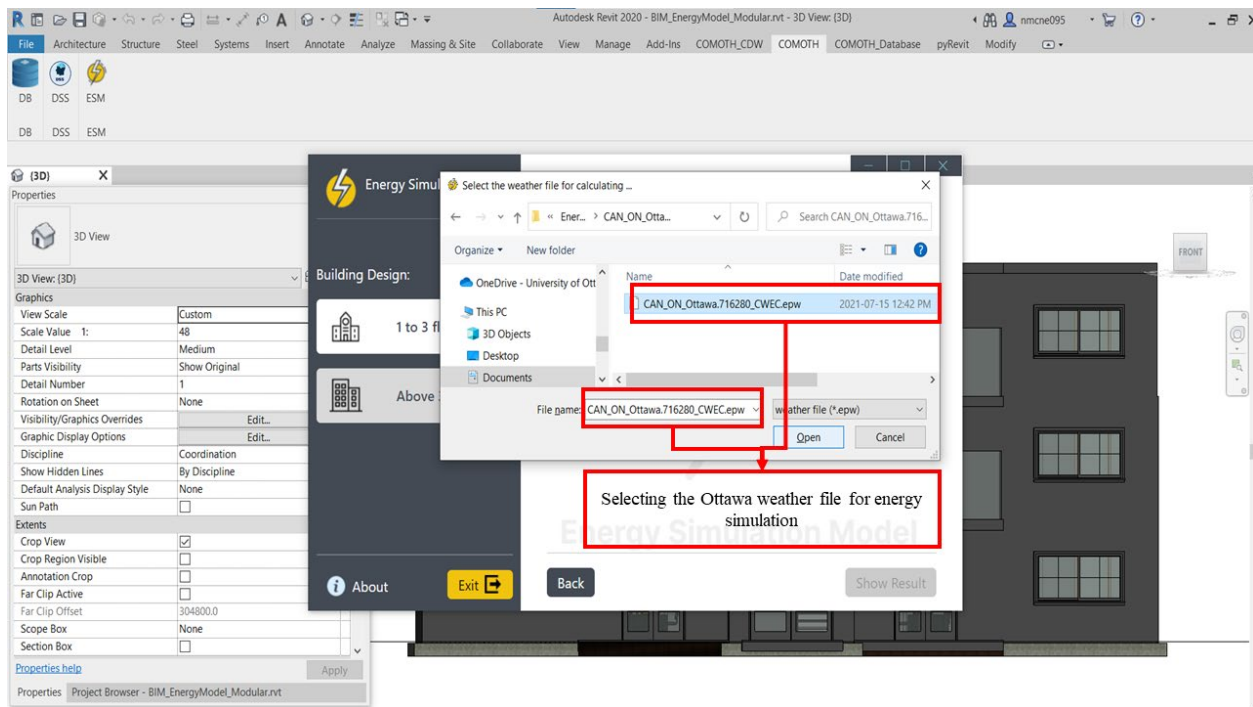


Figure 6.18 - Selecting and uploading of weather file for energy simulation

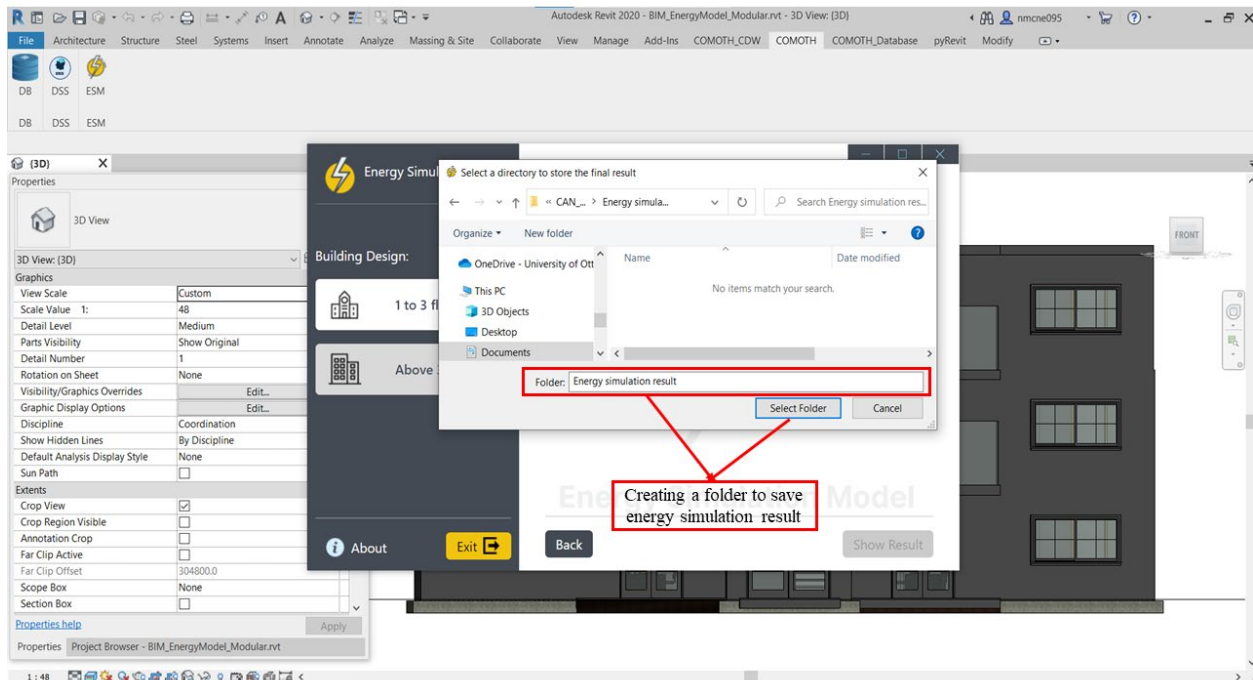


Figure 6.19- Process of creating a folder for energy analysis result

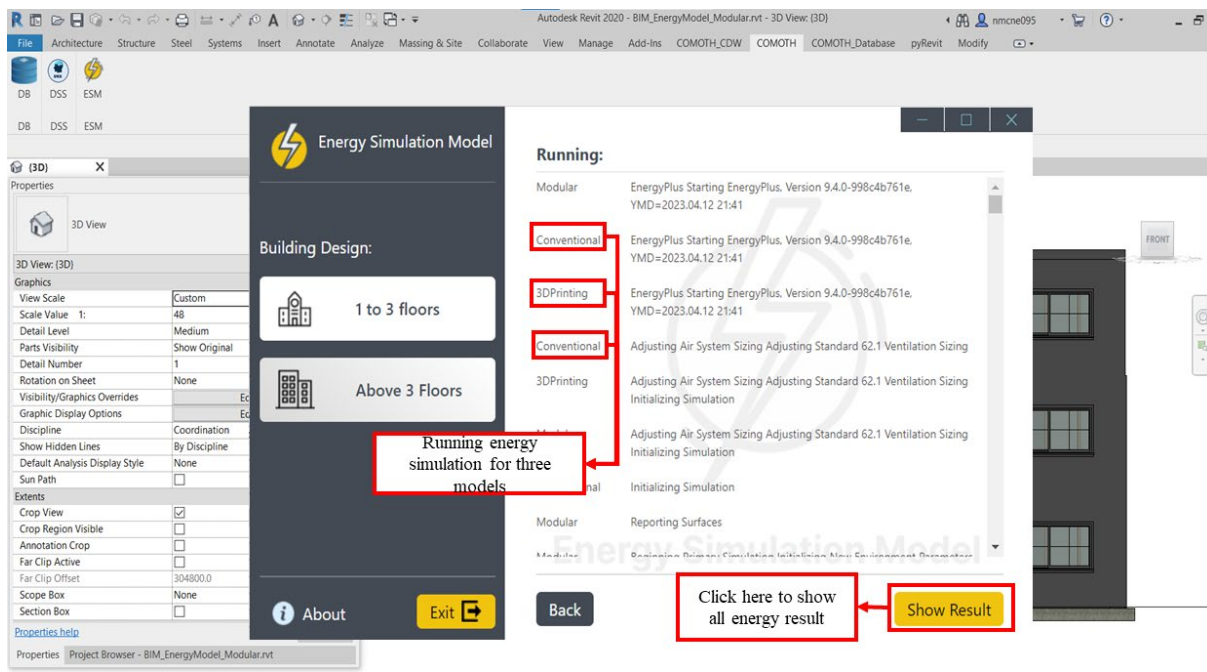


Figure 6.20 - Energy performance calculation for three models

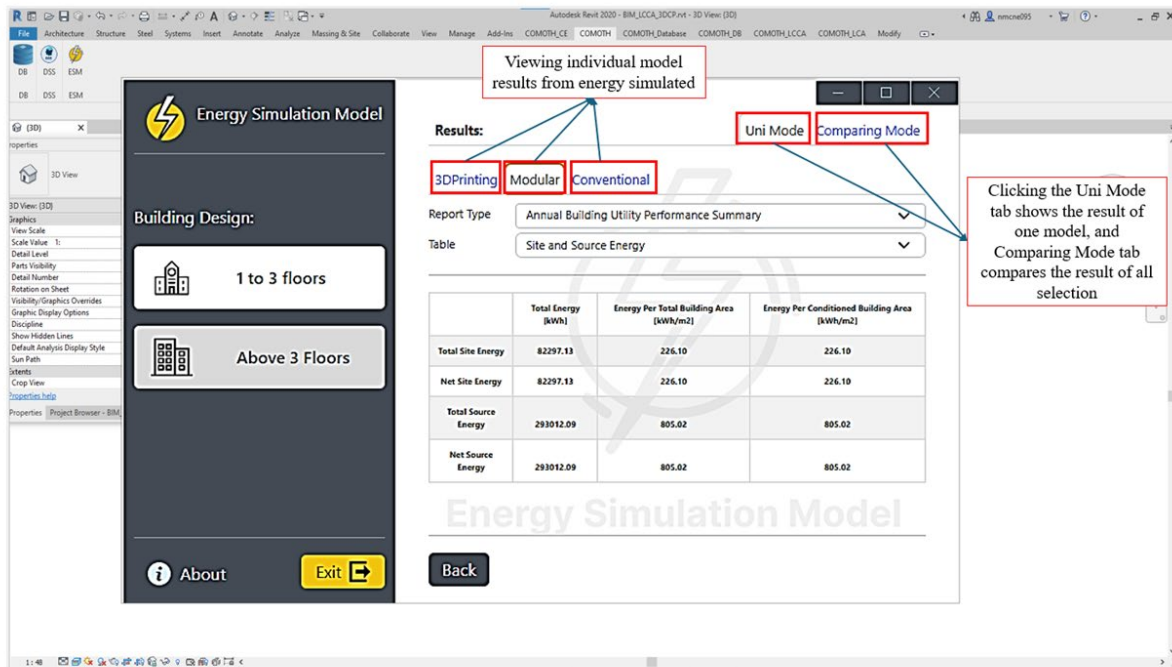


Figure 6.21 - Energy simulation results display modes

Once a file path to save the result is defined, the integrated energy tool starts the analysis of energy use and performance of the building for the selected 3D model(s). For example, in Figure 6.20, the three models (i.e., conventional, modular, and 3D concrete printing) were selected and simulated simultaneously. By clicking the show result bottom, which will be highlighted once the energy calculation is completed, the results for each simulated energy model will be displayed in a table format. Figure 6.21 shows the result of the annual utility performance summary. Users can use the dropdown button to select, view and save various categories of the energy module results. Additionally, users can click on the Uni Mode tab to see the result of an individual model or the Comparing Mode tab to compare the energy analysis results of the three selected models with each other graphically. Figures 6.22a and 6.22b show a graph that compares the three designs' monthly heating and cooling results by their annual average.

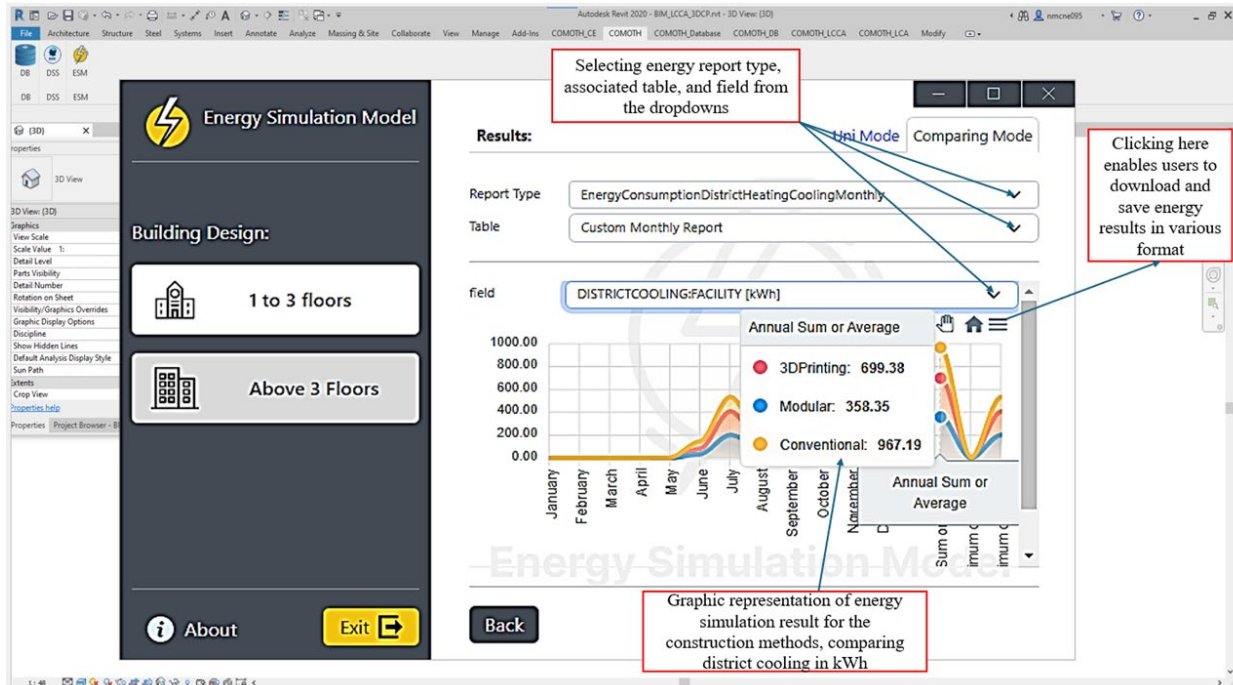


Figure 6.22a - Comparing results for monthly cooling

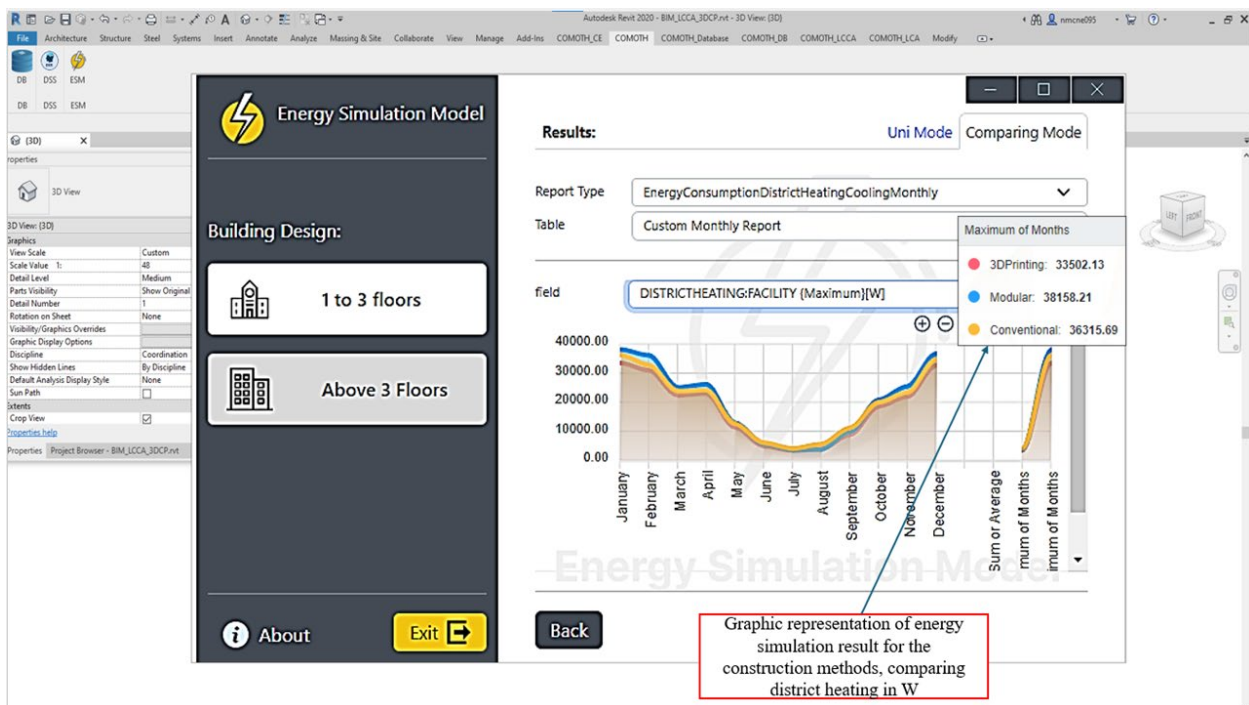


Figure 6.22b - Comparing results for monthly heating

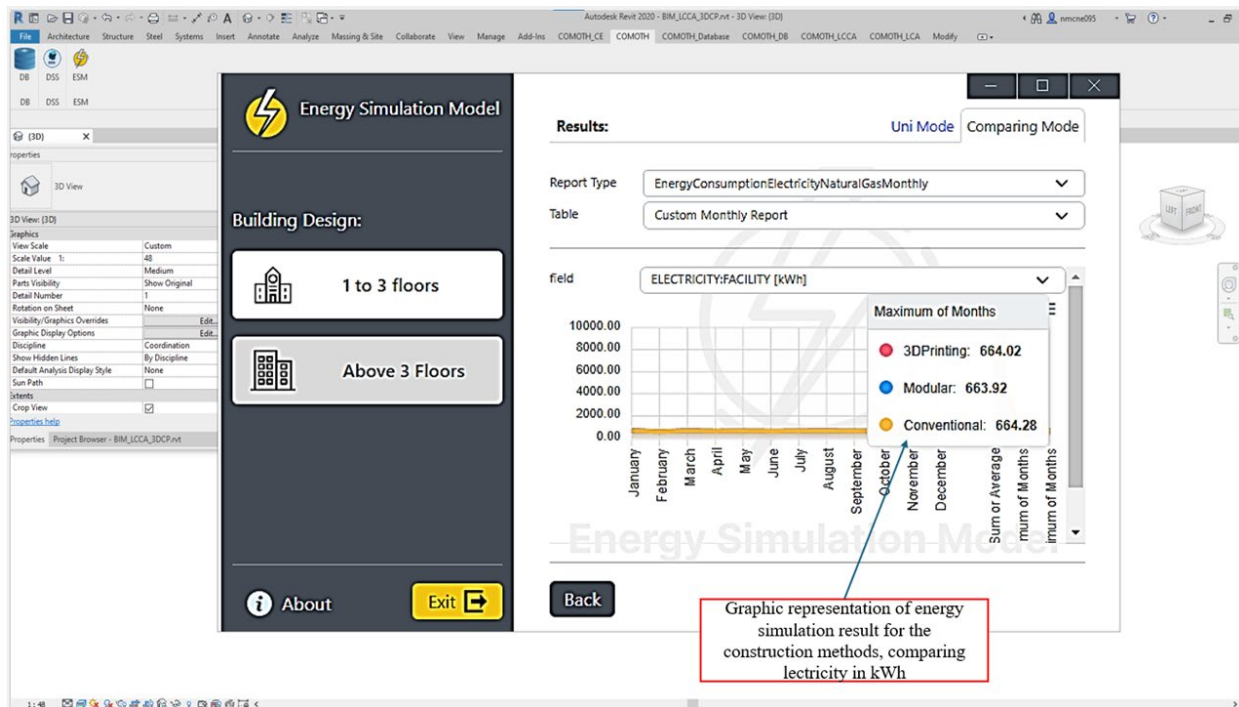


Figure 6.23 - Comparing electricity consumption of the construction methods

Figure 6.23, the electricity consumption of the three construction methods is compared by selecting the "Comparing Mode" of the energy module. All energy result categories provided by the DesignBuilder tool are categorized under the report type dropdown, such as annual building performance, system analysis, and energy consumption electricity/natural gas and district heating/cooling. Using the developed module, users have the option to utilize the table dropdown for each report type to access the complete report and choose their preferred outcome. Similarly, users can utilize the dropdown menus for report type, table, and field within the Comparing Mode to visualize a graphical representation comparing each model against the others. Additionally, users can click on the selection menu to download and save energy results in various formats.

6.6 Testing and verifying the developed Circular Economy module

The developed CE modules were tested using the case projects described in Figure 6.1, the associated material QTO in Figures 6.1b through 6.1d and estimates of the quantity of wasted materials following the mass balance principle at the construction stage suggested by Guerra et al., (2020) and the total material incorporated in the existing building for the end-of-life are accessed from the COMOTH_CE icon at the top taskbar in Autodesk Revit©. Through this, users are able to assess the material waste generated during both the construction and deconstruction phases of their projects. This evaluation involves employing the three construction methods described and completing the estimate of the productivity for the waste handling equipment, alongside exploring their associated cost options. These steps are essential for selecting the most suitable equipment for effectively managing construction and deconstruction waste (CDW). First, the designer starts by clicking on the COMOTH_CE plug-in tab and the circular economy push button to open the user interfaces, ready for the commence analysis. At this step, users will be required to make a selection from the two options for the number of floors (1-3 floors and above three floors); one from the construction methods (conventional, modular and 3D concrete printing); and one of the lifecycle stage (construction and end of life), then the form of waste and the type of analysis from the dropdown menu, as shown in Figure 6:24b. After choosing the type of waste, users need to select “Waste Handling Equipment Productivity” and input the necessary data to initiate and finalize the analysis. Within the user input window, the developed plug-in automatically generates the wasted material according to the selected waste type (as shown in Figure 6.24a) and populates the material quantity relevant cell. However, users must select the map icon to see Google Maps and provide the start and end location to transport the wasted material. Although bulk waste was used for the illustration in Figure 6.25, the same process is applicable for measuring the four forms

of wasted materials in this developed module. Subsequently, users can proceed with the process by clicking on the map icon within the distance cell. This action launches the Google Maps application on a new screen, with a cell for users to select a location for the starting point and delivery facilities (end location) for the wasted material. After that, users can choose to compare different facilities before making a final selection, as shown in Figure 6.26.

Construction Material_Conventional												
Family and Type	Material: Name	Material: Area (m ²)	Material: Volume (m ³)	Bulk Density (kg/m ³)	QTO Material Weight (kg)	Material Loss Rate (%)	Bulk Material Waste (kg)	Total Material Purchased (kg)	Recyclable Construction Materials (%)	Total Recyclable Materials (kg)	Landfill Construction Waste (%)	Total Landfill Material (kg)
Basic Wall: Exterior - Brick on Wooden Stud for conventional	Wood - Stud Layer	269	26.07	608	15850.56	9.2	1458.25	17308.81	65	947.863	35	510.388
Basic Wall: Exterior - Brick on Wooden Stud for conventional	Wood - Sheathing - particleboard/ OSB	192	1.92	544	1044.48	9.2	96.09	1140.57	65	62.460	35	33.632
Basic Wall: Exterior - Brick on Wooden Stud for conventional	Masonry - Brick	192	4.79	830.6	3978.574	7	278.50	4257.07	0	0.000	100	278.500
Basic Wall: Exterior - Brick on Wooden Stud for conventional	Gypsum, USG Sheetrock® Board	340	5.27	785	4136.95	19	786.02	4922.97	0	0.000	100	786.021
Basic Wall: Exterior - Brick on Wooden Stud for conventional	Fiberglass Batt	192	9.59	91	872.69	8	69.82	942.51	0	0.000	100	69.815
Basic Wall: Exterior - Brick on Wooden Stud for conventional	Air Barrier - Air Infiltration Barrier	192	0.000	0.184	35.328	3	1.06	36.39	0	0.000	100	1.060
Basic Roof: Wood Rafter 184mm - Asphalt Shingles for conventional	Rigid Fiberglass Batt	170	8.66	265	2294.9	8	183.59	2478.49	0	0.00	100	183.59
Basic Roof: Wood Rafter 184mm - Asphalt Shingles for conventional	Roofing - Asphalt Shingle	170	1.7	7824	13300.8	15	1995.12	15295.92	0	0.00	100	1995.12
Basic Roof: Wood Rafter 184mm - Asphalt Shingles for conventional	Structure - Wood Joist/Rafter	170	22.76	608	13838.08	9.2	1273.10	15111.18	65	827.52	35	445.59
Basic Roof: Wood Rafter 184mm - Asphalt Shingles for conventional	Wood - Sheathing - particleboard/ OSB	170	2.55	544	1387.2	9.2	127.62	1514.82	65	82.95	35	44.67
Floor: Wood Joist 220mm - Wood Finish Conventional Floor	Structure - Wood Joist/Rafter Layer	121	26.56	608	16148.48	9.2	1485.66	17634.14	65	965.68	35	519.98
Floor: Wood Joist 220mm - Wood Finish Conventional Floor	Wood - Sheathing - particleboard/ OSB	242	4.22	544	2295.68	9.2	211.20	2506.88	65	137.28	35	73.92
Compound Ceiling: Gypsum Conventional Ceiling Board	Gypsum, USG Sheetrock® Board	116	1.74	785	1365.9	19	259.52	1625.42	0	0.000	100	259.521
Compound Ceiling: Gypsum Conventional Ceiling Board	Wood Batten	116	5.82	544	3166.08	9.2	291.28	3457.36	65	189.332	35	101.948

Figure 6.24a - Sample of the quantity of the wasted material using mass balance principle

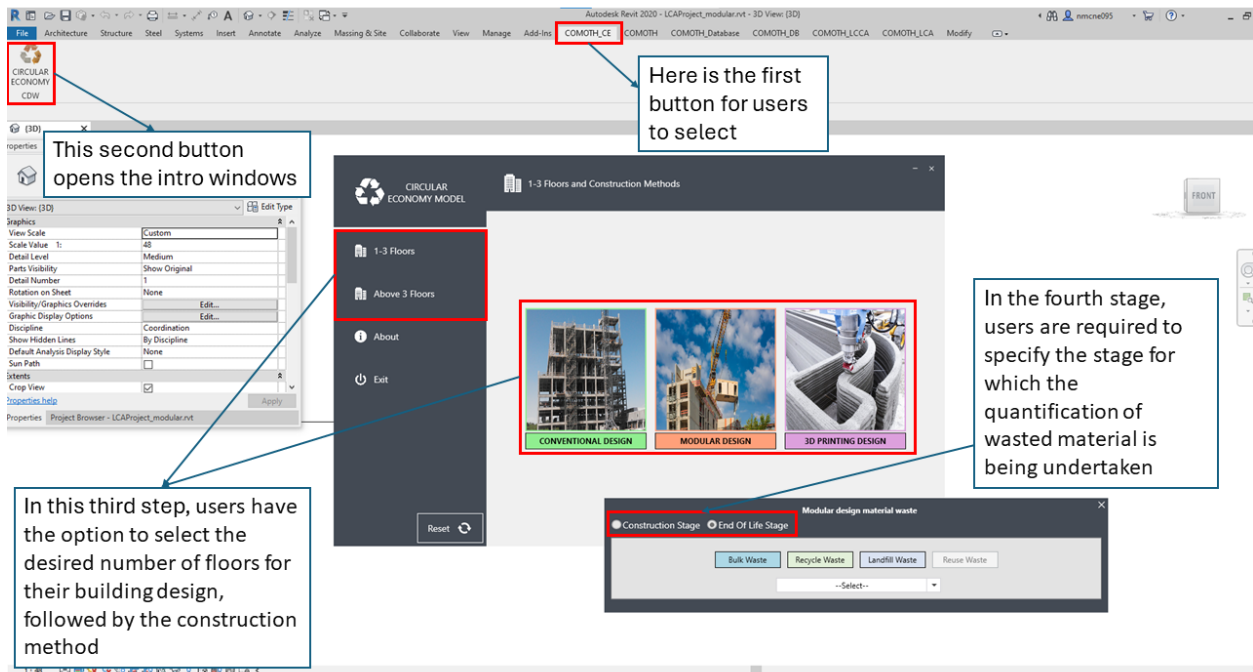


Figure 6.24b - Module processes to commencing CDW evaluation

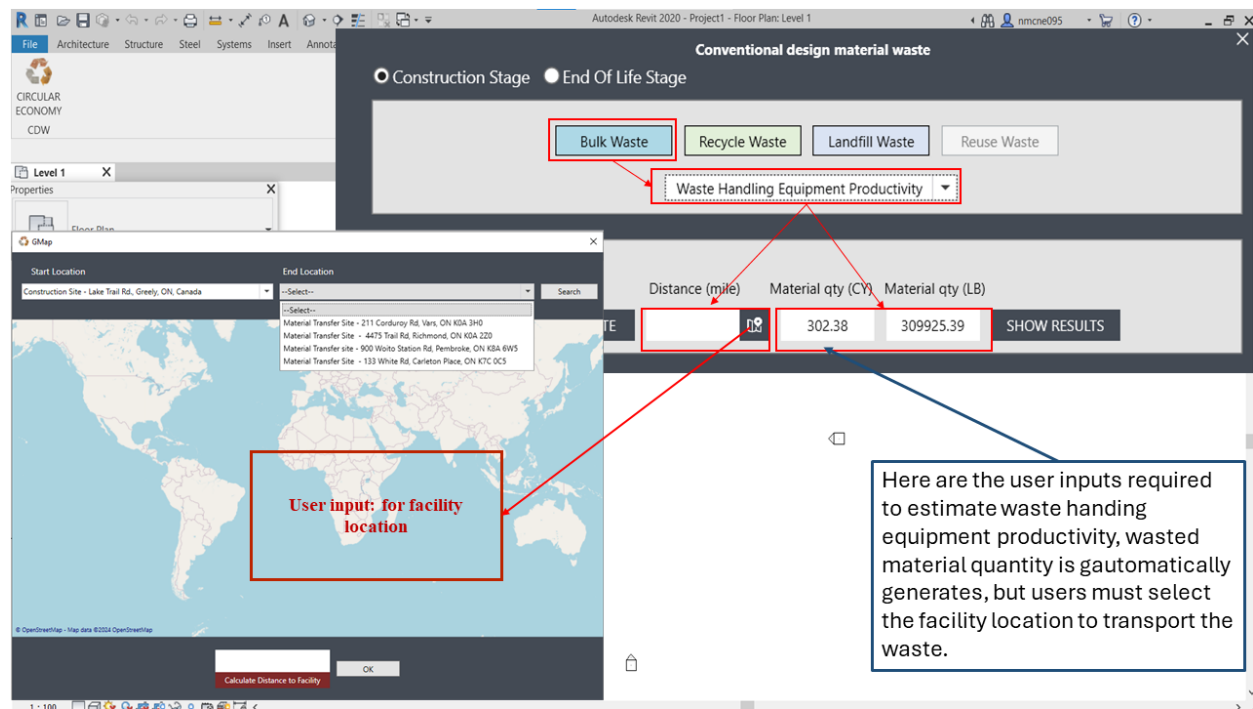


Figure 6.25 - Integrated GoogleMap used as facility locator

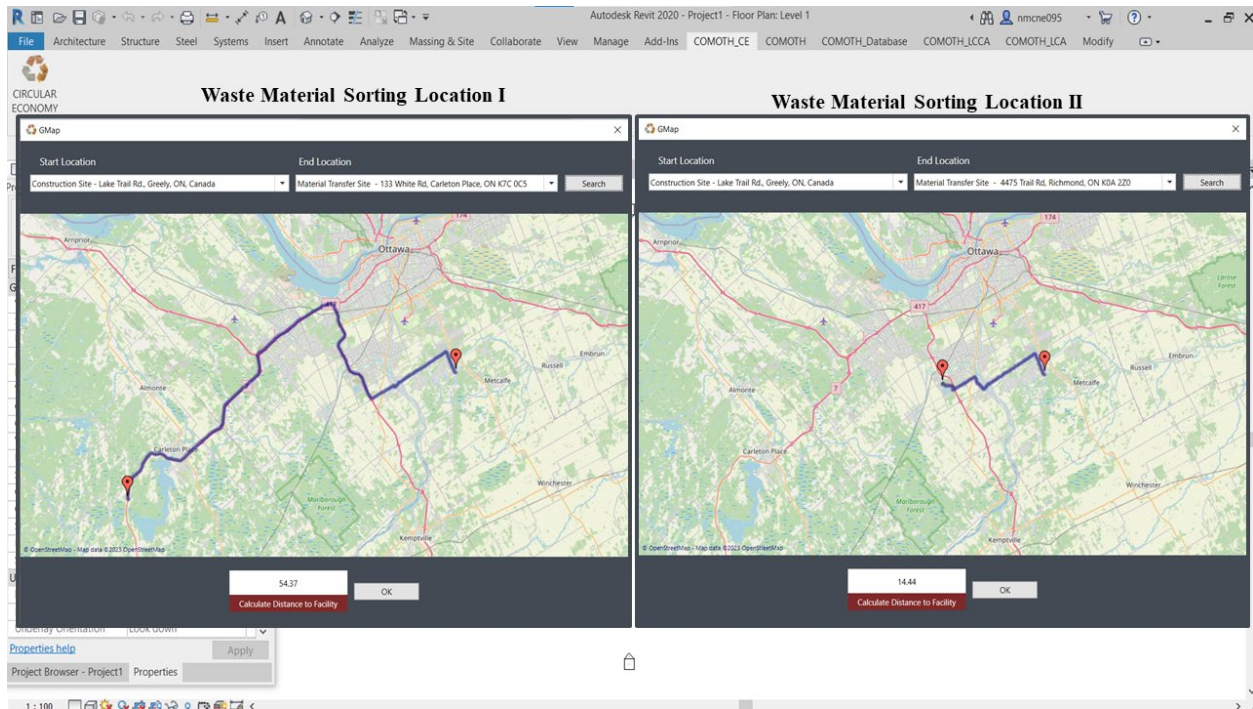


Figure 6.26 - Comparing two waste facility locations in GoogleMaps

After selecting the waste facility as required, the module will initiate a search and compute the distances between the facilities to ascertain the closest, fastest, or safest route among various locations. This information is then used to calculate the travel time and to determine the equipment production rates. An example of distance's calculation between the construction site and the bulk waste material sorting facility amounts to 14.44 miles, as shown in Figure 6.27. Users can employ the same methodology to calculate distances between any waste material pickup location and its corresponding delivery point within the scope of this module, whether it be a recycling yard, reuse centre, or landfill site. Next, the module algorithm leverages the entire set of customized parameters included in the database to compute the productivity of waste handling equipment by nominalizing all requirements to generate the most reliable estimation. Afterwards, the model undertakes all requisite calculations and valuations in the background and then furnishes users with the production rates for various equipment options, as shown in Figure 6.27.

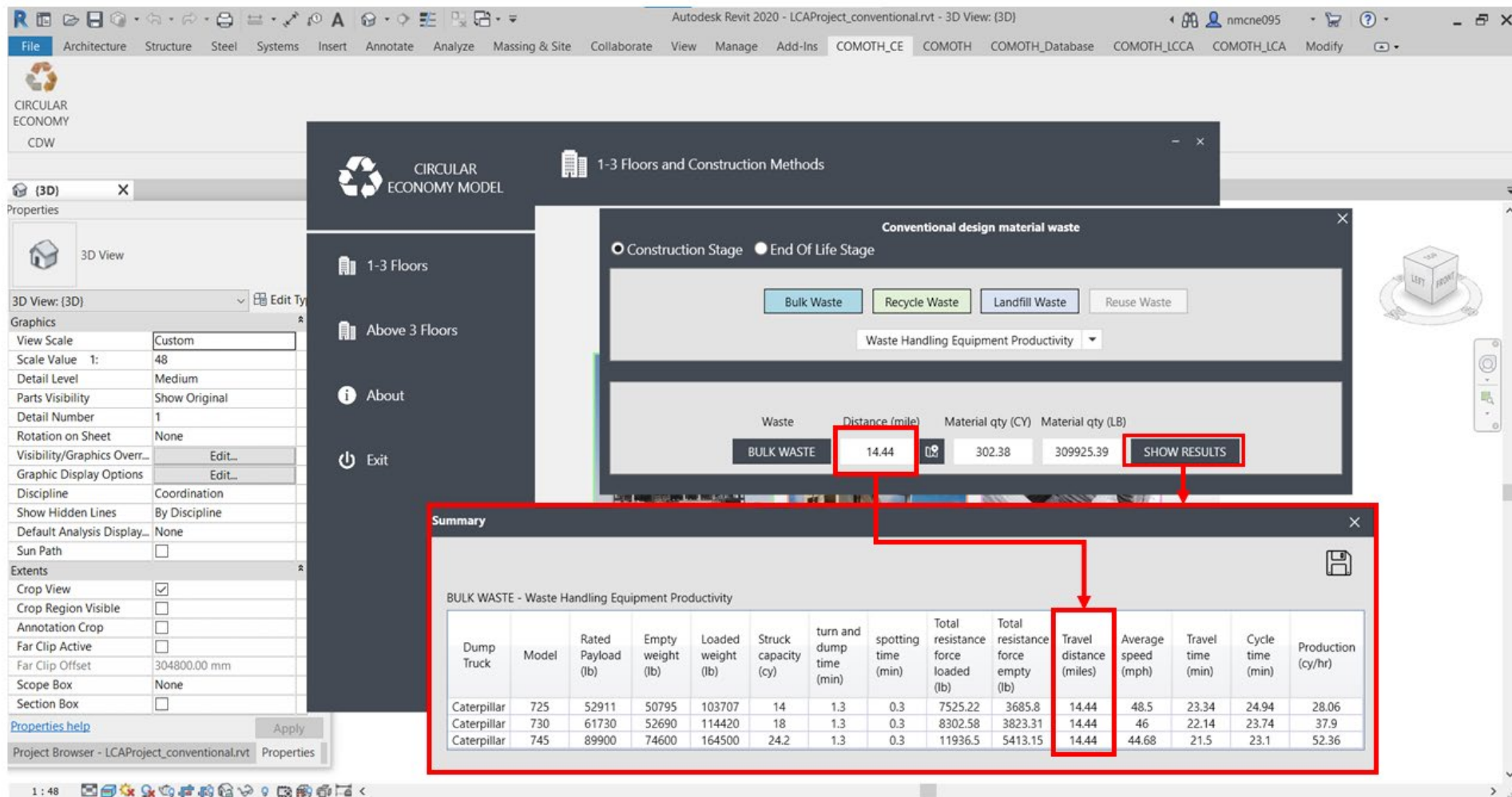


Figure 6.27 - Result of the waste handling equipment productivity

Upon generating the equipment production rates for various equipment, users will proceed to estimate the cost associated with the waste handling equipment by selecting “Equipment Cost Options” from the dropdown menu, which then opens a secondary selection menu containing a list of associated cost options: buy, lease and rent options as, shown in Figure 6.28.

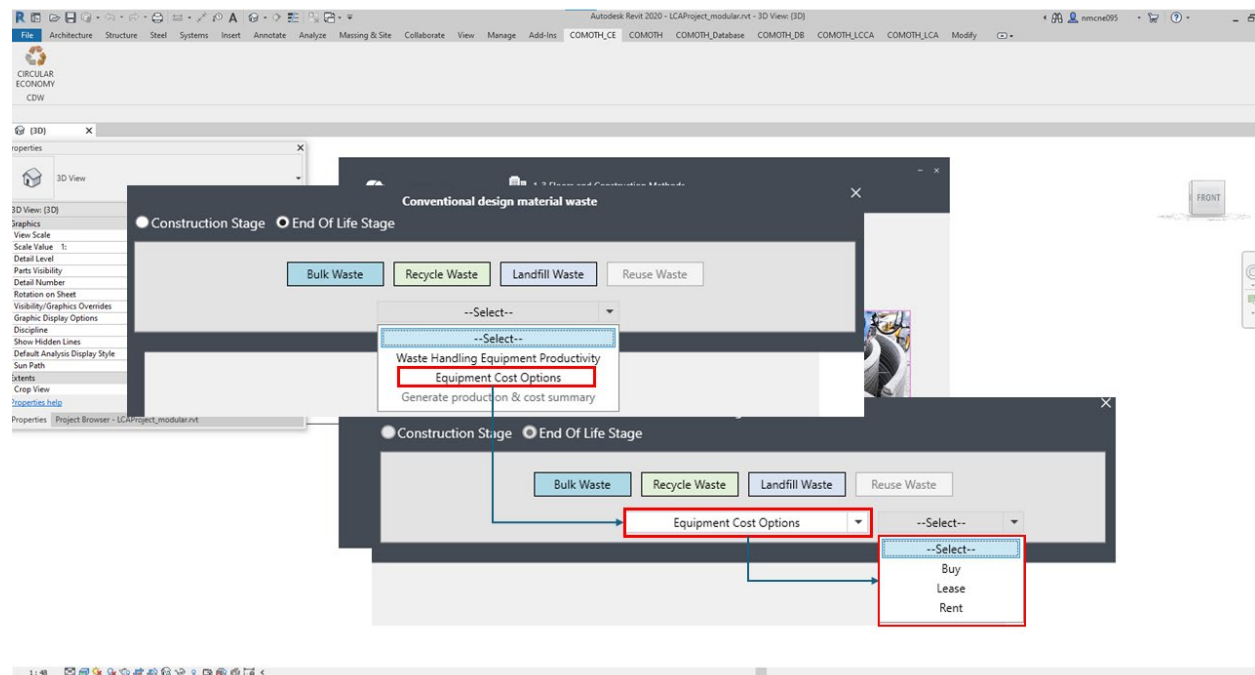


Figure 6.28 - Equipment cost options and selection processes

After making the described selections, another window emerges for users to input cost-related information. Here, the required user input for finalizing the equipment cost modelling for the developed module is the fuel cost expressed in dollars/gallon. Hence, users provide this cost and click on show results, and then the model retrieves other essential and supporting information from the database. It then proceeds to perform all the required calculations and assessments in the backend, ultimately providing users with the equipment cost, as demonstrated in Figure 6.29. It is worth noting that while the illustration uses the “buy” cost option, the same procedure applies to estimating other options, such as lease and rent.

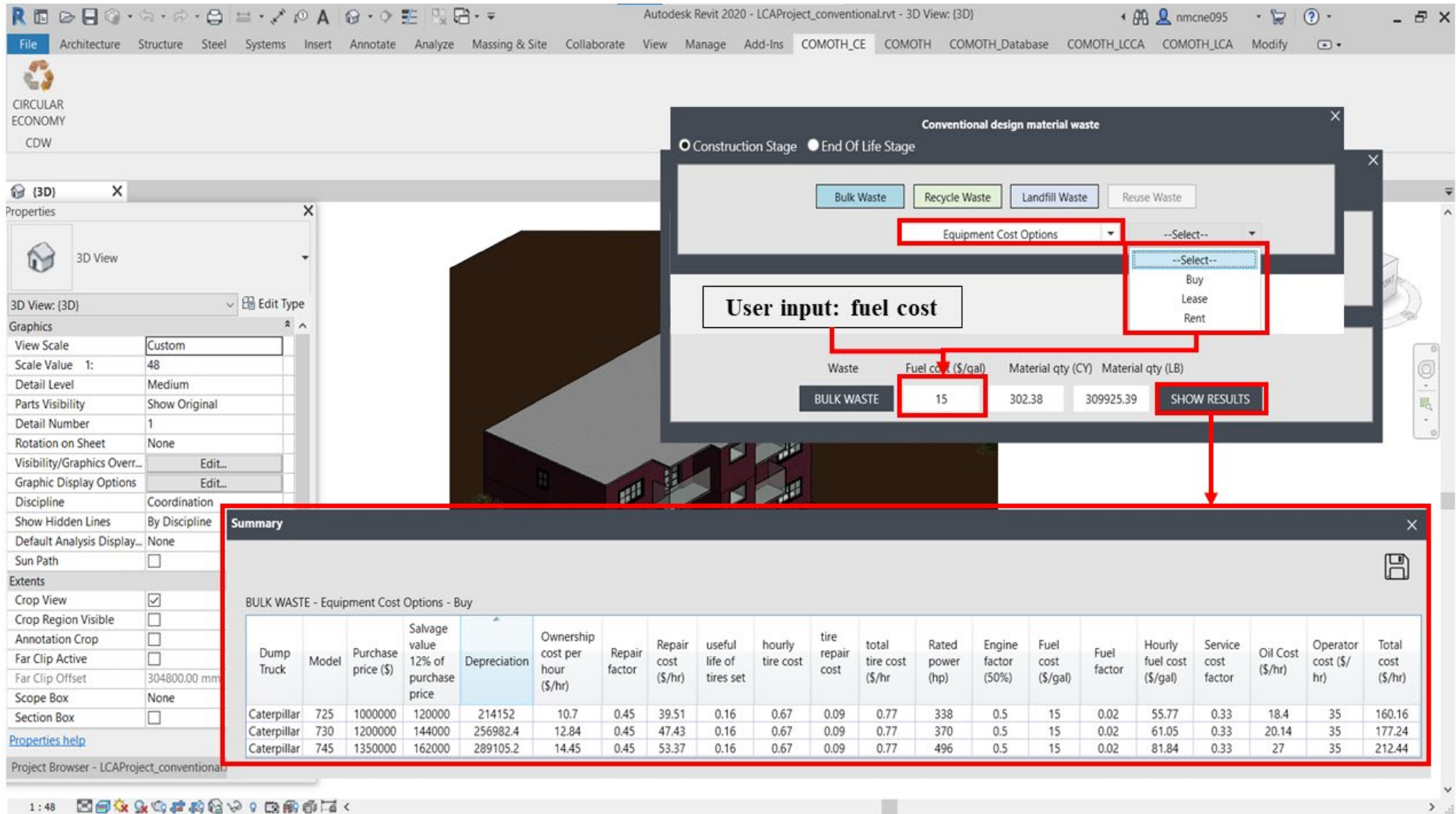


Figure 6.29 - Result of the waste handling equipment cost (buy option)

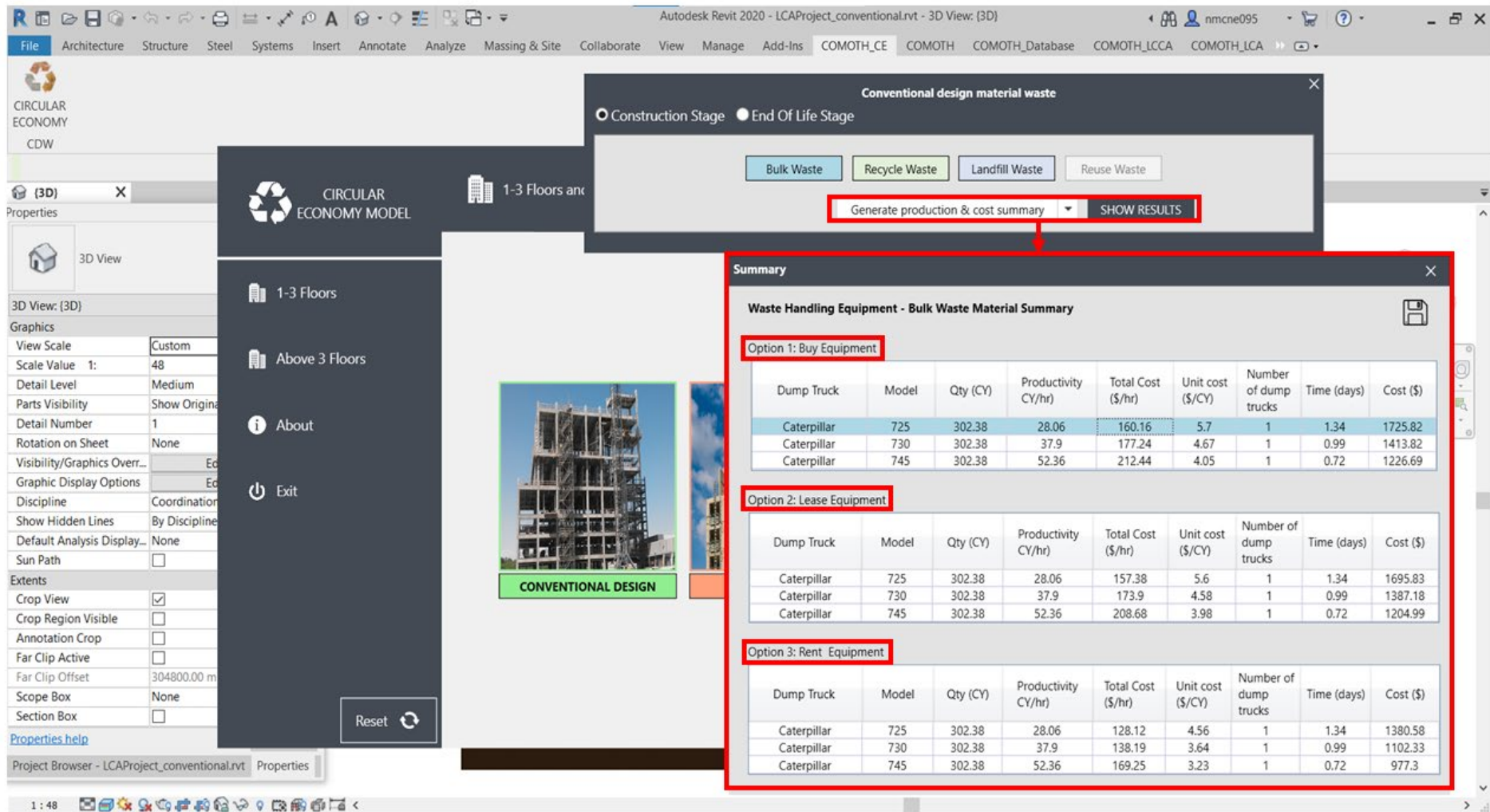


Figure 6.30 - Summary of production rate and cost for CDW management

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Upon completing the equipment production rate and cost evaluation, the Generated production and cost summary will be activated and ready for users to select in order to generate the analysis summary by clicking the final button, “Generated production and cost summary,” which allows users to compare different equipment options in terms of production rates and costs. Consequently, users can confidently select the most efficient and cost-effective option, as shown in Figure 6.30.

6.7 Testing and verifying the developed LCA module

The developed LCA module is tested by using the case buildings described in Figure 6.1 and the details of the material in Figures 6.1a through 6.1d. Users can use the developed module to evaluate the environmental footprint/impact associated with the materials’ production, construction, building operation and end-of-life for their design via the new plug-in created in the BIM (e.i. Autodesk Revit©) named COMOTH_LCA to access the user interface. To start, users must select the number of floors for the building under design by selecting from either 1-3 floors or above 3 floors. After that, they must specify the construction method before clicking the generate button, as depicted in Figure 6.31. It is important to note that the same process applies to the three construction methods.

For example, in order to assess the environmental impact of the materials’ production, Autodesk Revit material associated with components of the design families are created in a detailed layer structure, as shown in the construction material and layers details, in ways that provide thorough information and data for ease of integration and assessment, as shown in Figure 6.32.

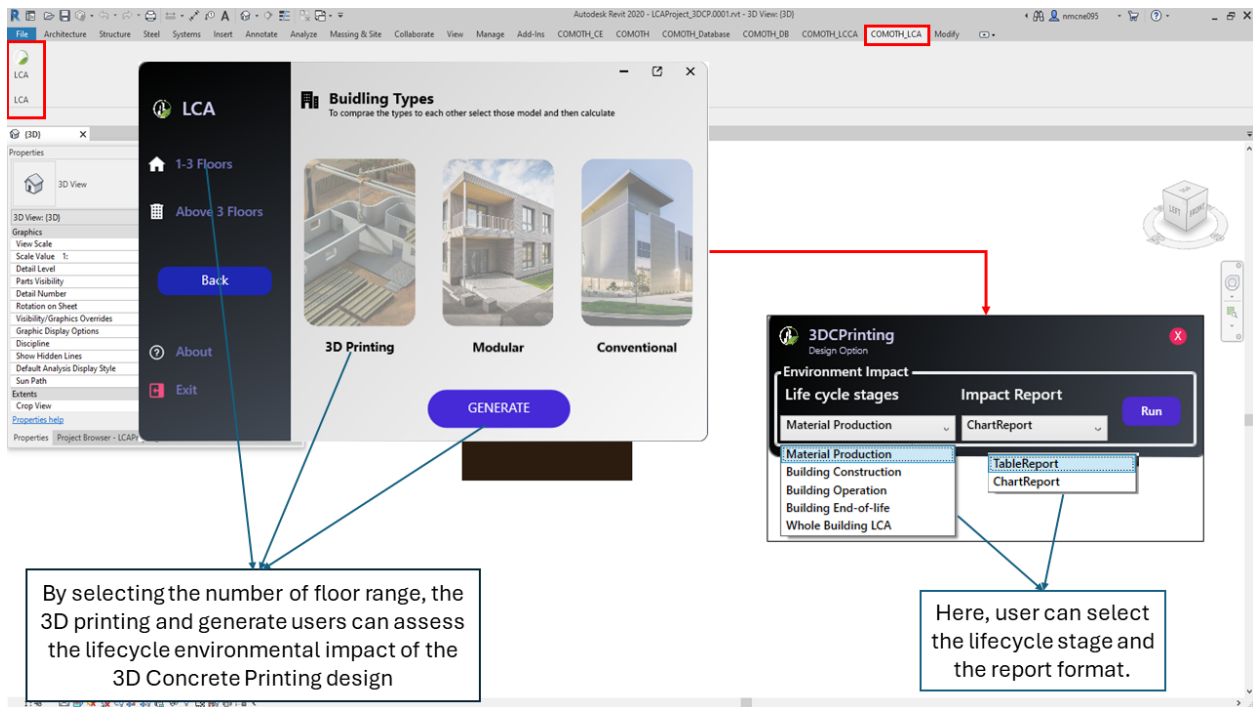


Figure 6.31 - Selection sequence to commencing evaluation in the LCA module

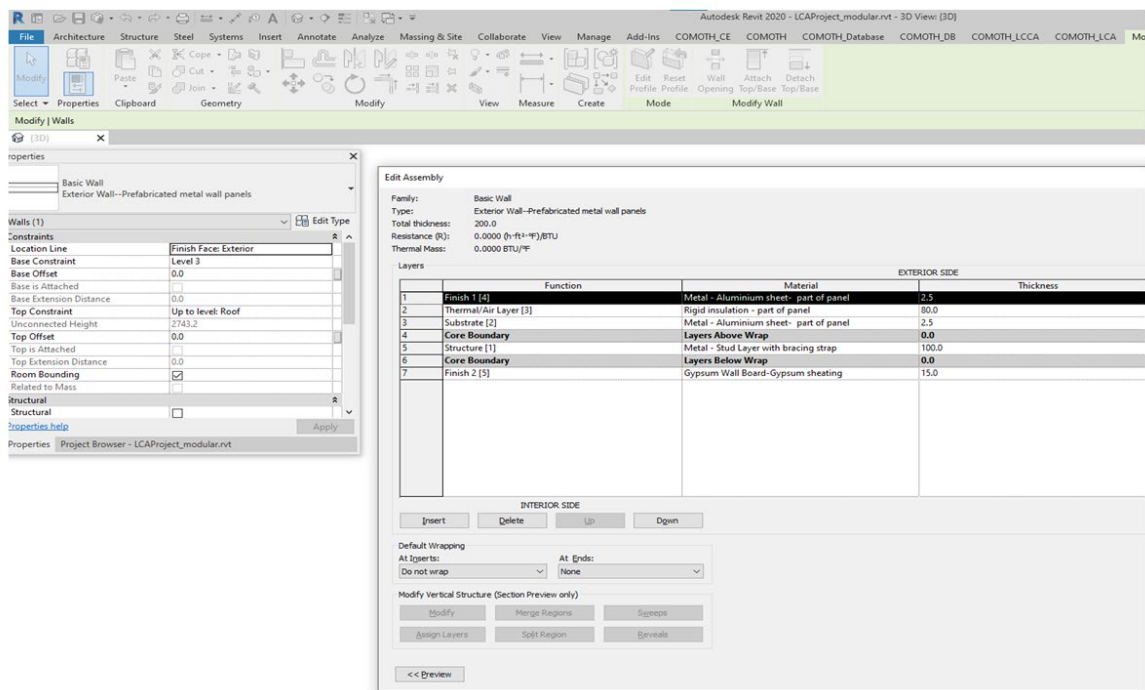


Figure 6.32 - Sample of Wall layers for LCA module

The materials quantity take-off of the components used in the 3D BIM model is extracted and integrated with the LCI of openLCA through a newly developed plug-in for the LCA module. Users are able to explore the materials' production stage for various construction methods by choosing "material production" from the dropdown menu of the life cycle stages, selecting the desired result format, and initiating the analysis by clicking the run button to generate the final report. The impact report of the materials' production stage is depicted in Figure 6.33 as a table report, while Figure 6.34 illustrates the same data in a chart format. Additionally, Table 6.9 shows a detailed comparison of the environmental impacts of the three construction methods, highlighting that modular construction has the highest impact, followed by 3D printing, whereas conventional construction exhibits the lowest impact at the materials' production stage.

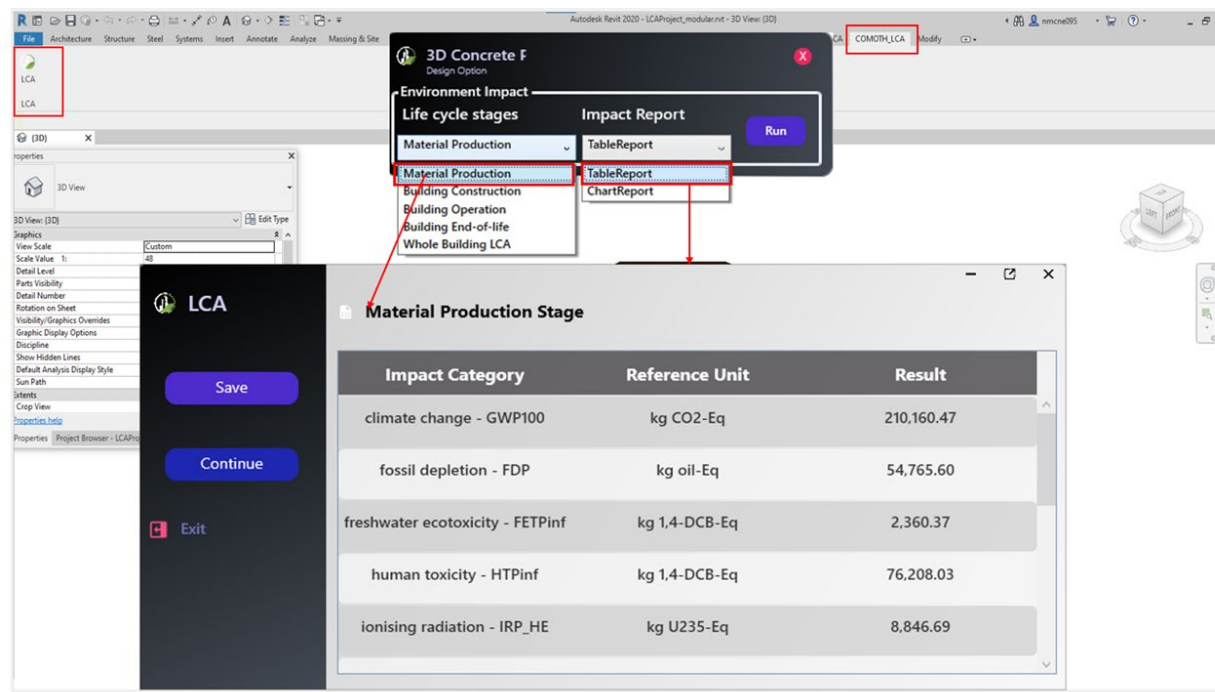


Figure 6.33 - EI of materials' production table in the developed module

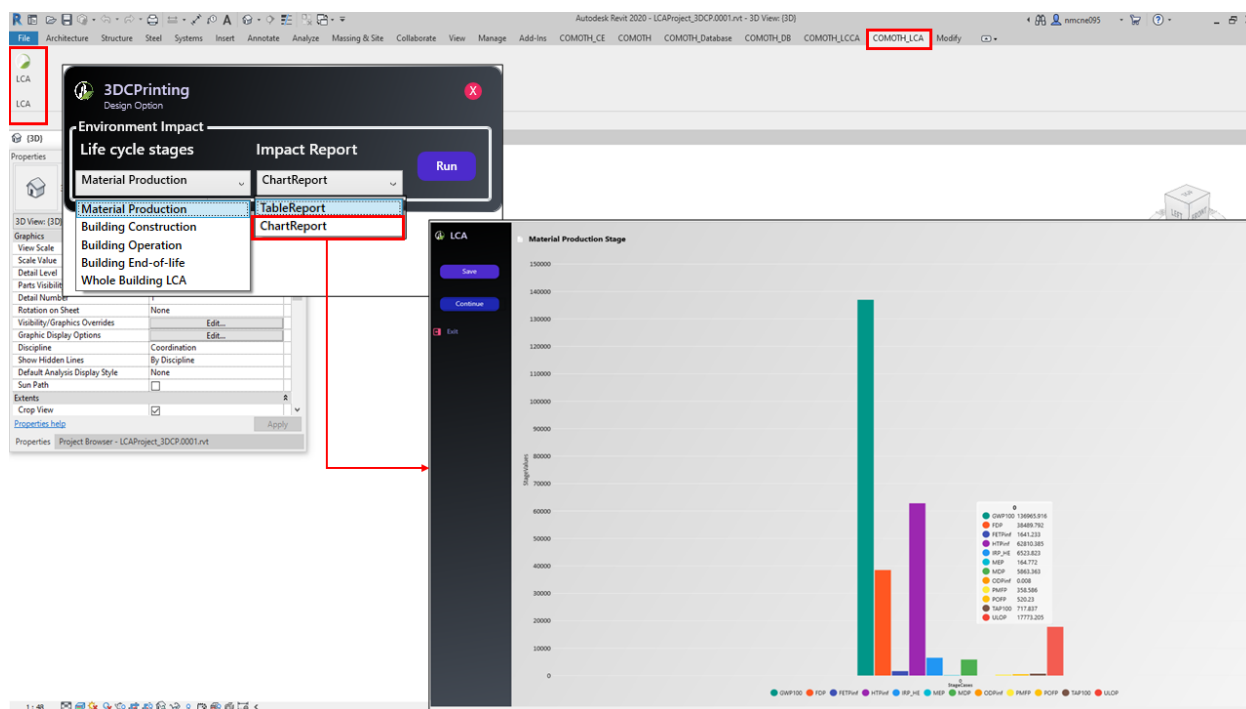


Figure 6.34 - EI of materials' production chart in the developed module

Table 6.9 - Environmental impact comparison of materials' production

Impact category	Reference unit	3DCPrinting	Conventional construction	Modular construction
climate change - GWP100	kg CO ₂ -Eq	210,160.47	136,965.92	374,750.32
fossil depletion - FDP	kg oil-Eq	54,765.60	38,489.79	106,749.04
freshwater ecotoxicity - FETPinf	kg 1,4-DCB-Eq	2,360.37	1,641.23	15,545.78
human toxicity - HTPinf	kg 1,4-DCB-Eq	76,208.03	62,810.39	169,141.51
ionising radiation - IRP_HE	kg U235-Eq	8,846.69	6,523.82	19,542.24
marine eutrophication - MEP	kg N-Eq	201.51	164.77	383.33
metal depletion - MDP	kg Fe-Eq	25,808.55	5,863.36	426,604.03
ozone depletion - ODPinf	kg CFC-11-Eq	0.01	0.01	0.02
particulate matter formation - PMFP	kg PM10-Eq	468.74	358.59	1,330.11
photochemical oxidant formation - POFP	kg NMVOC	675.78	520.23	1,297.19
terrestrial acidification - TAP100	kg SO ₂ -Eq	911.08	717.84	1,802.38
urban land occupation - ULOP	m ² a	3,388.30	17,773.20	5,284.88

To evaluate the environmental impact of the construction stage, the average electricity and diesel consumption, estimated at approximately 60 MJ and 15 MJ per building area, respectively, were utilized. Ecoinvent inventory data is referenced to assess the diesel and electricity consumption during the construction, as detailed in the methodology. Users can assess the impact of the construction stage for various construction methods by selecting "Building construction" from the dropdown menu of the life cycle stages, specifying the desired result format, and initiating the analysis by clicking the run button to generate the final report, as shown in Figure 6.35. For the comparative impact for the building construction stage, Table 6.10 illustrates that 3D concrete printing presents the highest impact, followed by conventional construction, whereas modular construction displays the lowest impact during this stage.

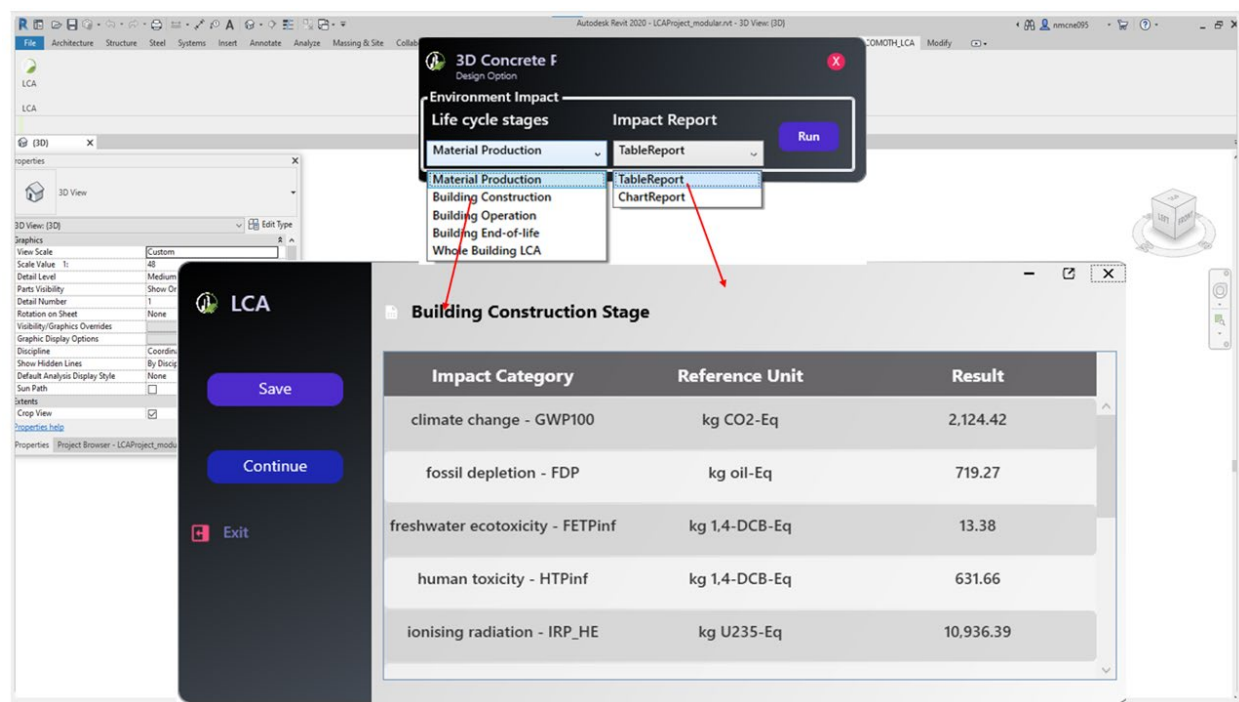


Figure 6.35 - Environmental impact of buildings’ construction stage

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Table 6.10 - Environmental impact comparison of building's construction

Impact category	Reference unit	3DCPrinting	Conventional construction	Modular construction
climate change - GWP100	kg CO2-Eq	2124.41	1,142.00	870.90
fossil depletion - FDP	kg oil-Eq	719.27	389.64	309.64
freshwater ecotoxicity - FETPinf	kg 1,4-DCB-Eq	13.38	6.52	36.78
human toxicity - HTPinf	kg 1,4-DCB-Eq	631.662	291.84	307.19
ionizing radiation - IRP_HE	kg U235-Eq	10936.39	5,473.10	3,702.02
marine eutrophication - MEP	kg N-Eq	4.269	2.92	1.19
metal depletion - MDP	kg Fe-Eq	114.17	59.03	314.66
ozone depletion - ODPinf	kg CFC-11-Eq	0.00	0.00	0.00
particulate matter formation - PMFP	kg PM10-Eq	4.29	2.80	17.08
photochemical oxidant formation - POFP	kg NMVOC	11.89	8.29	6.11
terrestrial acidification - TAP100	kg SO2-Eq	8.87	5.68	3.61
urban land occupation - ULOP	m2a	14.02	12.25	13.71

The environmental impacts during the operation stage of buildings primarily stem from three major sources: energy consumed by households, water usage and materials' replacement. The energy requirements for the operational stage are determined from the DesignBuilder simulation tool, while the materials' replacement is estimated using R.S.Menas online cost data, and both are integrated with BIM tool (Autodesk Revit) as described in the methodology. Consequently, users can evaluate the impact of the operation stage for different construction methods using the developed module by selecting "Building operation" from the dropdown menu of the life cycle stages, specifying the desired result format, and executing the analysis by clicking the run button to generate the final report, as illustrated in Figure 6.36. The result shows that this stage has the highest impact among all the lifecycle stages, with modular buildings having the least impact,

followed by conventional construction, and 3DCP showing the highest impact when compared among the three construction methods, as illustrated in Table 6.11.

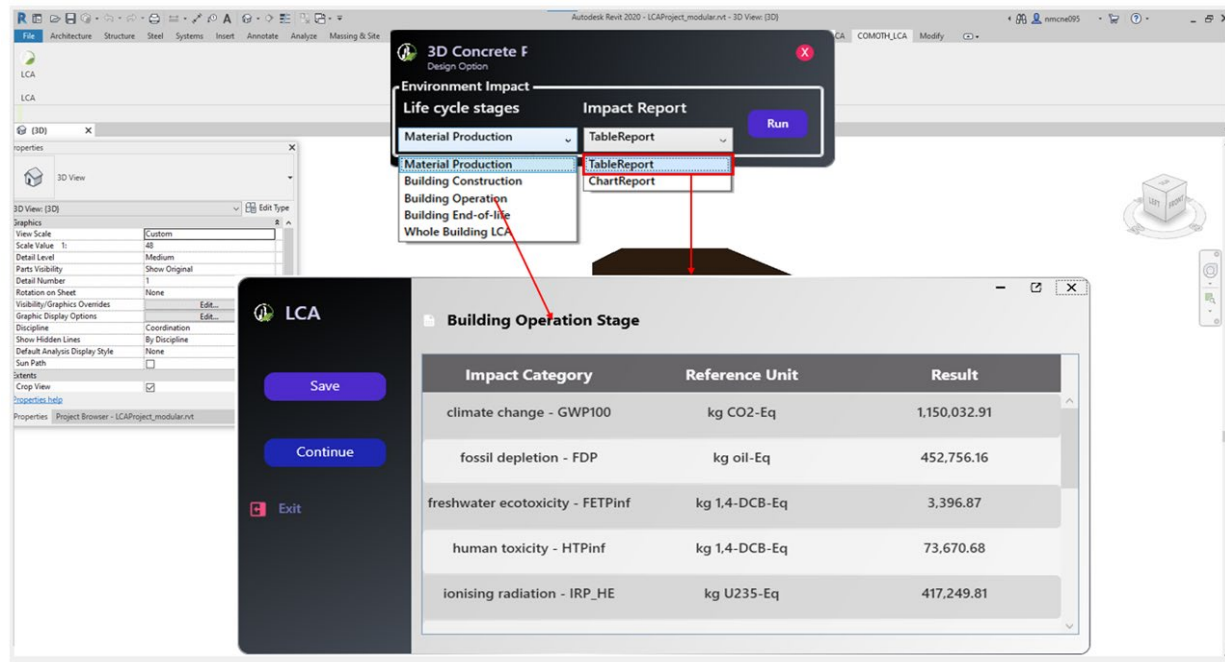


Figure 6.36 - Environmental impact of building's operation stage

Table 6.11 - Environmental impact comparison of building's operation

Impact category	Reference unit	3DCPrinting	Conventional construction	Modular construction
climate change - GWP100	kg CO2-Eq	1,150,032.91	1,130,020.31	1,084,769.99
fossil depletion - FDP	kg oil-Eq	452,756.16	444,596.45	426,979.33
freshwater ecotoxicity - FETPinf	kg 1,4-DCB-Eq	3,396.87	3,406.97	3,197.07
human toxicity - HTPinf	kg 1,4-DCB-Eq	73,670.68	74,522.31	69,767.31
ionising radiation - IRP_HE	kg U235-Eq	417,249.81	417,892.77	416,641.04
marine eutrophication - MEP	kg N-Eq	228.11	227.91	215.46
metal depletion - MDP	kg Fe-Eq	15,316.13	15,454.30	14,463.57
ozone depletion - ODPinf	kg CFC-11-Eq	0.14	0.14	0.14
particulate matter formation - PMFP	kg PM10-Eq	439.56	436.99	414.89
photochemical oxidant formation - POFP	kg NMVOC	1,203.42	1,186.43	1,136.41
terrestrial acidification - TAP100	kg SO2-Eq	1,048.36	1,039.54	990.36
urban land occupation - ULOP	m2a	1,249.49	1,244.54	1,182.19

The main consideration for end-of-life impacts is the equipment for loading and hauling the wasted materials during the building's deconstruction or demolition involving activities such as reuse, recycling, or disposal in a landfill. All the transportation and handling of materials to various facilities sites is considered via the Circular Economy module, which uses a distance of 30 km. On the other hand, recycled materials are transported to the recycling yard, a distance of 25 km. Similarly, reusable materials are also transported to a dedicated reusable materials centre, with an estimated distance of approximately 40 km. Users can assess the associated environmental impacts by selecting the “Building End-of-life,” as shown in Figure 6.37. Moreover, Table 6.12 provides users with a detailed comparison of the three construction methods. Toward the end, the overall impact of the entire building can be evaluated by choosing the “ Whole Building LCA” option, as shown in Figure 6.38, and then be compared across the three construction methods, as described in Table 6.13.

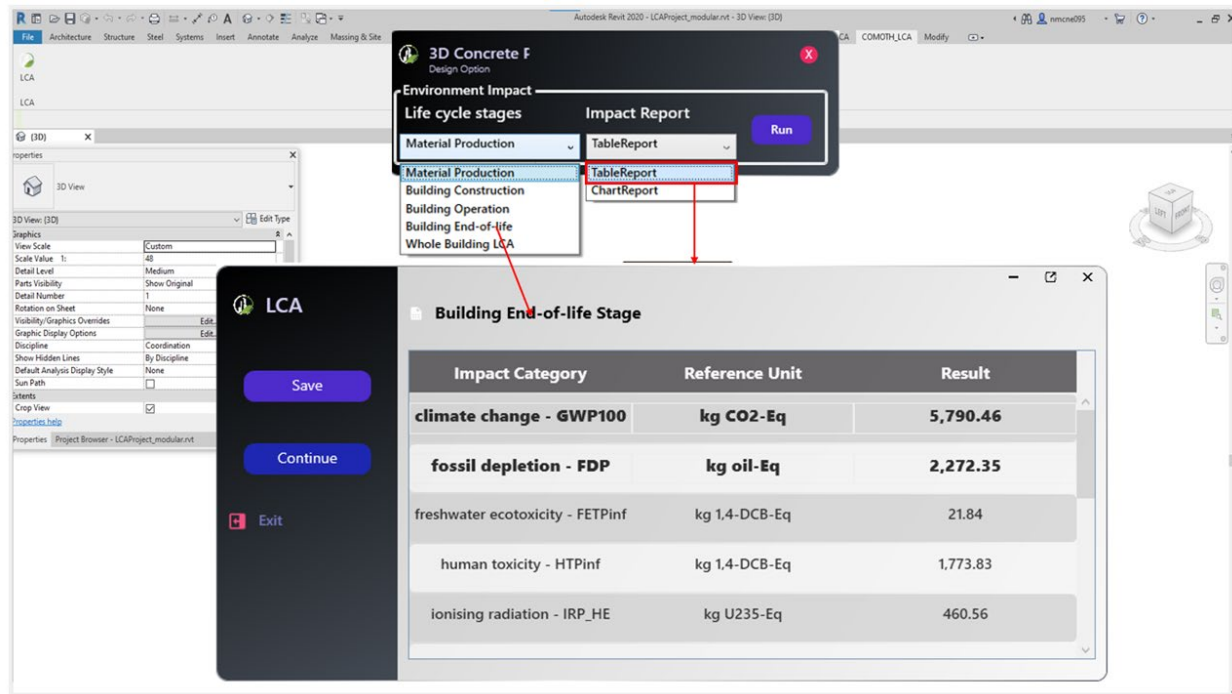


Figure 6.37 - Environmental impact of End-of-Life of buildings

Table 6.12 - Environmental impact comparison of building's end-of-life

Impact category	Reference unit	3DCPrinting	Conventional	Modular
climate change - GWP100	kg CO2-Eq	5,790.46	4,204.42	4,282.19
fossil depletion - FDP	kg oil-Eq	2,272.35	805.45	1,675.85
freshwater ecotoxicity - FETPinf	kg 1,4-DCB-Eq	21.84	13.17	15.85
human toxicity - HTPinf	kg 1,4-DCB-Eq	1,773.83	1,307.68	1,269.97
ionising radiation - IRP_HE	kg U235-Eq	460.56	167.93	338.46
marine eutrophication - MEP	kg N-Eq	11.65	4.39	9.06
metal depletion - MDP	kg Fe-Eq	175.80	107.13	130.68
ozone depletion - ODPinf	kg CFC-11-Eq	0.00	0.00	0.00
particulate matter formation - PMFP	kg PM10-Eq	14.41	5.40	10.94
photochemical oxidant formation - POFP	kg NMVOC	37.33	12.89	28.87
terrestrial acidification - TAP100	kg SO2-Eq	25.19	8.97	19.25
urban land occupation - ULOP	m2a	526.60	-151.41	374.29

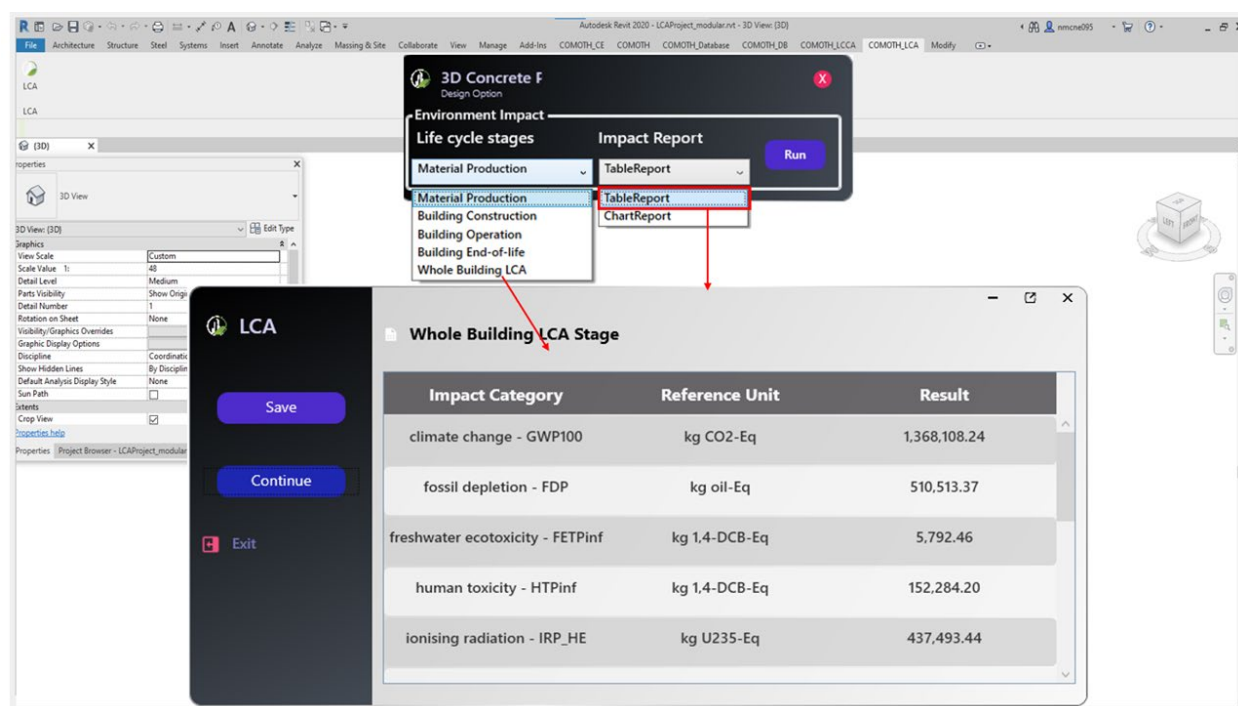


Figure 6.38 - Whole building's environmental impact

Table 6.13 - Whole building environmental impact comparison

Impact category	Reference unit	3DCPrinting	Conventional	Modular
climate change - GWP100	kg CO2-Eq	1,368,108.24	1,272,332.62	1,464,673.40
fossil depletion - FDP	kg oil-Eq	510,513.37	484,281.33	535,713.86
freshwater ecotoxicity - FETPinf	kg 1,4-DCB-Eq	5,792.46	5,067.89	18,795.48
human toxicity - HTPinf	kg 1,4-DCB-Eq	152,284.20	138,932.19	240,485.98
ionising radiation - IRP_HE	kg U235-Eq	437,493.44	430,057.63	440,223.76
marine eutrophication - MEP	kg N-Eq	445.54	399.99	609.04
metal depletion - MDP	kg Fe-Eq	41,414.64	21,483.82	441,512.94
ozone depletion - ODPinf	kg CFC-11-Eq	0.15	0.15	0.16
particulate matter formation - PMFP	kg PM10-Eq	927.01	803.77	1,773.02
photochemical oxidant formation - POFP	kg NMVOC	1,928.42	1,727.84	2,468.58
terrestrial acidification - TAP100	kg SO2-Eq	1,993.50	1,772.03	2,815.60
urban land occupation - ULOP	m2a	5,178.40	18,868.58	6,855.07

6.8 Testing and verifying the developed LCCA module

The developed LCCA module is tested for its capability, workability and flexibility by using the case buildings described in Figure 6.1 and the materials' details in Figures 6.1b through 6.1d. Users can initiate the Life Cycle Cost Analysis for the project using the developed module by accessing it from COMOTH_LCCA tab in Autodesk Revit and following the sequence of commands sequence. The first step in testing the developed module involves populating the general information with all required data. The detailed consideration and assumptions made and used to test the LCCA module is provided in Table 6.14.

Table 6.14 - 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 labour	Default value: 7.0%	Based on current construction costs increase in Canada
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 represents an average rate over the last ten years (Rad et al., 2021). Moreover, 10% serves as a target rate for evaluating the project investment, suitable for average risk, with residential buildings falling under standard risk investments (Park, 2007). Next is the building's total gross area and perimeter, which are automatically populated by the module. 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 6.39.

General information

Time horizon	25	Year
MARR	10	%
Gross floor area	8,399.14	SF
Perimeter	213.18	LF
Structure type	Brick Veneer/Wood Frame	
Cash flow pattern	☒ Uniform series ☐ Geometric series	

Submit

Figure 6.39 - LCCA module general information

The developed module integrates the cost database to populate the associated initial cost, as shown in Figure 6.40. Table 6.15 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 RSMeans 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/m³ for a gantry system 3D concrete printer, considering labour, material, and equipment expenses, with material constituting approximately 45% (\$414/m³), labour 35% (\$322/m³), and equipment 20% (184 CAD/m³), based on the information adopted from the studies conducted by Batikha et al., (2022) and Holt et al., (2019).

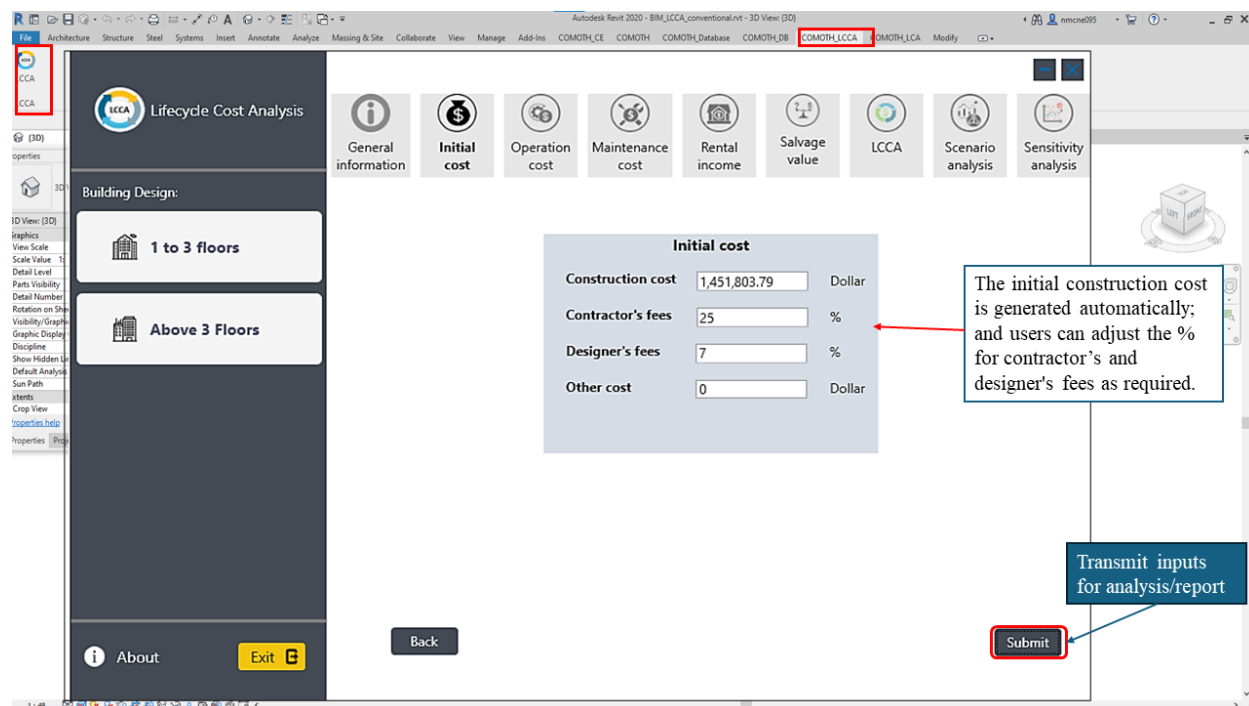


Figure 6.40 - Modeling initial costs in the LCCA module

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Table 6.15 - Summary of total initial cost

Construction method	Project cost (CAD)	Other costs (CAD)	Total cost (CAD)
Conventional construction	1,916,381.03	0	1,916,381.03
Modular construction	1,783,213.04	121,582.71	1,904,795.75
3D concrete printing	1,566,778.49	59,568.00	1,626, 346.49

Operation cost is calculated as the annual future cost of energy that will be utilized to operate the building efficiently. This study has provided 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 6.16. The HVCA 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 m³, and the associated CO₂ emission from the operating energy is priced in dollars/ton, as discussed previously in the development and illustrated in Figure 6.41. Hence, the total annual operating cost for the construction method was calculated based on the operating energy demand simulation by DesignBuilder.

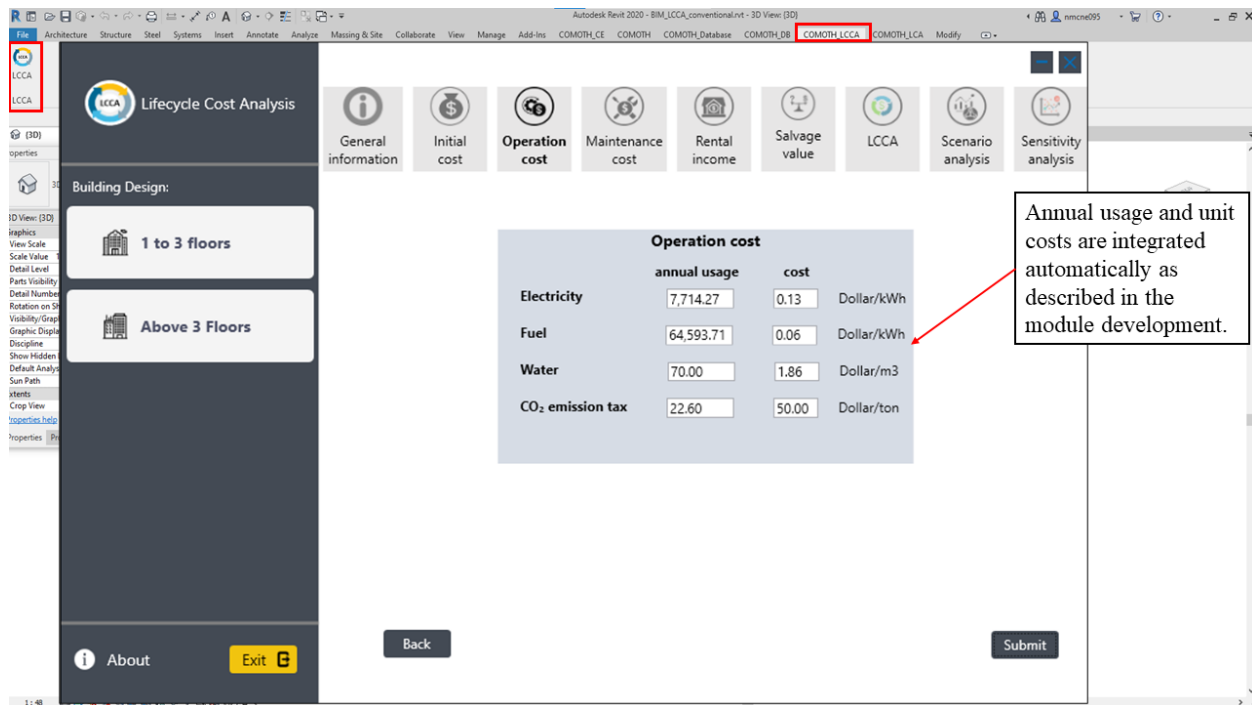


Figure 6.41 - Modeling the operating costs using the LCCA module

Table 6.16 - Summary of the operating costs

Operating cost	Conventional construction (CAD)	Modular construction (CAD)	3D concrete printing (CAD)
Initial value	6,229.30	6,087.69	6,330.07
Uniform series value	79,631.38	77,821.15	80,919.50
Geometric series value	106,345.10	103,927.60	108,065.35

Maintenance costs consist of annual minor repairs and major replacements. Minor repairs cover the administrative routine maintenance and are calculated based on one percent of the total project cost, as shown in Table 6.17. 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 module, 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 6.18. 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 module and shown in Figure 6.42.

Table 6.17 - Summary of minor repair costs

Minor Repairs	Conventional construction (CAD)	Modular Construction (CAD)	3D concrete printing (CAD)
Initial value	19,076.77	19,0479.57	16,263.46
Uniform series value	173,160.63	172,899.07	147,624.12
Geometric series value	327,159.85	325,182.04	277,645.87

Table 6.18 - Summary of major replacement cost

Replacement Cycles	Conventional construction (CAD)	Modular prefabrication (CAD)	3D concrete printing (CAD)
Year 05	21,066.05	14,865.19	21,065.05
Year 10	111,128.43	102,432.80	111,128.43
Year 15	531,079.26	508,241.24	579,856.01
Year 20	481,102.59	463,996.97	481,102.59
Year 25	81,515.11	57,523.60	81,515.11

Maintenance cost

Total building cost: 1,916,381.00 Dollar

Annual minor repairs: 1 %

Major replacements

Year	Elements	Future cost	
5	Painting	21,065.05	Dollar
10	Painting, Flooring	111,128.41	Dollar
15	Painting, Roof shine	531,079.24	Dollar
20	Painting, Flooring, E	481,102.58	Dollar
25	Painting	81,515.09	Dollar

Submit

Figure 6.42 - Modeling maintenance costs in LCCA module

For the rental income, the rentable area is automatically generated from the design model, while \$17.20/ft² cost per rentable area and the total number of months of 12 are used to multiply the generated value, as shown in Figure 6.43. 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 linear depreciation method. However, this module also allows users to input a salvage value or a salvage cost in the provided UI, as shown in Figure 6.44.

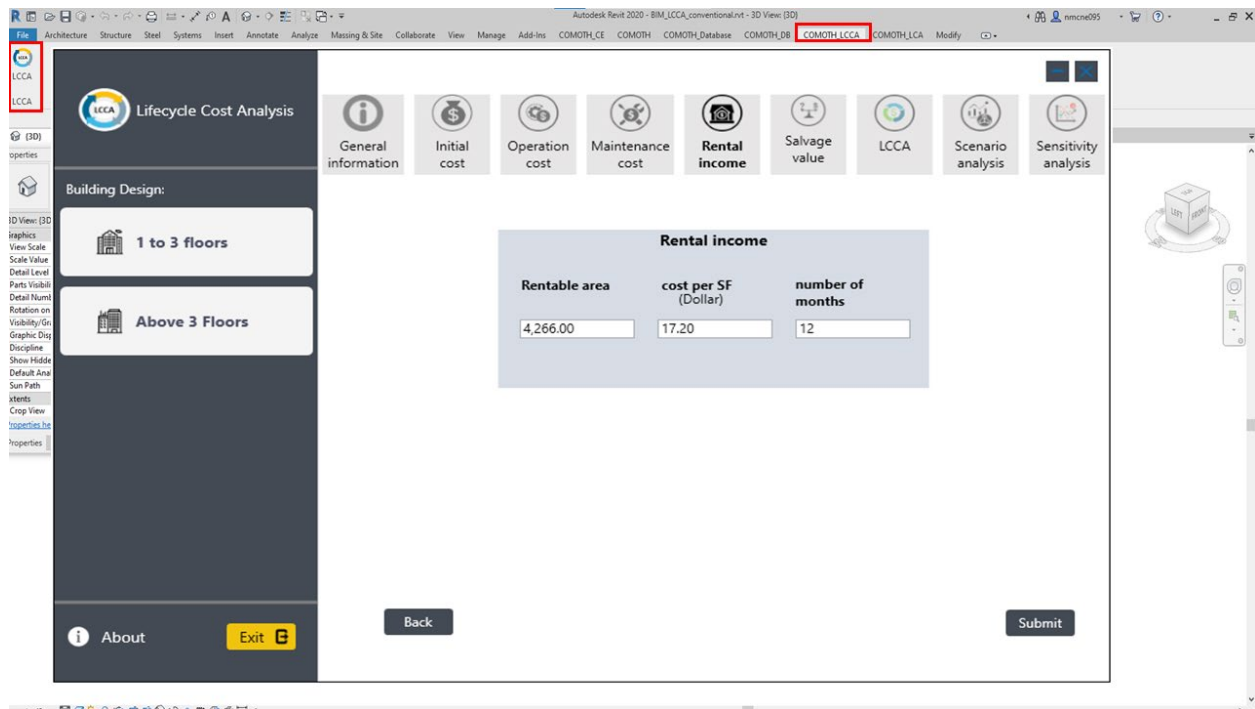


Figure 6.43 - Modeling rental income in LCCA module

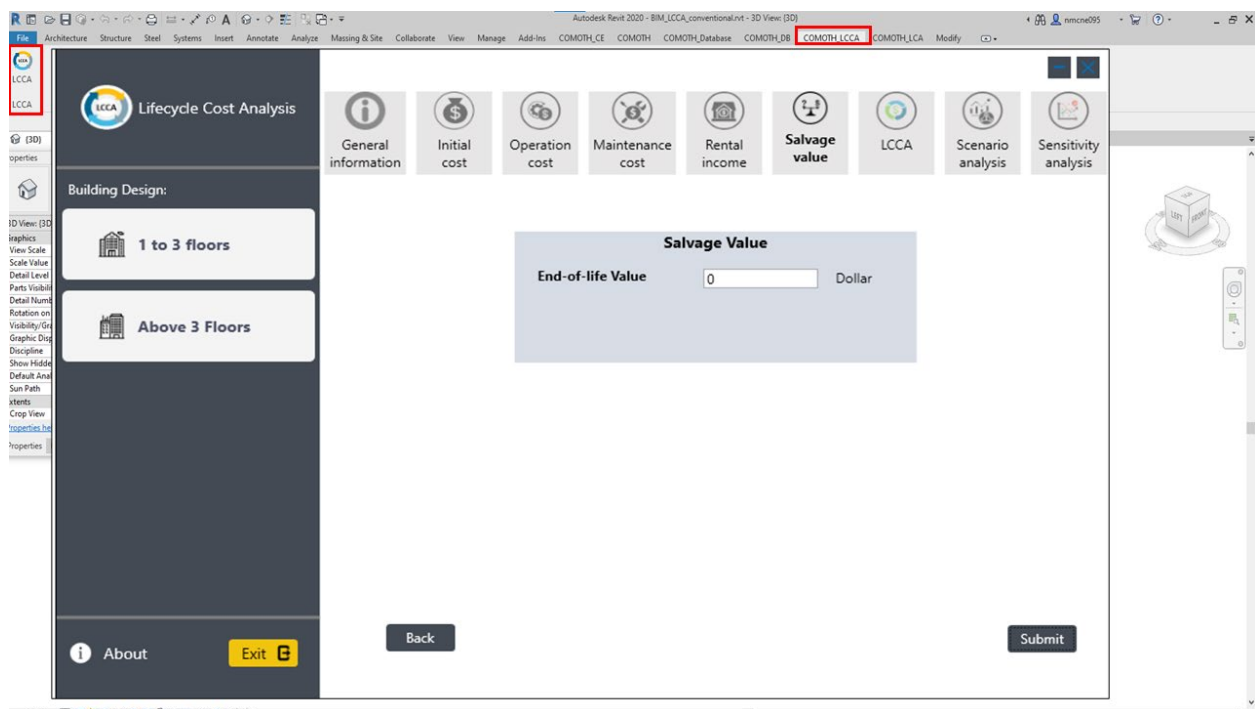


Figure 6.44 - Modeling salvage value/cost in LCCA module

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 reports, starting with LCCA reports, accessed by selecting the dropdown menu button to generate the cash flow diagram and the life cycle cost summary, as illustrated in Figures 6.45 and 6.46.

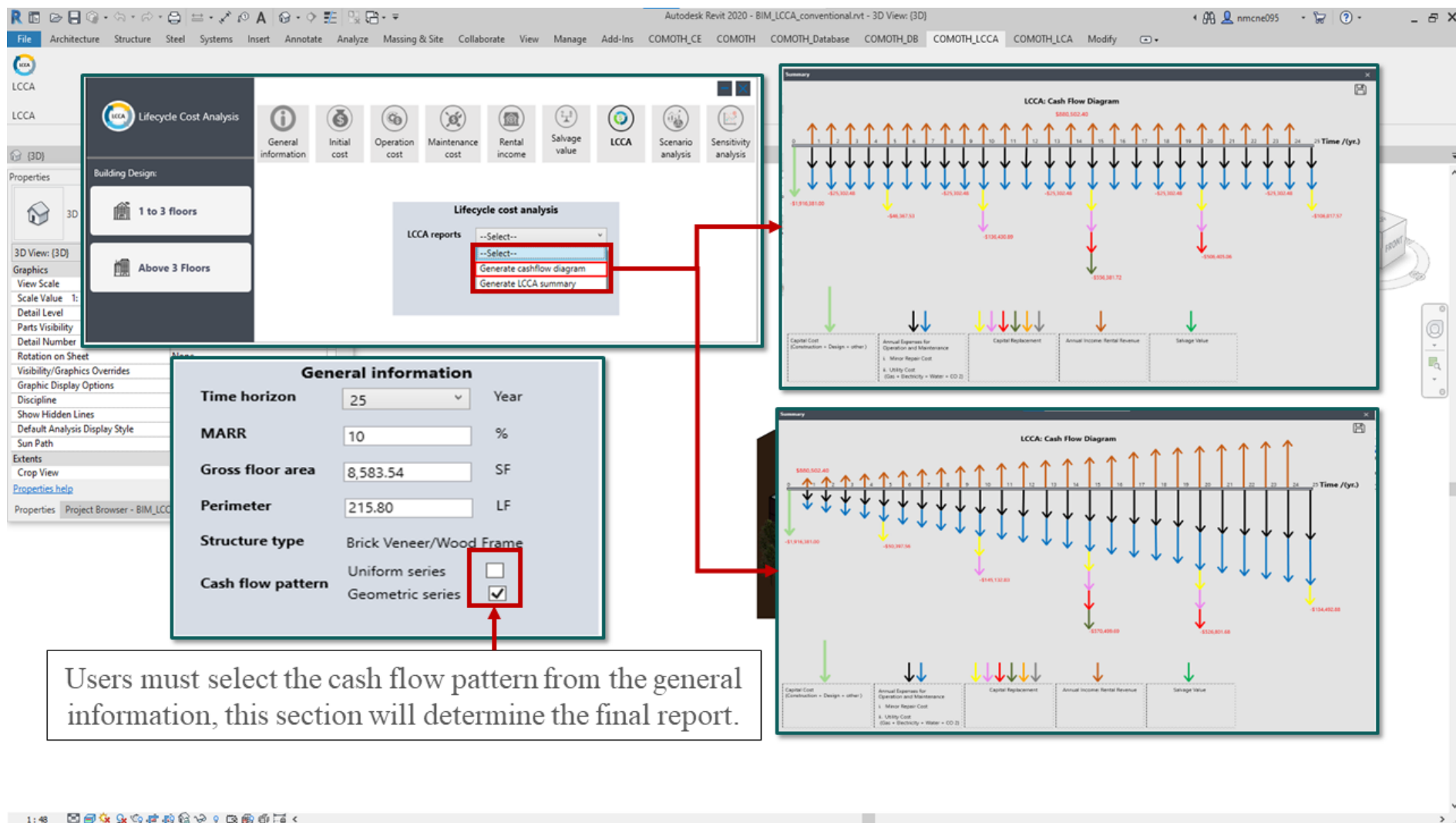


Figure 6.45 - Uniform and Geometric series cash flow patterns

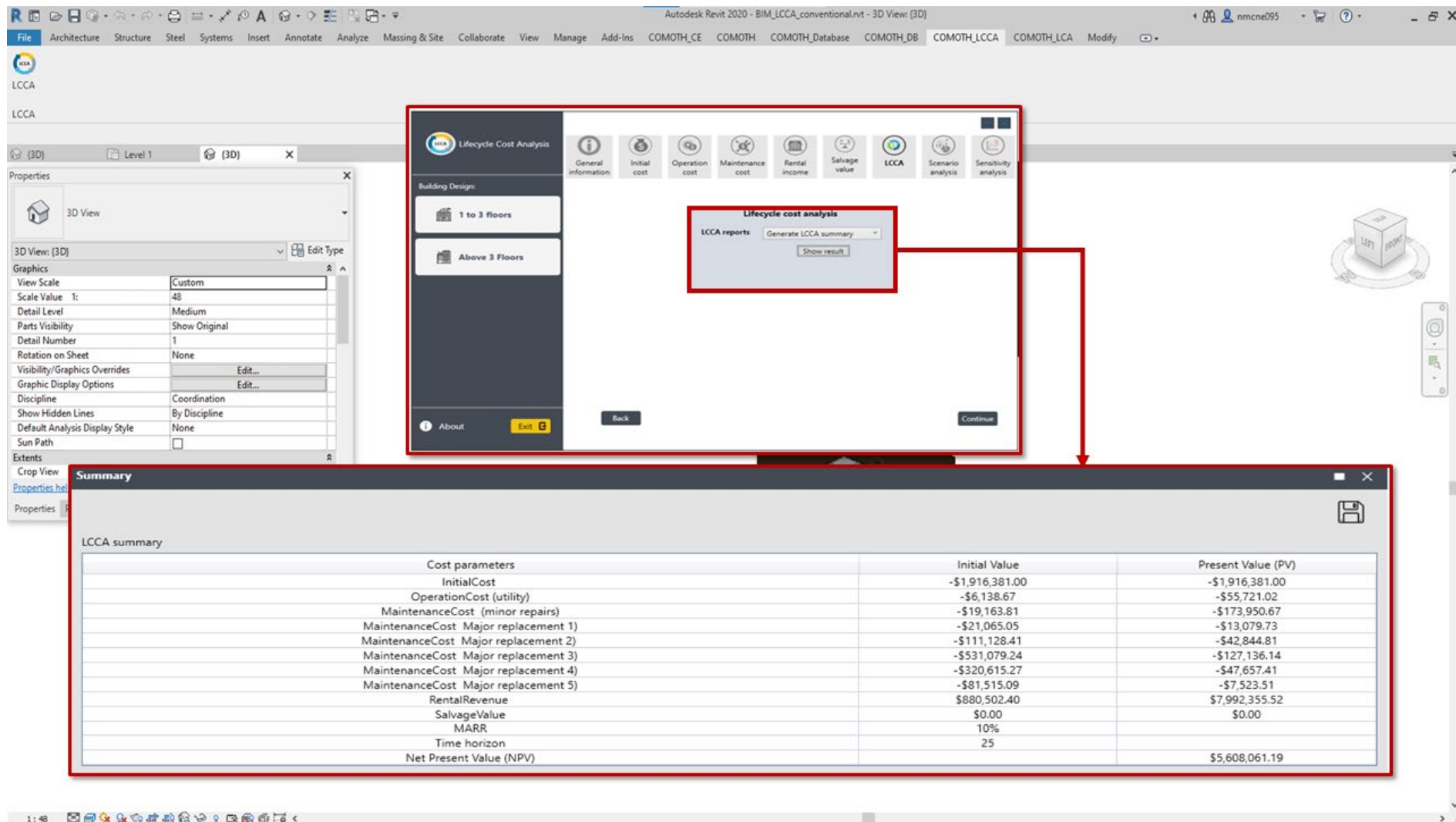


Figure 6.46 - Life cycle cost summary of the LCCA module

The cash flow diagram and the NPV are developed for the 25-year analysis period for the uniform and geometric series, as shown in Figure 6.45, 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 in testing the developed LCCA module, a 10% MARR is utilized to discount future cash flows, users have the flexibility to input an alternative discount value that aligns with their project requirements and objectives. However, it is important to note that a higher discount rate will result in a lower present value. Moreover, while the NPV evaluation raises uncertainty for most parameters, the influence of specific 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 module can aid users in implementing these assessments by selecting the scenarios analysis from the dropdown button to generate the LCCA scenarios and their corresponding NPV reports, as shown in Figure 6.47.

The LCCA module used the sensitivity analysis method to evaluate the sensitivity of all parameters using a range of errors based on a ± 25 percent range of the baseline net present value (NPV). Figure 6.48 shows the sensitivity analysis graph for the NPV of the rental revenue, MARR, and initial project 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 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 6.49.

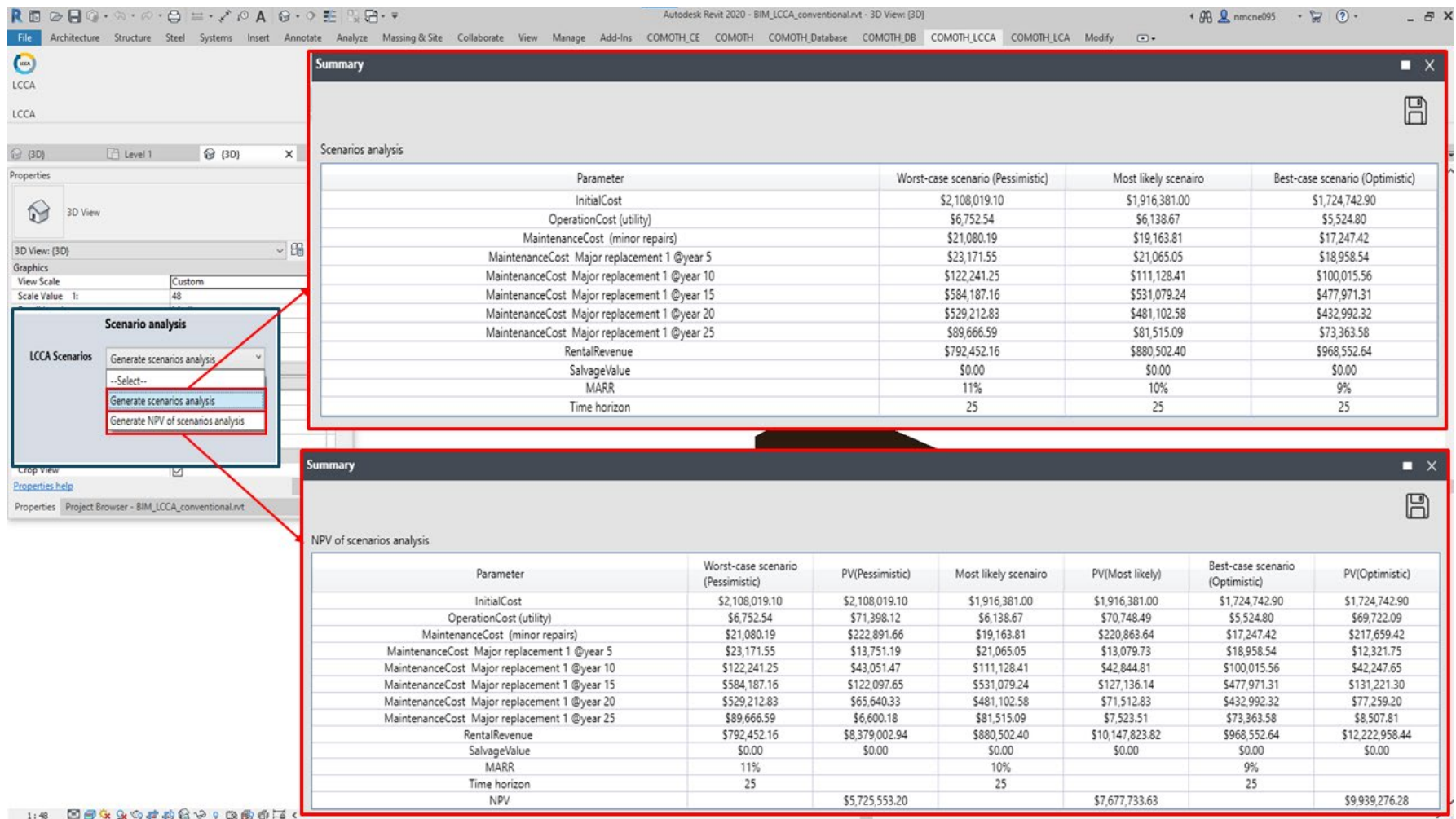


Figure 6.47 - LCC scenarios and their corresponding NPV reports

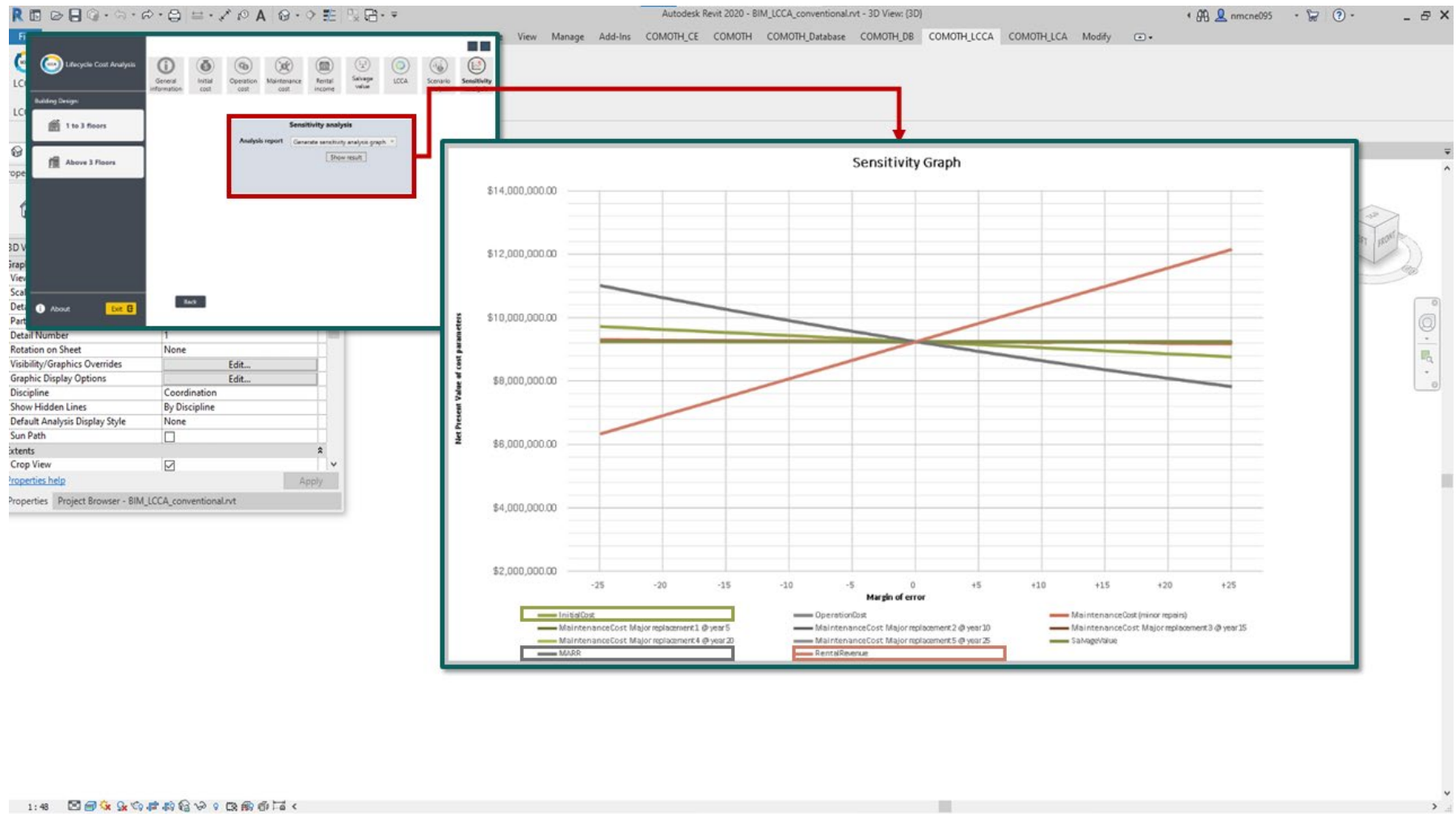


Figure 6.48 - Sensitivity analysis graph highlighting rental revenue, MARR, and initial project cost

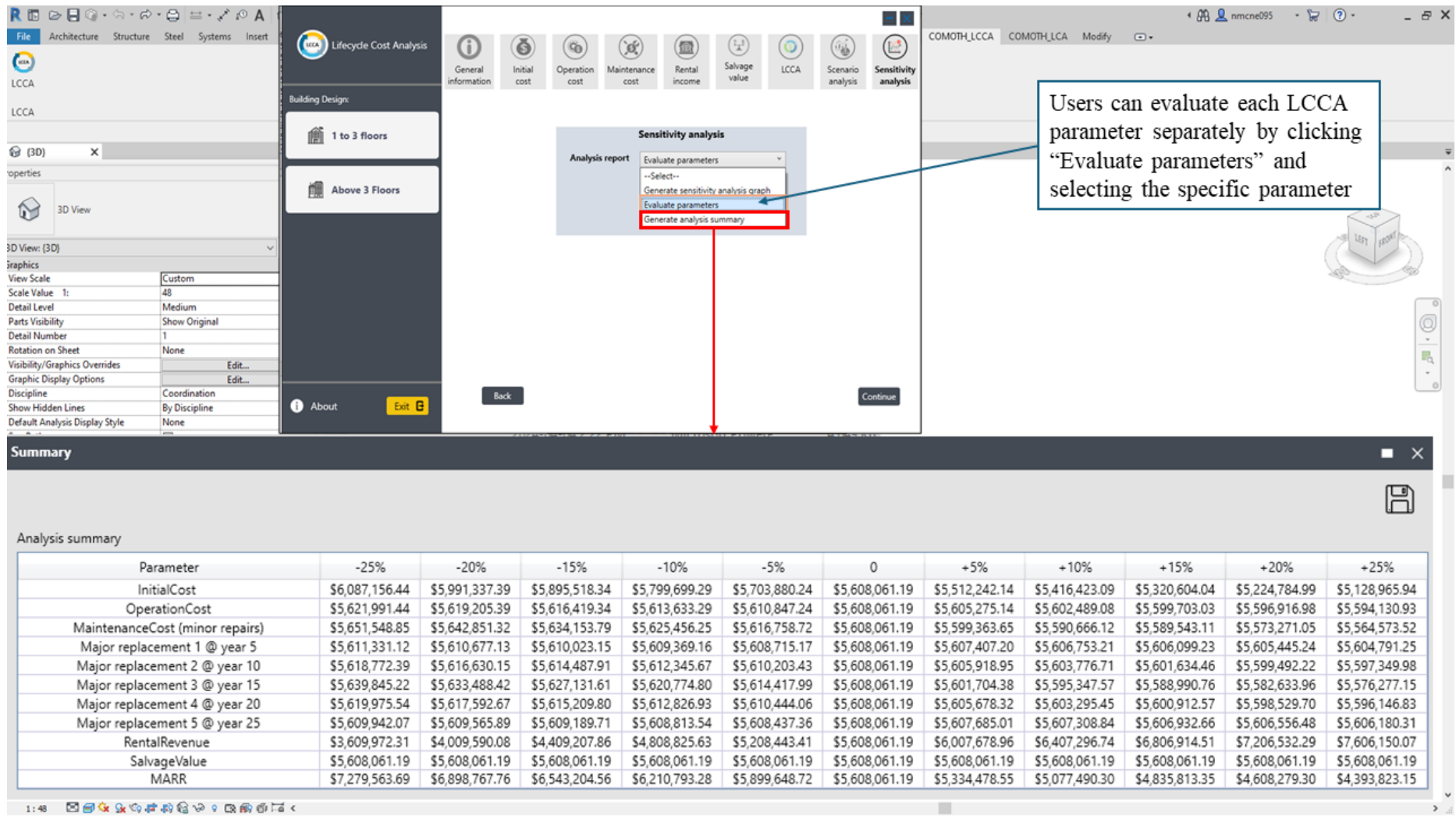


Figure 6.49 - Summary of sensitivity analysis

6.9 Evaluating the developed model

The integrated model developed in this study facilitates the automated evaluation and selection of associated construction methods via the integration of BIM-sustainability tools and data that aids designers in exploring various design alternatives, enabling them to make an informed decision about the most suitable construction methods early in the design process. This model adopts a “forward-thinking” approach that prioritizes sustainability and responsible resource management. It incorporates end-of-life considerations into the design stage of buildings by employing sustainability indicators and criteria, including circular economy principles, to enhance lifecycle construction sustainability at the design stage of buildings through: i) design (using design for deconstruction (DfD) concept that integrates the circular construction); ii) construction (using methods that standardize, prefabricated components and 3D concrete printing); and iii) end-of-life (using selective disassemble, circular economy for CDW management).

Nevertheless, comparing the developed model to an actual project is challenging due to the scarcity of data on real projects that have utilized 3D concrete printing techniques and design for deconstruction (DfD) principles in conjunction with modular prefabrication. Additionally, many existing models are primarily based on the 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. Furthermore, one can better understand the correctness of the model presented in this study by comparing it with

existing models found in the literature that integrated BIM with sustainability and/or sustainable design tools during the conceptual design phase. This comparative approach highlights several key advantages of the model as follows:

- Ability to integrate various construction methods, including conventional, modular, and 3D concrete printing.
- Efficiency in executing building designs for both 1-3 floors and more than 3-floors using the three construction methods.
- Effectiveness in implementing waste management strategies from the design phase to the end-of-life stages.
- Ability to equip designers with easily accessible predefined data, enhancing swift decision-making throughout the design process.
- Potential to conduct life cycle cost analysis using two different cash flow models: a uniform series of equal payments and a geometric series of payments, providing investors with improved insights.
- Capacity to assess the environmental impact associated with the life cycle stages of the three construction methods.
- Proficiency in conducting various energy demand/consumption analyses, including annual building performance, system analysis, and energy consumption involving electricity, natural gas, and district heating and cooling.

Those aspects collectively contribute to the model's strengths and completeness, which are essential considerations in advancing sustainability goals within the construction industry.

6.10 Summary

This chapter tested and verified the integrated model that is developed for selecting associated construction methods at the conceptual design stage of buildings based on the integration of BIM with sustainability tools in an attempt to develop a versatile and flexible model to help professionals during the early design stage. The presented model is designed in a modular format and consists of six modules: 1) a database management system (DBMS) module for collecting, storing and retrieving design data; 2) a decision support system (DSS) module; 3) an energy and thermal simulation module that facilitates the analysis of the energy performance of buildings; 4) a circular economy (CE) module for construction and deconstruction waste (CDW) management strategies; 5) a Lifecycle Assessment (LCA) module, which is used to evaluate the environmental impact of the various stages of the building project; 6) Lifecycle Cost Analysis (LCCA) module, to facilitate a detailed assessment of the financial implications of design options throughout its life cycle.

Each module is presented in a way that provides a clear idea about its capability, its functions, and its outcomes. Three identical 3D BIM conceptual case projects are used to test and verify the workability, functions, and performance of the different modules included in the integrated model development by using a three-story residential building project located in Ottawa, ON, Canada, which has its 3D BIM model(s) been created for the three building construction methods. The total gross area of the case project is 8,584 ft², with a perimeter of 216 LF, and it is currently under design. To accurately represent each building's characteristics, its associated materials were customized with additional parameters that defined their identity, appearance, graphics, as well as physical and thermal properties.

CHAPTER 7

Conclusion, Contributions, Limitations and Recommendations

7.1 Conclusion

This study aimed to develop a versatile and flexible integrated model for the selection of associated construction methods at the conceptual design stage of buildings based on the integration of BIM with sustainability tools to assist practitioners in making efficient and early design decisions.

The information on the construction processes, materials and methods to enhance the sustainability efforts, the requirements for integrating BIM and sustainability tools and the need to define the existing challenges and to align the project's objectives were drawn and established from an intense literature review, including published data. This study looked at the gaps and expectations of the AEC industry for a solution to the existing models that have their sustainability frameworks primarily based on conventional design and on-site construction methods and how the integration of BIM and sustainability tool would establish the groundwork for a flexible and practical solution for the process of selecting the suitable construction method at the conceptual design stage. Following this, a framework for integrating BIM and sustainability for a COMOTH model was established, followed by an analysis to determine the functionalities and requirements that could potentially be improved to achieve BIM-sustainability integration. After that, the integrated model was structured, designed and developed in a modular format comprising six primary modules. The development and design approach allow the integrated model to be flexible and user-friendly, empowering users to address several tasks of the COMOTH process efficiently and promptly. The six developed modules are database management system (DBMS); decision support system (DSS); energy and thermal simulation; circular (CE) economy for CDW management; lifecycle

assessment (LCA), and lifecycle cost analysis (LCCA). In order to achieve the development of the integrated BIM-sustainability model that is intended to aid in the selection of appropriate construction methods, the majority of functions within BIM tool (Autodesk Revit©) and various sustainability tools were customized by creating new functionalities as applications/extensions in the form of plugins, which were then activated through a user interface linkage to the BIM tool, serving as the central integration environment. Finally, the integrated model was tested and verified by using the described three identical 3D BIM case building projects (for conventional, modular and 3D concrete printing), and the developed model was proven to be capable of conducting the required evaluation, analysis, assessment and calculations related to the selection of the suitable construction method for buildings in an efficient and timely manner.

The BIM integrated model is distinguished through the following characteristics:

- Knowledge and information-intensive: it allows for a collaborative platform and a data-rich environment with information related to construction processes, materials and methods to enhance sustainability efforts, including design families in three separate databases that are collected, stored and used to improve the functionality of BIM tools based on the predefined criteria for effective performance of the whole building.
- Practical: it provides applicable and effective procedures that address real needs, challenges, and constraints while providing a complete solution for executing prompt calculations by applying available methods and tools (expressions, equations and Structured Query Language SQL) to complete the analysis, evaluation and simulations required for the integrated COMOTH environment.
- Flexible: The modular design of the integrated model enables its scalability, allowing for the seamless incorporation of additional modules and functions, whether derived from existing

literature or through future research efforts, thus further enhancing the integrated model. Furthermore, this feature empowers users to easily add and adjust data in a user-friendly manner.

- Efficient: it supports users in applying their knowledge and experience while using the model to accomplish various tasks that facilitate COMOTH processes throughout the design and selection of the different construction alternatives.
- Automatic: it provides users with instant support in data processing, decision-making, or execution of actions through the integration of the six primary modules that consist of the integrated model, hence enhancing the selection process for the best construction method that suits the provided adequate design parameters.

7.2 Research contribution

The contributions of this study emerge from the following:

1. Implementing a methodology for developing an integrated model to be used for the selection of associated construction methods at the conceptual design stage of buildings by linking BIM and sustainability tools. The model assists and engages professionals during the early design stage by supporting all evaluations, analyses, assessments, and calculations related to selecting the appropriate construction method for buildings through its detailed, intuitive, and practical design.
2. Designing a detailed, integrated BIM-sustainability tool, which consists of six modules: database management system (DBMS); decision support system (DSS); energy and thermal simulation; circular (CE) economy for CDW management; lifecycle assessment (LCA), and lifecycle cost analysis (LCCA). The model achieves data standardization, communication, interaction, testing, and verification, which covers the essential requirements and

functionalities for the COMOTH processes. It can also accommodate further modification and extension to include more modules and functions.

3. Developing a flexible model that presents to users a general range of options, including two design alternatives (one to three-floor and above three-floor designs); three construction method choices (conventional, modular, and 3D concrete printing); and specific for various waste handling equipment specifications (loaders, dumpers, and haulers); three equipment cost alternatives (buy, lease, and rental); and four waste disposal methods (bulk, recycling, reuse, and landfill) within two distinct lifecycle stages (construction and end-of-life).
4. Implementing a model that exhibits elements of the Industrial Production layer of Construction 4.0 within the integrated BIM-sustainability model (i.e., 3D printing, prefabrication, modularity, circular economy, and BIM) and incorporating design, construction and deconstruction at the conceptual stage through the integrated model.
5. Implementing an automatic approach to integrating various data that aligns with low carbon, sustainability, circular economy principles through energy analysis, life-cycle assessment, and life-cycle cost analysis to facilitate the execution of a complete assessment of the financial implications of a design option by considering their initial construction costs, long-term operational and maintenance costs, rental income and salvage value to empower designers expand their exploration of design options, provide a detailed economic viewpoint on a proposed building project investment and help stakeholders comprehend the enduring financial implications of design decisions.

7.3 Limitations of the current study

The results presented in this thesis have shown that the integrated model can be an effective tool to assist practitioners in making efficient decisions early during the design stage related to the selection of associated construction methods at the conceptual design stage of buildings based on the integration of BIM with sustainability tools. However, there are several limitations in the current study, which are:

- The model's implementation is centred around Autodesk Revit, which is widely adopted as a BIM tool in the AEC industry. However, experience and familiarity are necessary for optimal productivity, especially when transitioning to Revit for design integration. Furthermore, it is important to note that the developed model may not be compatible with other BIM tools.
- The model's analysis, development and testing scope focuses on using the three constructions to evaluate and justify environmental and economic sustainability indicators, associated criteria, and various sub-criteria. These include environmental impact, waste management, lifecycle cost analysis, building operational energy demand, and thermal comfort; hence, social sustainability is beyond the scope of this research.
- This study assumes that all the three identical 3D BIM model case projects used for testing and verification have a similar foundation; therefore, it excluded all substructural elements and associated materials for works below the floor slab.
- The DBMS module implementation is designed to handle data currently associated with the integrated model, therefore, further extension of the model's components may require an enhancement to the database, hence, there is a limitation in the collected data for this module.

- Interoperability problems between BIM and sustainability tools can lead to loss of information during the transition process, which affects the model's data management and analysis capabilities. In some cases, this often requires users to input data manually.
- The circular economy module is presently restricted to selecting specific types of construction equipment, namely loaders, dumpers, and haulers. This constraint restricts users from choosing from the model's predetermined equipment options.
- The model's implementation is limited to the design of 3D concrete printing buildings to three floors in this study, and the user should select three floors and above the design option from the user interface, the model will show an error message that reads “not compatible.”
- The LCA module is limited to the impact categories associated with the lifecycle stages of the three construction methods and has not studied or compared the impact of the individual construction material used in the different buildings.

7.4 Recommendations for future research

The following recommendations can be considered to enhance the developed model:

- Integrate the LEED building certification systems in the COMOTH process within the BIM sustainability model.
- Extend the developed model to include additional types of modules, data or analysis related to BIM and sustainability applications (such as CO2 emission accounting, decarbonization, net zero carbon, resilience and climate adaptation). Such topics are hotspots and useful in the construction sustainability process.
- Enable the model to perform combined analysis and selection of construction methods for all three options simultaneously rather than executing analysis individually.

- Included all substructural elements and associated materials for works below the floor slab as this study assumes that all three identical 3D BIM model case projects used for testing and verification have a similar foundation; therefore, the future can include all substructure element and their material.
- Develop a seamless integration of a broad database capable of storing detailed information pertaining to a wider range of construction equipment from various manufacturers in North America, including their specific data required for analysis, such as production rates, specifications, and cost parameters etc., adding these data will enhance the model substantially, extend its functionality, and augment its capacity to facilitate decision-making in planning and managing construction material waste.
- Integrate weather files for various regions in North America in the energy and thermal simulation module, which can provide a realistic simulation result for users outside of the model design location.

CHAPTER 8

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Appendix I - Codes for developing plug-ins of the modules using Microsoft Visual Studio

Codes for developing the DSS module

```
15 [TransactionAttribute(TransactionMode.Manual)]
16 public class CurveTotalLength : IExternalCommand
17 {
18
19     static AddInId appId = new AddInId(new Guid("7C5D7460-D323-4EE0-BB3A-66DB7FB00222"));
20     public Result Execute(ExternalCommandData commandData, ref string message, ElementSet elements)
21     {
22         Form1 frm = new Form1();
23         frm.Show();
24         return Result.Succeeded;
25     }
26 }
27 public class supplierClass
28 {
29     public string CriteriaName { get; set; }
30     public string LowerFuzzyNumber { get; set; }
31     public string MiddleFuzzyNumber { get; set; }
32     public string UpperFuzzyNumber { get; set; }
33     public string Weight { get; set; }
34 }
35 class Program
36 {
37     public List<T> GetList<T>(ExcelWorksheet sh)
38     {
39         List<T> lis = new List<T>();
40         var columninfo = Enumerable.Range(1, sh.Dimension.Columns).ToList().Select(n =>
41             new { Index = n, ColumnName = sh.Cells[1, n].Value.ToString() }
42         );
43         if (!(sh.Cells[2, 1].Value == null))
44         {
45             for (int row = 2; row <= sh.Dimension.Rows; row++)
46             {
47                 T obj = (T)Activator.CreateInstance(typeof(T)); //generic object
48                 foreach (var prop in typeof(T).GetProperties())
49                 {
50                     int col = columninfo.SingleOrDefault(c => c.ColumnName == prop.Name).Index;
51                     var val = sh.Cells[row, col].Value;
52                     var proptype = prop.PropertyType;
53                     prop.SetValue(obj, Convert.ChangeType(val, proptype));
54                 }
55                 lis.Add(obj);
56             }
57         }
58     }
59 }
```



```

56     }
57 }
58 return lis;
59 }
60
61 public List<T> GetListDefault<T>(ExcelWorksheet sh)
62 {
63     List<T> lis = new List<T>();
64     var columninfo = Enumerable.Range(1, 2).ToList().Select(n =>
65         new { Index = n, ColumnName = sh.Cells[4, n].Value.ToString() }
66     );
67     for (int row = 5; row <= sh.Dimension.Rows; row++)
68     {
69         T obj = (T)Activator.CreateInstance(typeof(T)); //generic object
70         foreach (var prop in typeof(T).GetProperties())
71         {
72             int col = columninfo.SingleOrDefault(c => c.ColumnName == prop.Name).Index;
73             var val = sh.Cells[row, col].Value;
74             var proptype = prop.PropertyType;
75             prop.SetValue(obj, Convert.ChangeType(val, proptype));
76         }
77         lis.Add(obj);
78     }
79     return lis;
80 }
81
82 }
83 [TransactionAttribute(TransactionMode.Manual)]
84 public class CurveTotalLength2 : IExternalCommand
85 {
86     public Result Execute(ExternalCommandData commandData, ref string message, ElementSet elements)
87     {
88
89
90         NewForm1 frm = new NewForm1(commandData);
91         frm.ShowDialog();
92         return Result.Succeeded;
93     }
94 }
95

```

```

70 public void copypaste(ExcelWorksheet sh, int a, int b, int f, int g, string s)
71 {
72     for (int i = 1; i <= a; i++)
73     {
74         for (int c = 1; c <= b; c++)
75         {
76             sh.Cells[i + f, c + g].Value = sh.Cells[s].Value;
77         }
78     }
79 }
80
81 public void row(ExcelWorksheet sh, int a, int b)
82 {
83     sh.Cells[a, b].Value = "EI";
84     sh.Cells[a + 1, b].Value = "E&A";
85     sh.Cells[a + 2, b].Value = "M&R";
86     sh.Cells[a + 3, b].Value = "CO";
87     sh.Cells[a + 4, b].Value = "TI";
88     sh.Cells[a + 5, b].Value = "CE";
89     sh.Cells[a + 6, b].Value = "IEQ";
90     sh.Cells[a + 7, b].Value = "DI";
91 }
92
93 public void column(ExcelWorksheet sh, int a, int b)
94 {
95     sh.Cells[a, b].Value = "EI";
96     sh.Cells[a, b + 1].Value = "E&A";
97     sh.Cells[a, b + 2].Value = "M&R";
98     sh.Cells[a, b + 3].Value = "CO";
99     sh.Cells[a, b + 4].Value = "TI";
100    sh.Cells[a, b + 5].Value = "CE";
101    sh.Cells[a, b + 6].Value = "IEQ";
102    sh.Cells[a, b + 7].Value = "DI";
103 }
104
105 public void Danp(ExcelWorksheet sh, int r, int c, int rs, int cs)
106 {
107     switch (sh.Cells[r, c].Value.ToString())
108     {
109         case "VHI":
110             sh.Cells[rs, cs].Value = 0.75;
111             sh.Cells[rs, cs + 1].Value = 1;
112             sh.Cells[rs, cs + 2].Value = 1;
113             break;
114         case "HI":
115             sh.Cells[rs, cs].Value = 0.5;
116             sh.Cells[rs, cs + 1].Value = 0.75;
117             sh.Cells[rs, cs + 2].Value = 1;
118             break;
119         case "LI":
120             sh.Cells[rs, cs].Value = 0.25;

```

```

121         sh.Cells[rs, cs + 1].Value = 0.5;
122         sh.Cells[rs, cs + 2].Value = 0.75;
123         break;
124     case "VLI":
125         sh.Cells[rs, cs].Value = 0;
126         sh.Cells[rs, cs + 1].Value = 0.25;
127         sh.Cells[rs, cs + 2].Value = 0.5;
128         break;
129     case "NOI":
130         sh.Cells[rs, cs].Value = 0;
131         sh.Cells[rs, cs + 1].Value = 0;
132         sh.Cells[rs, cs + 2].Value = 0.25;
133         break;
134     default:
135         sh.Cells[rs, cs].Value = 0;
136         sh.Cells[rs, cs + 1].Value = 0;
137         sh.Cells[rs, cs + 2].Value = 0.25;
138         break;
139     }
140 }
141
142
143
144 public void WF(ExcelWorksheet sh, int r, int c, int rs, int cs)
145 {
146     switch (sh.Cells[r, c].Value.ToString())
147     {
148     case "VH":
149         sh.Cells[rs, cs].Value = 7;
150         sh.Cells[rs, cs + 1].Value = 9;
151         sh.Cells[rs, cs + 2].Value = 9;
152         break;
153     case "H":
154         sh.Cells[rs, cs].Value = 5;
155         sh.Cells[rs, cs + 1].Value = 7;
156         sh.Cells[rs, cs + 2].Value = 9;
157         break;
158     case "M":
159         sh.Cells[rs, cs].Value = 3;
160         sh.Cells[rs, cs + 1].Value = 5;
161         sh.Cells[rs, cs + 2].Value = 7;
162         break;
163     case "L":
164         sh.Cells[rs, cs].Value = 1;
165         sh.Cells[rs, cs + 1].Value = 3;
166         sh.Cells[rs, cs + 2].Value = 5;
167         break;
168     case "VL":
169         sh.Cells[rs, cs].Value = 1;
170         sh.Cells[rs, cs + 1].Value = 1;
171         sh.Cells[rs, cs + 2].Value = 3;
172         break;

```

```

210
211 private void button4_Click(object sender, EventArgs e)
212 {
213     UIApplication uiApp = commandData.Application;
214     UIDocument uidoc = uiApp.ActiveUIDocument;
215     Document doc = uidoc.Document;
216     Autodesk.Revit.ApplicationServices.Application app = uiApp.Application;
217     string fileman = @"C:\DSS\DSSRate.xlsx";
218     if (File.Exists(fileman) == false)
219     {
220         TaskDialog.Show("Error Implemntation", "please implement Danp Fuzzy and Element Take off plugins");
221     }
222     else
223     {
224         if (IsFileInUse(fileman))
225         {
226             TaskDialog.Show("File in Use", " Please close excel file");
227         }
228         else
229         {
230             using (ExcelPackage package = new ExcelPackage(new FileInfo(fileman)))
231             {
232
233                 //ExcelWorksheet sheet = package.Workbook.Worksheets["DANPFuzzyRate"];
234                 ExcelWorksheet sheet1 = package.Workbook.Worksheets["Door"];
235                 ExcelWorksheet sheet2 = package.Workbook.Worksheets["Wall"];
236                 ExcelWorksheet sheet3 = package.Workbook.Worksheets["Windows"];
237                 ExcelWorksheet sheet4 = package.Workbook.Worksheets["Ceiling"];
238                 ExcelWorksheet sheet5 = package.Workbook.Worksheets["Floor"];
239
240
241                 //Wall---//////////////////////////////////////
242
243                 int re = sheet2.Dimension.Rows;
244                 int count = 4;
245                 for (int i = 5; i <= re; i++)
246                 {
247                     if (!(sheet2.Cells[i, 1].Value == null))
248                     {
249                         count++;
250                     }
251                 }
252                 sheet2.Cells[count + 1, 4, 1000, 1000].Clear();
253                 package.Save();
254
255
256
257

```

```

261
262
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312

int f = sheet2.Dimension.Rows;

int num = sheet2.Dimension.Rows - 4;
//int i = 1;
for (int i = 5; i <= f; i++)
{
    if (!(sheet2.Cells[i, 5].Value == null))
        WF(sheet2, i, 5, f + 3 + i - 5, 5);
    if (!(sheet2.Cells[i, 6].Value == null))
        WF(sheet2, i, 6, f + 3 + i - 5, 8);
    if (!(sheet2.Cells[i, 7].Value == null))
        WF(sheet2, i, 7, f + 3 + i - 5, 11);
    if (!(sheet2.Cells[i, 8].Value == null))
        WF(sheet2, i, 8, f + 3 + i - 5, 14);
    if (!(sheet2.Cells[i, 9].Value == null))
        WF(sheet2, i, 9, f + 3 + i - 5, 17);
    if (!(sheet2.Cells[i, 10].Value == null))
        WF(sheet2, i, 10, f + 3 + i - 5, 20);
    if (!(sheet2.Cells[i, 11].Value == null))
        WF(sheet2, i, 11, f + 3 + i - 5, 23);
    if (!(sheet2.Cells[i, 12].Value == null))
        WF(sheet2, i, 12, f + 3 + i - 5, 26);

    //sheet.Cells[32, 9].Value=1;
    try
    {
        package.Save();
    }
    catch (Exception)
    {
    }
}

int h = sheet2.Dimension.Rows;
sheet2.Cells[h + 2, 4].Value = "Min";
sheet2.Cells[h + 3, 4].Value = "Max";
package.Save();
int fi = sheet2.Dimension.Rows;
if (!(sheet2.Cells[1, 5].Value == null) && sheet2.Cells[1, 5].Value.Equals("p"))
{
    sheet2.Cells[h + 3, 7].Formula = "MAX(G" + (f + 3) + ":G" + h + ")";
    sheet2.Cells[h + 3, 7].Calculate();
    for (int i = 1; i <= num; i++)
    {
        for (int c = 1; c <= 3; c++)
        {
            sheet2.Cells[fi + 1 + i, c + 4].Value = Convert.ToDouble(sheet2.Cells[

```

Codes for developing energy and thermal simulation module.

```
16 namespace RevitAddIn {
17     1 reference
18     public class ExternalApplication : IExternalApplication {
19
20         private string pluginTabName = "COMOTH";
21         private string PanelName = "ESM";
22
23         private string PipeName = "pipe.server";
24         //private static PipeServer PipeServer = null;
25
26         0 references
27         Result IExternalApplication.OnShutdown(UIControlledApplication application) {
28             try {
29                 ExternalApplication.CloseApp();
30             } catch (System.Exception) {
31             }
32             return Result.Succeeded;
33         }
34
35         0 references
36         Result IExternalApplication.OnStartup(UIControlledApplication application) {
37             try {
38                 // create a tab in the revit toolbar
39                 RevitUIFactory.AddRibbonTab(application, this.pluginTabName);
40
41                 List<RibbonPanel> panels = application.GetRibbonPanels(this.pluginTabName);
42                 RibbonPanel EPPanel = panels.FirstOrDefault(x => x.Name == this.PanelName);
43                 if (EPPanel == null)
44                     EPPanel = application.CreateRibbonPanel(this.pluginTabName, this.PanelName);
45                 else
46                     EPPanel.AddSeparator();
47
48                 PushButtonData btn =
49                     new PushButtonData(
50                         "esm",
51                         "ESM",
52                         Assembly.GetExecutingAssembly().Location,
53                         typeof(EnergySimulationCommand).FullName
54                     );
55                 //Uri uriImage = new Uri(Path.Combine(
56                 //    new FileInfo(Assembly.GetExecutingAssembly().FullName).DirectoryName,
57                 //    "icon.png"));
```

```

17 namespace RevitAddIn {
18     public class ExternalApplication : IExternalApplication {
19
20         private string pluginTabName = "Comoth";
21         private string PanelName = "COMOTH Panel";
22
23         private string PipeName = "pipe.server";
24         //private static PipeServer PipeServer = null;
25
26
27         Result IExternalApplication.OnShutdown(UIControlledApplication application) {
28             try {
29                 ExternalApplication.CloseApp();
30             } catch (System.Exception) {
31             }
32             return Result.Succeeded;
33         }
34
35         Result IExternalApplication.OnStartup(UIControlledApplication application) {
36             try {
37
38                 //ExternalApplication.PipeServer = new PipeServer(this.PipeName);
39                 //ExternalApplication.PipeServer.OnConnect += Ps_OnConnect;
40                 //ExternalApplication.PipeServer.MessageReceived += Ps_MessageReceived;
41                 //ExternalApplication.PipeServer.OnDisconnect += Ps_OnDisconnect;
42                 //ExternalApplication.PipeServer.OpenConnection();
43
44                 // create a tab in the revit toolbar
45                 RevitUIFactory.AddRibbonTab(application, this.pluginTabName);
46
47
48                 List<RibbonPanel> panels = application.GetRibbonPanels(this.pluginTabName);
49                 RibbonPanel EPPanel = panels.FirstOrDefault(x => x.Name == this.PanelName);
50                 if (EPPanel == null)
51                     EPPanel = application.CreateRibbonPanel(this.pluginTabName, this.PanelName);

```

```

11 namespace EPParsers
12 {
13     3 references
14     public class Runner
15     {
16         string exec = "energyplus";
17         string idfFilePath;
18         string weatherFilePath;
19         string outputDir;
20
21         public event DataReceivedEventHandler processOutputDataReceivedHandler;
22
23         /// <summary>
24         /// this variable has been set to false to prevent extra data being printed
25         /// such as "D:/..." and so forth
26         /// </summary>
27         private bool shouldDispatchEvent = false;
28         1 reference
29         public Runner(string idfFilePath, string weatherFilePath, string outputDir = null)
30         {
31             this.idfFilePath = idfFilePath;
32             this.weatherFilePath = weatherFilePath;
33             this.outputDir = outputDir ?? "";
34         }
35         1 reference
36         string makeCommand()
37         {
38             StringBuilder sb = new StringBuilder(this.exec);
39             sb.Append(" -w ").Append(this.weatherFilePath);
40
41             // checks if the output was not empty, output dir should be added to command line
42             if (!String.IsNullOrEmpty(this.outputDir)) sb.Append(" -d ").Append(this.outputDir);
43
44             sb.Append(" ").Append(this.idfFilePath);
45             return sb.ToString();
46         }
47         1 reference
48         public int runCommand()
49         {
50             string command = this.makeCommand();
51             Process process = new Process();
52             process.StartInfo.FileName = "cmd.exe";
53             // process.StartInfo.CreateNoWindow = true;
54             process.StartInfo.RedirectStandardInput = true;
55             process.StartInfo.RedirectStandardOutput = true;
56             process.StartInfo.UseShellExecute = false;
57
58             // event to catch output data emitted from energyplus process
59             process.OutputDataReceived += processOutputHandler;

```



```

58     process.Start();
59
60     // start event for data receiving
61     process.BeginOutputReadLine();
62
63     // next three line is for executing energy plus command
64     process.StandardInput.WriteLine(command);
65     process.StandardInput.Flush();
66     process.StandardInput.Close();
67     process.WaitForExit();
68     // Console.Write(process.StandardOutput.ReadToEnd());
69
70     // this exit code shows the result of calculating
71     int exitCode = process.ExitCode;
72     // process.Close();
73
74     return exitCode;
75 }
76
77 1 reference
78 void processOutputHandler(object sender, DataReceivedEventArgs e)
79 {
80     // checks if event should be dispatched
81     if (this.shouldDispatchEvent)
82         this.processOutputDataReceivedHandler?.Invoke(sender, e);
83     else
84     {
85         // regular expresion to check if this line is the start of the energyplus command
86         Regex re = new Regex(@"^\.:[\\\/]");
87         if (re.IsMatch(e.Data))
88             this.shouldDispatchEvent = true;
89     }
90 }
91 }

```

Codes for developing Circular Economy module

```
11 namespace CDW_UI.ViewModel
12 {
13     public class CDW_MainViewModel : ViewModelBase
14     {
15         MainWindow _mainWindow = null;
16         const string _home = "Home";
17         const string str = "and Construction Methods";
18         const string _3Floor = "1-3 Floors "+str;
19         const string _above3Floor = "Above 3 Floors "+str;
20         const string _about = "About";
21
22         private ViewModelBase contentViewModel;
23         public ViewModelBase ContentViewModel
24         {
25             get { return contentViewModel; }
26             set
27             {
28                 contentViewModel = value;
29                 RaisePropertyChanged();
30             }
31         }
32
33         private ImageSource _SourceImgPath;
34         public ImageSource SourceImgPath
35         {
36             get { return _SourceImgPath; }
37             set
38             {
39                 _SourceImgPath = value;
40                 RaisePropertyChanged();
41             }
42         }
43
44         private string _Content;
45         public string Content
46         {
47             get { return _Content; }
48             set
49             {
50                 _Content = value;
51                 RaisePropertyChanged();
52             }
53         }
54
55         Commands
56     }
57 }
58
59
60
61
62
63
64
```

```

65 public CDW_MainViewModel(MainWindow mainWindow)
66 {
67     _mainWindow = mainWindow;
68     Floors1_3Command = new RelayCommand(Floors1_3CommandHandler);
69     AboutCommand = new RelayCommand(AboutCommandHandler);
70     ExitCommand = new RelayCommand(ExitCommandHandler);
71     ResetCommand = new RelayCommand(ResetCommandHandler);
72     CancelCommand = new RelayCommand(CancelCommandHandler);
73     Above3FloorsCommand = new RelayCommand(Above3FloorsCommandHandler);
74
75     HomeIconAndContent();
76 }
77
78 private void Above3FloorsCommandHandler(object obj)
79 {
80     ShowFloorsView(obj, true);
81 }
82
83 private void CancelCommandHandler(object obj)
84 {
85     _mainWindow.Close();
86 }
87
88 private void ResetCommandHandler(object obj)
89 {
90     HomeIconAndContent();
91 }
92
93 private void HomeIconAndContent()
94 {
95     ContentViewModel = new HomeViewModel();
96     Content = _home;
97     SourceImgPath = new BitmapImage(new Uri("pack://application:,,,/CDW_UI;component/Resources/Home.png"));
98 }
99
100 private void ExitCommandHandler(object obj)
101 {
102     _mainWindow.Close();
103 }
104
105 private void AboutCommandHandler(object obj)
106 {
107     this.ContentViewModel = new AboutViewModel();
108     Content = _about;
109     SourceImgPath = new BitmapImage(new Uri("pack://application:,,,/CDW_UI;component/Resources/About.png"));
110 }
111
112 private void Floors1_3CommandHandler(object obj)
113 {
114     ShowFloorsView(obj, false);
115 }

```

Codes for developing Google Maps interface

```
namespace CDW_UI.ViewModel {  
  
    /// <summary>  
    /// GMapViewModel  
    /// </summary>  
    public partial class GMapViewModel : System.Windows.Controls.UserControl, System.Windows.Markup.IComponentConnector {  
  
        private bool _contentLoaded;  
  
        /// <summary>  
        /// InitializeComponent  
        /// </summary>  
        [System.Diagnostics.DebuggerNonUserCodeAttribute()]  
        [System.CodeDom.Compiler.GeneratedCodeAttribute("PresentationBuildTasks", "4.0.0.0")]  
        public void InitializeComponent() {  
            if (_contentLoaded) {  
                return;  
            }  
            _contentLoaded = true;  
            System.Uri resourceLocater = new System.Uri("/CDW_UI;component/viewmodel/gmapviewmodel.xaml", System.UriKind.Relative);  
  
            #line 1 "..\\..\\..\\ViewModel\\GMapViewModel.xaml"  
            System.Windows.Application.LoadComponent(this, resourceLocater);  
  
            #line default  
            #line hidden  
        }  
  
        [System.Diagnostics.DebuggerNonUserCodeAttribute()]  
        [System.CodeDom.Compiler.GeneratedCodeAttribute("PresentationBuildTasks", "4.0.0.0")]  
        [System.ComponentModel.EditorBrowsableAttribute(System.ComponentModel.EditorBrowsableState.Never)]  
        [System.Diagnostics.CodeAnalysis.SuppressMessageAttribute("Microsoft.Design", "CA1033:InterfaceMethodsShouldBeCallableByChildTypes")]  
        [System.Diagnostics.CodeAnalysis.SuppressMessageAttribute("Microsoft.Maintainability", "CA1502:AvoidExcessiveComplexity")]  
        [System.Diagnostics.CodeAnalysis.SuppressMessageAttribute("Microsoft.Performance", "CA1800:DoNotCastUnnecessarily")]  
        void System.Windows.Markup.IComponentConnector.Connect(int connectionId, object target) {  
            this._contentLoaded = true;  
        }  
    }  
}
```

```

11 namespace CDW_RevitPlugin.COMOTH.EXCEL_CALCS
12 {
13     class ExcelReadWrite
14     {
15     public static System.Data.DataTable ReadExcel(ExcelApplication excelApp, Workbook workBook, int sheetIndex, string cellRange1
16     {
17         System.Data.DataTable dataTable = new System.Data.DataTable();
18         System.Data.DataTable dataTable2 = new System.Data.DataTable();
19
20         //ExcelApplication excelApp = new ExcelApplication();
21         //Workbook workBook;
22         Worksheet workSheet;
23         Range range;
24         Range range2;
25
26         //workBook = excelApp.Workbooks.Open(filePath);
27         workSheet = workBook.Worksheets[sheetIndex];
28
29         if(cellRange2 == null)
30         {
31             range = workSheet.Range[cellRange1];
32             //range2 = null;
33
34             // DATA TABLE 1
35             // Populate excel range columns headers data into DataTable
36             for (int i = 1; i <= range.Columns.Count; i++)
37             {
38                 DataColumn column = new DataColumn(range.Cells[1, i].Value);
39                 dataTable.Columns.Add(column);
40             }
41
42             // Add the data rows to the DataTable
43             for (int i = 2; i <= range.Rows.Count; i++)
44             {
45                 DataRow row = dataTable.NewRow();
46                 for (int j = 1; j <= range.Columns.Count; j++)
47                 {
48                     row[j - 1] = range.Cells[i, j].Value;
49                 }
50                 dataTable.Rows.Add(row);
51             }
52
53             return dataTable;
54         }
55         else
56         {
57             range = workSheet.Range[cellRange1];
58             range2 = workSheet.Range[cellRange2];
59

```

```

10 namespace CDW_RevitPlugin.COMOTH.COMMAND
11 {
12     [TransactionAttribute(TransactionMode.Manual)]
13     public class NK_MainForm_Command : IExternalCommand
14     {
15         public class WindowHandle : IWin32Window
16         {
17             IntPtr _hwnd;
18             public WindowHandle(IntPtr h)
19             {
20                 _hwnd = h;
21             }
22             public IntPtr Handle
23             {
24                 get
25                 {
26                     return _hwnd;
27                 }
28             }
29         }
30
31         public static WindowHandle _hwndRevit = null;
32
33         public void SetHandle()
34         {
35             if (null == _hwndRevit)
36             {
37                 Process[] processes = Process.GetProcessesByName("Revit");
38
39                 if (0 < processes.Length)
40                 {
41                     IntPtr h = processes[0].MainWindowHandle;
42                     _hwndRevit = new WindowHandle(h);
43                 }
44             }
45         }
46
47         public Result Execute(ExternalCommandData commandData, ref string message, ElementSet elements)
48         {
49             UIApplication uiApp = commandData.Application;
50             UIDocument uidoc = uiApp.ActiveUIDocument;
51             Document doc = uidoc.Document;
52
53             using (System.Windows.Forms.Form form = new NK_IntroForm(doc, uiApp))
54             {
55                 SetHandle();
56
57                 if (_hwndRevit != null)
58                 {
59                     form.ShowDialog();
60                 }
61             }
62         }
63     }
64 }

```

Codes for developing LCA module

```

12 namespace LCA.Register
13 {
14     internal class RevitApp : IExternalApplication
15     {
16         public static RevitApp Instance;
17         public IntroWindow Form;
18         //public MainView Form;
19         //public ExternalEvent CreateLCA;
20
21         public Result OnStartup(UIControlledApplication application)
22         {
23             string assemblyName = Assembly.GetExecutingAssembly().Location;
24
25             string path = System.IO.Path.GetDirectoryName(assemblyName);
26
27
28             Instance = this;
29             string tabName = "COMOTH_LCA";
30             string panelName = "LCA";
31             string buttonName = "LCA";
32             string imagePath = "pack://application:,,,/LCA;component/Images/LogoNew.png";
33
34             try
35             {
36                 try
37                 {
38                     // Create Ribbon Tab
39                     application.CreateRibbonTab(tabName);
40                 }
41                 catch (Exception)
42                 {
43                     // ignored
44                 }
45
46                 try
47                 {
48                     application.CreateRibbonPanel(tabName, panelName);
49                 }
50                 catch (Exception)
51                 {
52                     // ignored
53                 }
54
55                 // Create Button Data
56                 PushButtonData button = new PushButtonData(buttonName, buttonName, assemblyName, typeof(Command).FullName);
57
58                 // Create Ribbon Panel
59                 RibbonPanel panel = application.GetRibbonPanels(tabName).FirstOrDefault(x => x.Name == panelName);
60
61                 // Adding Button image
62                 PushButton push = panel.AddItem(button) as PushButton;
63                 push.LargeImage = new BitmapImage(new Uri(imagePath));
64
65                 //var handler = new LCAHandler();

```

```

66             return Result.Succeeded;
67         }
68         catch (Exception ex)
69         {
70             TaskDialog.Show("Exception while creating Ribbon", ex.Message);
71             return Result.Failed;
72         }
73     }
74
75     public Result OnShutdown(UIControlledApplication application)
76     {
77         return Result.Succeeded;
78     }
79
80     public void ShowForm()
81     {
82         Form = new IntroWindow();
83         //CreateLCA = ExternalEvent.Create(new RegisterHandler());
84         Form.Show();
85     }
86
87     public void DisposeForm()
88     {
89         Form = null;
90         //CreateLCA = null;
91     }
92 }

```

```

28 namespace LCA.Helper
29 {
30     internal class HelperDb
31     {
32         static ObservableCollection<DataItem> DataItems_3dPrinting = new ObservableCollection<DataItem>();
33         static ObservableCollection<ObservableCollection<DataItem>> DataItems_Modular = new ObservableCollection<ObservableCollection<DataItem>>();
34         static ObservableCollection<ObservableCollection<DataItem>> DataItems_Conventional = new ObservableCollection<ObservableCollection<DataItem>>();
35         static ObservableCollection<string> DataItems_3dPrinting_Name = new ObservableCollection<string>();
36
37
38         private ObservableCollection<ObservableCollection<DataItem>> _stagesContainer = new ObservableCollection<ObservableCollection<DataItem>>();
39         public ObservableCollection<ObservableCollection<DataItem>> stagesContainer
40         {
41             get => _stagesContainer;
42             set
43             {
44                 _stagesContainer = value;
45             }
46         }
47         private void AddStagesToContainer()
48         {
49             stagesContainer.Clear();
50             stagesContainer.Add(Stage_Production);
51             stagesContainer.Add(Stage_Construction);
52             stagesContainer.Add(Stage_Operation);
53             stagesContainer.Add(Stage_EndOfLife);
54             stagesContainer.Add(Stage_WholeBuilding);
55         }
56
57         Stage_Production
58
59         Stage_Construction
60
61         Stage_Operation
62
63         Stage_EndOfLife
64
65         Stage_WholeBuilding
66
67         public static List<string> filePaths = new List<string>();
68         // 3D Printing
69         public static void UploadData_3dPrinting()
70         {
71             filePaths.Clear();
72             filePaths = Get_3dPrinting_ExcelFiles();
73
74             if (filePaths != null)
75             {
76                 //ExcelDataService excelDataService = new ExcelDataService();
77                 DataItems_3dPrinting_Name.Clear();
78                 foreach (var stageFile in filePaths)
79                 {
80                     //DataItems_3dPrinting.Add(excelDataService.GetDataFromExcel(stageFile));
81                     DataItems_3dPrinting_Name.Add(Path.GetFileName(stageFile));
82                 }
83             }
84         }
85     }
86 }

```

```

147     {
148         MessageBox.Show("Exce file is Empty.", "Data Required", MessageBoxButton.OK, MessageBoxImage.Warning);
149     }
150 }
151 }
152 public static void GetStageData(string Document_Name)
153 {
154     foreach (var stageFile in filePaths)
155     {
156         string fileName = Path.GetFileName(stageFile);
157         if (fileName == Document_Name)
158         {
159             ExcelDataService excelDataService = new ExcelDataService();
160             DataItems_3dPrinting.Clear();
161             var dataItems = excelDataService.GetDataFromExcel(stageFile);
162             foreach (var item in dataItems)
163             {
164                 DataItems_3dPrinting.Add(item);
165             }
166         }
167     }
168 }
169 }

```



```

170 public static void GetStageData(List<Tuple<string, Stages>> Document_Name)
171 {
172     ExcelDataService excelDataService = new ExcelDataService();
173
174     foreach (var stageFile in filePaths)
175     {
176         string fileName = Path.GetFileName(stageFile);
177         bool foundMatchingStage = false;
178
179         foreach (var stage in Document_Name)
180         {
181             if (fileName == stage.Item1)
182             {
183                 var dataItems = excelDataService.GetDataFromExcel(stageFile);
184
185                 switch (stage.Item2)
186                 {
187                     case Stages.Production:
188                         Stage_Production.Clear();
189                         foreach (var item in dataItems)
190                         {
191                             Stage_Production.Add(item);
192                         }
193                         foundMatchingStage = true;
194                         break;
195
196                     case Stages.Construction:
197                         Stage_Construction.Clear();
198                         foreach (var item in dataItems)
199                         {
200                             Stage_Construction.Add(item);
201                         }
202                         foundMatchingStage = true;
203                         break;

```

```

205         case Stages.Operation:
206             Stage_Operation.Clear();
207             foreach (var item in dataItems)
208             {
209                 Stage_Operation.Add(item);
210             }
211             foundMatchingStage = true;
212             break;
213
214         case Stages.EndOfLife:
215             Stage_EndOfLife.Clear();
216             foreach (var item in dataItems)
217             {
218                 Stage_EndOfLife.Add(item);
219             }
220             foundMatchingStage = true;
221             break;
222
223         case Stages.WholeBuilding:
224             Stage_WholeBuilding.Clear();
225             foreach (var item in dataItems)
226             {
227                 Stage_WholeBuilding.Add(item);
228             }
229             foundMatchingStage = true;
230             break;
231     }
232
233     if (foundMatchingStage)
234     {
235         break; // Exit the inner foreach loop if a matching stage is found
236     }
237 }
238 }
239 }
240 }
241
242 public static void GetStageData(List<string> StagesNames)
243 {
244     foreach (var stageName in StagesNames)
245     {
246         foreach (var stageFile in filePaths)
247         {
248             string fileName = Path.GetFileName(stageFile);
249             if (fileName == stageName)
250             {
251                 ExcelDataService excelDataService = new ExcelDataService();
252                 DataItems_3dPrinting.Clear();
253                 var dataItems = excelDataService.GetDataFromExcel(stageFile);
254                 foreach (var item in dataItems)
255                 {
256                     DataItems_3dPrinting.Add(item);
257                 }
258             }
259         }
260     }
261 }

```

```

358         List<string> filePaths = new List<string>();
359
360         if (openFileDialog.ShowDialog() == true)
361         {
362             filePaths = openFileDialog.FileNames.ToList();
363         }
364         return filePaths;
365     }
366
367     private static List<string> GetExcelFilesFromDirectory(string directoryPath)
368     {
369         List<string> filePaths = new List<string>();
370
371         string[] excelFiles = Directory.GetFiles(directoryPath, "*.xls*");
372
373         foreach (string file in excelFiles)
374         {
375             if (IsExcelFile(file))
376             {
377                 filePaths.Add(file);
378             }
379         }
380
381         return filePaths;
382     }
383
384     private static bool IsExcelFile(string filePath)
385     {
386         string extension = Path.GetExtension(filePath);
387
388         // Check if the file extension corresponds to an Excel file
389         return extension.Equals(".xls", StringComparison.OrdinalIgnoreCase) ||
390             extension.Equals(".xlsx", StringComparison.OrdinalIgnoreCase) ||
391             extension.Equals(".xlsm", StringComparison.OrdinalIgnoreCase) ||
392             extension.Equals(".xlsb", StringComparison.OrdinalIgnoreCase) ||
393             extension.Equals(".csv", StringComparison.OrdinalIgnoreCase);
394     }
395
396     public static List<string> Get_Conventional_ExcelFiles()
397     {
398         string directoryPath = @"C:\COMOTH_LCA\LCA_CO";
399
400         List<string> filePaths = GetExcelFilesFromDirectory(directoryPath);
401
402         return filePaths;
403     }
404
405     public static List<string> Get_Modular_ExcelFiles()
406     {
407         string directoryPath = @"C:\COMOTH_LCA\LCA_MO";
408
409         List<string> filePaths = GetExcelFilesFromDirectory(directoryPath);
410
411         return filePaths;
412     }
413

```

```

512 {
513     string fileName = Path.GetFileNameWithoutExtension(filePath);
514     string stage = GetStageFromFileName(fileName);
515     var dataItems = excelDataService.GetDataFromExcel(filePath);
516     // Add the file path to the corresponding stage
517     switch (stage)
518     {
519         case "Production":
520             // Add the file to the Production stage
521             Stage_Production.Clear();
522             foreach (var item in dataItems)
523             {
524                 Stage_Production.Add(item);
525             }
526             foundMatchingStage = true;
527             break;
528         case "Construction":
529             // Add the file to the Construction stage
530             Stage_Construction.Clear();
531             foreach (var item in dataItems)
532             {
533                 Stage_Construction.Add(item);
534             }
535             foundMatchingStage = true;
536             break;
537         case "Operation":
538             // Add the file to the Operation stage
539             Stage_Operation.Clear();
540             foreach (var item in dataItems)
541             {
542                 Stage_Operation.Add(item);
543             }
544             foundMatchingStage = true;
545             break;
546         case "EndOfLife":
547             // Add the file to the EndOfLife stage
548             Stage_EndOfLife.Clear();
549             foreach (var item in dataItems)
550             {
551                 Stage_EndOfLife.Add(item);
552             }
553             foundMatchingStage = true;
554             break;
555         case "WholeBuilding":
556             // Add the file to the WholeBuilidng stage
557             Stage_WholeBuilding.Clear();
558             foreach (var item in dataItems)
559             {
560                 Stage_WholeBuilding.Add(item);
561             }
562             foundMatchingStage = true;
563             break;
564         //default:
565         //    // Handle files that don't match any stage
566         //    MessageBox.Show("Check Data Source!!!");
567         //    break;
568     }
569 }

```

```

571     }
572     catch (Exception ex)
573     {
574         string message = ex.Message;
575     }
576 }
577
578 private static string GetStageFromFileName(string fileName)
579 {
580     // Perform string matching to identify the stage based on the file name
581     if (fileName.Contains("Production"))
582         return "Production";
583     else if (fileName.Contains("Construction"))
584         return "Construction";
585     else if (fileName.Contains("Operation"))
586         return "Operation";
587     else if (fileName.Contains("EndOfLife"))
588         return "EndOfLife";
589     else if (fileName.Contains("WholeBuilding"))
590         return "WholeBuilding";
591     else
592         return "Unknown"; // Return "Unknown" or handle unrecognized file names accordingly
593 }
594
595 public static void SaveDataAsExcel()
596 {
597     try
598     {
599         // Get the ObservableCollection<DataItem>
600         var dataItems = LCAHandler.GetViewModel().DataItems_Current;
601
602         // Create a new Excel package
603         using (ExcelPackage excelPackage = new ExcelPackage())
604         {
605             // Create a new worksheet
606             ExcelWorksheet worksheet = excelPackage.Workbook.Worksheets.Add("Sheet1");
607
608             // Get the column headers from the DataItem properties and write them to the worksheet
609             worksheet.Cells[1, 1].Value = "ImpactCategory";
610             worksheet.Cells[1, 2].Value = "Reference Unit";
611             worksheet.Cells[1, 3].Value = "Result";
612
613             // Get the data from the ObservableCollection<DataItem> and write it to the worksheet
614             int count = 1;
615             foreach (var data in dataItems)
616             {
617                 count++;
618                 worksheet.Cells[count, 1].Value = data.ImpactCategory;
619                 worksheet.Cells[count, 2].Value = data.ReferenceUnit;
620                 worksheet.Cells[count, 3].Value = data.Result;
621             }
622         }
623     }

```

```

624
625 // Open a file dialog to choose the save location
626 using (SaveFileDialog saveFileDialog = new SaveFileDialog())
627 {
628     saveFileDialog.Filter = "Excel Workbook|*.xlsx";
629     saveFileDialog.Title = "Save Data as Excel";
630     if (saveFileDialog.ShowDialog() == DialogResult.OK)
631     {
632         // Save the Excel package to the chosen file path
633         string filePath = saveFileDialog.FileName;
634         excelPackage.SaveAs(new System.IO.FileInfo(filePath));
635     }
636 }
637
638 }
639 catch (Exception ex)
640 {
641     // Handle the exception (e.g., display an error message)
642     Console.WriteLine("An error occurred while saving the data as Excel: " + ex.Message);
643 }
644 }
645
646
647 public static void SaveChartAsImage()
648 {
649     try
650     {
651         // Get the chart control
652         CartesianChart chart = LCAHandler.GetTablesWindow().MyChart; // Replace with your actual method to retrieve the chart control
653
654         // Convert the chart to an image
655         using (var bitmap = new System.Drawing.Bitmap((int)chart.ActualWidth, (int)chart.ActualHeight))
656         {
657             var visual = new DrawingVisual();
658
659             using (var context = visual.RenderOpen())
660             {
661                 context.DrawRectangle(new System.Windows.Media.VisualBrush(chart), null, new System.Windows.Rect(new System.Windows.Point(),
662                     context.Close();
663             }
664
665             // Open a file dialog to choose the save location
666             using (SaveFileDialog saveFileDialog = new SaveFileDialog())
667             {
668                 saveFileDialog.Filter = "PNG Image|.png";
669                 saveFileDialog.Title = "Save Chart Image";
670                 if (saveFileDialog.ShowDialog() == DialogResult.OK)
671                 {
672                     // Save the image to the chosen file path
673                     string filePath = saveFileDialog.FileName;
674                     using (var fileStream = new System.IO.FileStream(filePath, System.IO.FileMode.Create))
675                     {
676                         BitmapEncoder encoder = new PngBitmapEncoder();
677                         encoder.Frames.Add(BitmapFrame.Create(BitmapFromVisual(visual)));
678                         encoder.Save(fileStream);
679                     }
680                 }
681             }
682         }
683     }
684     catch (Exception ex)
685     {
686         // Handle the exception (e.g., display an error message)
687         Console.WriteLine("An error occurred while saving the chart as image: " + ex.Message);
688     }
689 }

```

Codes for developing LCCA module

```
21 namespace LCCA_UI.ViewModel
22 {
23     public class DynamicDataGridViewModel : ViewModelBase
24     {
25         DataTable dataTable = new DataTable();
26         private List<string> _ColumnNames;
27         public List<string> ColumnNames
28         {
29             get { return _ColumnNames; }
30             set
31             {
32                 _ColumnNames = value;
33                 RaisePropertyChanged();
34             }
35         }
36
37         private List<RowDataItem> _Items;
38         public List<RowDataItem> Items
39         {
40             get { return _Items; }
41             set
42             {
43                 _Items = value;
44                 RaisePropertyChanged();
45             }
46         }
47
48         private string _Title;
49         public string Title
50         {
51             get { return _Title; }
52             set { _Title = value; RaisePropertyChanged(); }
53         }
54
55         private string _DataGridTitle;
56         public string DataGridTitle
57         {
58             get { return _DataGridTitle; }
59             set { _DataGridTitle = value; RaisePropertyChanged(); }
60         }
61
62         public double _Height;
63         public double Height
64         {
65             get { return _Height; }
66             set { _Height = value; RaisePropertyChanged(); }
67         }
68
69         MainWindow _mainWindow;
70         bool isMaximized = true;
71
72         ICommand
73
74         public DynamicDataGridViewModel(MainWindow mainWindow)
75         {
76             _mainWindow = mainWindow;
77         }
78     }
79 }
80
```

```

79     {
80         _mainWindow = mainWindow;
81         DataGridTitle = CostAnalysisViewModel.costAnalysisViewModel.DataGridTitle;
82         Title = "Summary";
83         Height = CostAnalysisViewModel.costAnalysisViewModel.DynamiccdgWindowHeight;
84         CancelCommand = new RelayCommand(CancelCommandHandler);
85         SaveBtnCommand = new RelayCommand(SaveBtnCommandHandler);
86         MaximizeWindowCommand = new RelayCommand(MaximizeWindowCommandHandler);
87         BindData();
88     }
89
90     private void SaveBtnCommandHandler(object obj)
91     {
92         string OutputFile = "";
93         System.Windows.Forms.SaveFileDialog saveFileDialog1 = new System.Windows.Forms.SaveFileDialog();
94         UI_Common.UICommonData.GetUserDirectory(out string docPath);
95         saveFileDialog1.InitialDirectory = docPath;
96         saveFileDialog1.Title = "Browse for folder";
97         saveFileDialog1.CheckPathExists = false;
98         saveFileDialog1.DefaultExt = ".xlsx";
99         saveFileDialog1.Filter = "XLSX Files (*.xlsx)|*.xlsx";
100        saveFileDialog1.RestoreDirectory = true;
101
102        if (saveFileDialog1.ShowDialog() == DialogResult.OK)
103            OutputFile = saveFileDialog1.FileName;
104        else
105            return;
106        try
107        {
108            using (ExcelPackage objExcelPackage = new ExcelPackage())
109            {
110
111                //Create the worksheet
112                ExcelWorksheet objWorksheet = objExcelPackage.Workbook.Worksheets.Add("Summary");
113                //Load the datatable into the sheet, starting from cell A1. Print the column names on row 1
114                objWorksheet.Cells["A1"].LoadFromDataTable(CostAnalysisViewModel.costAnalysisViewModel._dataTable, true);
115                objWorksheet.Cells.AutoFitColumns();
116                //Format the header
117                using (ExcelRange objRange = objWorksheet.Cells["A1:XFD1"])
118                {
119                    objRange.Style.Font.Bold = true;
120                    objRange.Style.HorizontalAlignment = ExcelHorizontalAlignment.Center;
121                    objRange.Style.VerticalAlignment = ExcelVerticalAlignment.Center;
122                    objRange.Style.Fill.PatternType = ExcelFillStyle.Solid;
123                }
124
125                //Write it back to the client
126                if (File.Exists(OutputFile))
127                    File.Delete(OutputFile);
128
129                //Create excel file on physical disk
130                FileStream objFileStrm = File.Create(OutputFile);
131                objFileStrm.Close();
132            }
133        }
134    }

```



```

149 {
150     string sheetName = "Summary";
151     ExcelPackage.LicenseContext = OfficeOpenXml.LicenseContext.Commercial;
152     var pck = new OfficeOpenXml.ExcelPackage();
153     using (var stream = File.OpenRead(path))
154     {
155         pck.Load(stream);
156     }
157     var ws = pck.Workbook.Worksheets[sheetName];
158
159     ws.Cells["B4"].Value = (((double)ws.Cells["B4"].Value) * -1).ToString();
160     ws.Cells["C4"].Value = (((double)ws.Cells["C4"].Value) * -1).ToString();
161     ws.Cells["B5"].Value = (((double)ws.Cells["B5"].Value) * -1).ToString();
162     ws.Cells["C5"].Value = (((double)ws.Cells["C5"].Value) * -1).ToString();
163     ws.Cells["B6"].Value = (((double)ws.Cells["B6"].Value) * -1).ToString();
164     ws.Cells["C6"].Value = (((double)ws.Cells["C6"].Value) * -1).ToString();
165     ws.Cells["B7"].Value = (((double)ws.Cells["B7"].Value) * -1).ToString();
166     ws.Cells["C7"].Value = (((double)ws.Cells["C7"].Value) * -1).ToString();
167     ws.Cells["B8"].Value = (((double)ws.Cells["B8"].Value) * -1).ToString();
168     ws.Cells["C8"].Value = (((double)ws.Cells["C8"].Value) * -1).ToString();
169     ws.Cells["B9"].Value = (((double)ws.Cells["B9"].Value) * -1).ToString();
170     ws.Cells["C9"].Value = (((double)ws.Cells["C9"].Value) * -1).ToString();
171     ws.Cells["B10"].Value = (((double)ws.Cells["B10"].Value) * -1).ToString();
172     ws.Cells["C10"].Value = (((double)ws.Cells["C10"].Value) * -1).ToString();
173     ws.Cells["B11"].Value = (((double)ws.Cells["B11"].Value) * -1).ToString();
174     ws.Cells["C11"].Value = (((double)ws.Cells["C11"].Value) * -1).ToString();
175     ws.Cells["C14"].Value = (((double)ws.Cells["C11"].Value) * -1).ToString();
176     pck.SaveAs(new FileInfo(path));
177     pck.Dispose();
178 }
179 catch (Exception ex)
180 {
181 }
182 }
183
184
185 public void BindData()
186 {
187     dataTable = CostAnalysisViewModel.costAnalysisViewModel._dataTable;
188     var lst = new List<string>();
189     foreach (DataColumn column in dataTable.Columns)
190     {
191         lst.Add(column.ColumnName);
192     }
193     ColumnNames = lst;
194
195     Items = new List<RowDataItem>();
196     foreach (DataRow row in dataTable.Rows)
197     {
198         Items.Add(new RowDataItem() { Values = row.ItemArray.ToList() });
199     }
200 }
201
202 public void CancelCommandHaldler(Object obj)
203 {
204     _mainWindow.Close();
205 }

```

Developing the cost analysis model

```

33 namespace LCCA_UI.ViewModel
34 {
35     public class CostAnalysisViewModel : ViewModelBase
36     {
37         public static CostAnalysisViewModel costAnalysisViewModel = null;
38
39         public InitialCost initialCost = new InitialCost();
40         public OperationCost operationCost = new OperationCost();
41         public MinorRepairsCost minorRepairsCost = new MinorRepairsCost();
42         public MajorReplaceCost majorReplaceCost = new MajorReplaceCost();
43         public RentalIncome rentalIncome = new RentalIncome();
44         SalvageValue salvageValue = new SalvageValue();
45         AnalysisResult analysisResult = new AnalysisResult();
46         public DataTable _dataTable = new DataTable();
47         public bool IsSelectedItemMARR = false;
48         public string DatagridTitle = String.Empty;
49         public double DynamicdgWindowHeight = 0;
50         public bool IsLCCADiagramExport = false;
51         int i = 0;
52
53         Visibility
125
126         Item source
263
264         Maintenance Cost Year ComboBox Selected Item
302
303         Analysis Icon
430
431         Properties
707
708         Command
714
715         public CostAnalysisViewModel()
716         {
717             costAnalysisViewModel = this;
718             ShowResultLCCACCommand = new RelayCommand(ShowResultLCCACCommandHandler);
719             ShowResultScenarioCommand = new RelayCommand(ShowResultScenarioCommandHandler);
720             ShowResultSensitivityCommand = new RelayCommand(ShowResultSensitivityCommandHandler);
721         }
722
723         public void BackBtnFunction()
724         {
725             if (InitialCostVisibility == Visibility.Visible)
726             {
727                 InitialCostVisibility = Visibility.Collapsed;
728                 InitialCost_Opacity = 0.5;
729                 InitialCost_FW = FontWeights.Normal;
730                 GeneralInfoVisibility = Visibility.Visible;
731                 Info_Opacity = 1;
732                 Info_FW = FontWeights.Bold;
733                 LCCA_MainViewModel.LCCA_MainViewModel.BtnContent = "Submit";
734             }
735             else if (OperationCostVisibility == Visibility.Visible)
736             {
737                 OperationCostVisibility = Visibility.Collapsed;
738                 OperationCost_Opacity = 0.5;

```

```

739         OperationCost_FW = FontWeights.Normal;
740         InitialCostVisibility = Visibility.Visible;
741         InitialCost_Opacity = 1;
742         InitialCost_FW = FontWeights.Bold;
743         LCCA_MainViewModel.LCCA_MainViewModel.BtnContent = "Submit";
744     }
745     else if (MaintenanceCostVisibility == Visibility.Visible)
746     {
747         MaintenanceCostVisibility = Visibility.Collapsed;
748         MaintenanceCost_Opacity = 0.5;
749         MaintenanceCost_FW = FontWeights.Normal;
750         OperationCostVisibility = Visibility.Visible;
751         OperationCost_Opacity = 1;
752         OperationCost_FW = FontWeights.Bold;
753         LCCA_MainViewModel.LCCA_MainViewModel.BtnContent = "Submit";
754     }
755     else if (RentalIncomeVisibility == Visibility.Visible)
756     {
757         RentalIncomeVisibility = Visibility.Collapsed;
758         RentalIncome_Opacity = 0.5;
759         RentalIncome_FW = FontWeights.Normal;
760         MaintenanceCostVisibility = Visibility.Visible;
761         MaintenanceCost_Opacity = 1;
762         MaintenanceCost_FW = FontWeights.Bold;
763         LCCA_MainViewModel.LCCA_MainViewModel.BtnContent = "Submit";
764     }
765     else if (SalvageValueVisibility == Visibility.Visible)
766     {
767         SalvageValueVisibility = Visibility.Collapsed;
768         SalvageValue_Opacity = 0.5;
769         SalvageValue_FW = FontWeights.Normal;
770         RentalIncomeVisibility = Visibility.Visible;
771         RentalIncome_Opacity = 1;
772         RentalIncome_FW = FontWeights.Bold;
773         LCCA_MainViewModel.LCCA_MainViewModel.BtnContent = "Submit";
774     }
775     else if (LifeCycleCostAnalysisVisibility == Visibility.Visible)
776     {
777         LifeCycleCostAnalysisVisibility = Visibility.Collapsed;
778         LCCACost_Opacity = 0.5;
779         LCCACost_FW = FontWeights.Normal;
780         SalvageValueVisibility = Visibility.Visible;
781         SalvageValue_Opacity = 1;
782         SalvageValue_FW = FontWeights.Bold;
783         LCCA_MainViewModel.LCCA_MainViewModel.BtnContent = "Submit";
784     }
785     else if (ScenarioAnalysisVisibility == Visibility.Visible)
786     {
787         ScenarioAnalysisVisibility = Visibility.Collapsed;
788         ScenarioAnalysis_Opacity = 0.5;
789         ScenarioAnalysis_FW = FontWeights.Normal;
790         LifeCycleCostAnalysisVisibility = Visibility.Visible;
791         LCCACost_Opacity = 1;
792         LCCACost_FW = FontWeights.Bold;
793         LCCA_MainViewModel.LCCA_MainViewModel.BtnContent = "Continue";
794     }

```

```

795         else if (SensitivityAnalysisVisibility == Visibility.Visible)
796         {
797             SensitivityAnalysisVisibility = Visibility.Collapsed;
798             SensitivityAnalysis_Opacity = 0.5;
799             SensitivityAnalysis_FW = FontWeights.Normal;
800             ScenarioAnalysisVisibility = Visibility.Visible;
801             ScenarioAnalysis_Opacity = 1;
802             ScenarioAnalysis_FW = FontWeights.Bold;
803             LCCA_MainViewModel.LCCA_MainViewModel.BtnContent = "Continue";
804         }
805     }
806 }
807
808 public void CheckboxcheckedFunction()
809 {
810     Uniform_Checkbox = true;
811     Geometric_Checkbox = false;
812     Visibility = Visibility.Collapsed;
813 }
814
815 public void CheckboxUncheckedFunction()
816 {
817     Uniform_Checkbox = false;
818     Geometric_Checkbox = true;
819     Visibility = Visibility.Visible;
820 }
821
822 public string GetFileName()
823 {
824     string fileName = String.Empty;
825     if (!LCCA_MainViewModel.LCCA_MainViewModel.IsConventionlBtn && LCCA_MainViewModel.LCCA_MainViewModel.IsModularBtn)
826         fileName = "LCCA_MODULAR.xlsx";
827     else if (LCCA_MainViewModel.LCCA_MainViewModel.IsConventionlBtn && !LCCA_MainViewModel.LCCA_MainViewModel.IsModularBtn)
828         fileName = "LCCA_CONVENTIONAL.xlsx";
829     else
830         fileName = "COMOTH_3DCP.xlsx";
831
832     return fileName;
833 }
834
835 public void SubmitBtnFunction()
836 {
837     if (GeneralInfoVisibility == Visibility.Visible)
838     {
839         if (SelectedTimeHorizon == UI_Common.SelectContent || SelectedStructType == UI_Common.SelectContent || String.IsNullOrEmpty(Perimeter))
840         {
841             MessageBox.Show("Please fill the values", "Attention!!!");
842             return;
843         }
844
845         GeneralInfoVisibility = Visibility.Collapsed;
846         Info_Opacity = 0.5;
847         Info_FW = FontWeights.Normal;
848         InitialCostVisibility = Visibility.Visible;
849         InitialCost_Opacity = 1;
850         InitialCost_FW = FontWeights.Bold;

```

```

1865
1866 public string ConvertNumberFormat(decimal value)
1867 {
1868     CultureInfo culture = new CultureInfo("en-US");
1869     string formattedValue = value.ToString("C", culture);
1870     return formattedValue;
1871 }
1872
1873 private DataColumn AddDataColumn(string columnName)
1874 {
1875     DataColumn dataColumn = new DataColumn(columnName, typeof(string));
1876     dataColumn.AllowDBNull = true;
1877     return dataColumn;
1878 }
1879
1880 public void WriteExcel(string range1, string range2, string range3, string range4, string range5, string sheetName, string path)
1881 {
1882     ExcelPackage.LicenseContext = OfficeOpenXml.LicenseContext.Commercial;
1883     var pck = new OfficeOpenXml.ExcelPackage();
1884     using (var stream = File.OpenRead(path))
1885     {
1886         pck.Load(stream);
1887     }
1888     var ws = pck.Workbook.Worksheets[sheetName];
1889
1890     ws.Cells[range1].Value = "Major replacement 1 @ year " + SelectItem1;
1891     ws.Cells[range2].Value = "Major replacement 2 @ year " + SelectItem2;
1892     ws.Cells[range3].Value = "Major replacement 3 @ year " + SelectItem3;
1893     ws.Cells[range4].Value = "Major replacement 4 @ year " + SelectItem4;
1894     ws.Cells[range5].Value = "Major replacement 5 @ year " + SelectItem5;
1895
1896     pck.SaveAs(new FileInfo(path));
1897 }
1898
1899 public double ConvertDouble(string val)
1900 {
1901     return Convert.ToDouble(val);
1902 }
1903
1904 public double CalculatePV(double A)
1905 {
1906     double PV = 0;
1907     if (SelectedTimeHorizon != UI.Common.SelectContent)
1908     {
1909         double val1 = Math.Pow(1 + Convert.ToDouble(MARR) / 100, Convert.ToDouble(SelectedTimeHorizon)) - 1;
1910         double val2 = Convert.ToDouble(MARR) / 100 * Math.Pow((1 + Convert.ToDouble(MARR) / 100), Convert.ToDouble(SelectedTimeHorizon));
1911         PV = A * (val1 / val2);
1912     }
1913     return PV;
1914 }
1915
1916 //MajorReplaceCost and SalvageValue
1917 public double GetPV(double F, double n)
1918 {
1919     double PV = 0;
1920     double val = Math.Pow(1 + Convert.ToDouble(MARR) / 100, n);

```

Codes for developing DBMS module

```
10 namespace COMOTH_DatabasePlugin.Load_Families
11 {
12     public partial class LoadDoorsForm : Form
13     {
14         public LoadDoorsForm(Document doc, UIApplication uiapp)
15         {
16             InitializeComponent();
17
18             ShowDialog();
19             if (DialogResult == DialogResult.OK)
20             {
21                 IList<string> constructionTypelist = new List<string>();
22
23                 if (checkBox_Conventional.Checked && !checkBox_Modular.Checked && !checkBox_3dPrinting.Checked)
24                 {
25                     constructionTypelist.Add("Conventional");
26                 }
27                 else if (checkBox_Conventional.Checked && checkBox_Modular.Checked && !checkBox_3dPrinting.Checked)
28                 {
29                     constructionTypelist.Add("Conventional");
30                     constructionTypelist.Add("Modular");
31                 }
32                 else if (checkBox_Conventional.Checked && checkBox_Modular.Checked && checkBox_3dPrinting.Checked)
33                 {
34                     constructionTypelist.Add("Conventional");
35                     constructionTypelist.Add("Modular");
36                     constructionTypelist.Add("3D Printing");
37                 }
38                 else if (!checkBox_Conventional.Checked && checkBox_Modular.Checked && !checkBox_3dPrinting.Checked)
39                 {
40                     constructionTypelist.Add("Modular");
41                 }
42                 else if (!checkBox_Conventional.Checked && checkBox_Modular.Checked && checkBox_3dPrinting.Checked)
43                 {
44                     constructionTypelist.Add("Modular");
45                     constructionTypelist.Add("3D Printing");
46                 }
47                 else if (!checkBox_Conventional.Checked && !checkBox_Modular.Checked && checkBox_3dPrinting.Checked)
48                 {
49                     constructionTypelist.Add("3D Printing");
50                 }
51                 else if (checkBox_Conventional.Checked && !checkBox_Modular.Checked && checkBox_3dPrinting.Checked)
52                 {
53                     constructionTypelist.Add("Conventional");
54                     constructionTypelist.Add("3D Printing");
55                 }
56
57                 //MessageBox.Show(string.Join("\n", constructionTypelist));
58
59                 try
60                 {
61                     using (Transaction tx = new Transaction(doc, "Load Family"))
62                     {
63                         tx.Start();
64
65                         string RevitVersionNo = uiapp.Application.VersionNumber;
```

```

65 string RevitVersionNo = uiapp.Application.VersionNumber;
66
67 foreach (string constructionType in constructionTypeList)
68 {
69     //string familyDirectory = null;
70     string familyDirectory = String.Format(@"C:\ProgramData\Autodesk\Revit\Addins\{0}\COMOTH\Database\{1}\Families\Doors", RevitVersionNo, constructionType);
71
72     if (constructionType == "3D Printing")
73     {
74         familyDirectory = String.Format(@"C:\ProgramData\Autodesk\Revit\Addins\{0}\COMOTH\Database\{1}\Families", RevitVersionNo, constructionType);
75     }
76
77     DirectoryInfo doors_Path = new DirectoryInfo(familyDirectory);
78
79
80     FileInfo[] doors_files = doors_Path.GetFiles("*.rfa");
81
82     IEnumerable<string> fileNames = doors_files.ToArray().Select(x => x.Name);
83
84     MessageBox.Show(string.Format("You are about to load {0} Door families \nfrom the {1} design Database", doors_files.Length, constructionType), "Load Doors");
85
86     List<bool> result = new List<bool>();
87
88     foreach (FileInfo file in doors_files)
89     {
90         if (CheckForFamily(doc, file.Name) == null && constructionType == "Conventional")
91         {
92             bool familyLoaded = LoadFamily(doc, familyDirectory + @"\" + file.Name, "CO");
93             result.Add(familyLoaded);
94         }
95         else if (CheckForFamily(doc, file.Name) == null && constructionType == "Modular")
96         {
97             bool familyLoaded = LoadFamily(doc, familyDirectory + @"\" + file.Name, "MO");
98             result.Add(familyLoaded);
99         }
100         else if (CheckForFamily(doc, file.Name) == null && constructionType == "3D Printing")
101         {
102             bool familyLoaded = LoadFamily(doc, familyDirectory + @"\" + file.Name, "TH");
103             result.Add(familyLoaded);
104         }
105     }
106
107     if (result.Contains(false))
108     {
109         DialogResult resultDialog = MessageBox.Show(result.Count.ToString() + "Doors Family(s) Loaded Successfully\n\nAlthough one or more families didn't load", "Load Doors", MessageBoxButtons.OKCancel, MessageBoxIcon.Warning);
110     }
111     else
112     {
113         DialogResult resultDialog = MessageBox.Show(result.Count.ToString() + string.Format("{0} Doors Family(s) Loaded Successfully", constructionType), "Load Doors", MessageBoxButtons.OKCancel, MessageBoxIcon.Information);
114     }
115 }
116
117

```

```

78 // groupBox6
79 //
80 this.groupBox6.Controls.Add(this.pictureBox6);
81 this.groupBox6.Controls.Add(this.label6);
82 this.groupBox6.Cursor = System.Windows.Forms.Cursors.Arrow;
83 this.groupBox6.Location = new System.Drawing.Point(32, 151);
84 this.groupBox6.Name = "groupBox6";
85 this.groupBox6.Size = new System.Drawing.Size(96, 138);
86 this.groupBox6.TabIndex = 40;
87 this.groupBox6.TabStop = false;
88 //
89 // label5
90 //
91 this.label5.BackColor = System.Drawing.Color.DarkGray;
92 this.label5.Cursor = System.Windows.Forms.Cursors.Hand;
93 this.label5.Font = new System.Drawing.Font("Microsoft Sans Serif", 9.75F, System.Drawing.FontStyle
94 this.label5.ForeColor = System.Drawing.Color.Black;
95 this.label5.Location = new System.Drawing.Point(13, 112);
96 this.label5.Name = "label5";
97 this.label5.Size = new System.Drawing.Size(69, 16);
98 this.label5.TabIndex = 19;
99 this.label5.Text = "Roof";
100 this.label5.TextAlign = System.Drawing.ContentAlignment.MiddleCenter;
101 this.label5.Click += new System.EventHandler(this.label5_Click);
102 //
103 // groupBox5
104 //
105 this.groupBox5.Controls.Add(this.pictureBox5);
106 this.groupBox5.Controls.Add(this.label5);
107 this.groupBox5.Cursor = System.Windows.Forms.Cursors.Arrow;
108 this.groupBox5.Location = new System.Drawing.Point(141, 151);
109 this.groupBox5.Name = "groupBox5";
110 this.groupBox5.Size = new System.Drawing.Size(96, 138);
111 this.groupBox5.TabIndex = 41;
112 this.groupBox5.TabStop = false;
113 //
114 // label3
115 //
116 this.label3.BackColor = System.Drawing.Color.DarkGray;
117 this.label3.Cursor = System.Windows.Forms.Cursors.Hand;
118 this.label3.Font = new System.Drawing.Font("Microsoft Sans Serif", 9.75F);
119 this.label3.ForeColor = System.Drawing.Color.Black;

```


Appendix II - Interview questions and results for expert opinion used in decision marking for developing the DSS module

Introduction

During the development of the DSS module, face-to-face interviews were conducted with building owners and building designers to get their expert opinion to identify, evaluate and rank the inter-relationship between sustainability factors (as shown in Table 1) in design components for three construction methods (modular, conventional, and 3DC printing) using. The interview questions have been designed using Saaty's 9-point scale, and the responses will be scored based on the criteria according to the linguistic scale in Table 2.

Table 1: Sustainability Factors

Goal	Indicators	Main Criteria	Sub Criteria
Sustainable Material Selection	Economic (S ₁)	Cost (C ₁)	Initial cost (SC ₁₁)
			Running cost (SC ₁₂)
		Time (C ₂)	Duration related cost (SC ₂₁)
		Circular Economy (C ₃)	Deconstruction cost (SC ₃₁)
			Flexibility and adaptability(SC ₃₂)
	Environmental (S ₂)	Energy and Atmosphere (C ₄)	Embodied energy (SC ₄₁)
			Energy saving (SC ₄₂)
			Operational energy demand (SC ₄₃)
		Material and Resources (C ₅)	Locally sourced material (SC ₅₁)
			CO ₂ emission (SC ₅₂)
			Renewable capability (SC ₅₃)

		Environmental Impacts (C ₆)	Global warming potential (SC ₆₁)
			Ozone depletion potential (SC ₆₂)
			Acidification potential (SC ₆₃)
	Social (S ₃)	Indoor Environmental Quality (C ₇)	Low-emitting materials (SC ₇₁)
			Indoor environment comfort (SC ₇₂)
			Thermal comfort (SC ₇₃)
		Design Innovation (C ₈)	Aesthetics (SC ₈₁)
			Daylight and views (SC ₈₂)

Table 2: Linguistic scale for DANP-fuzzy input

Semantic attributes	Corresponding values
Very high	5
High	4
Moderate	3
Low	2
Very low	1

1. Sustainability criteria for *conventional* construction walls

Question 1: Part A – For Building Designers

On a 5 point scale, rate your opinion on design consideration in the selection of sustainable walls for four alternatives (Tables 3) in relation to the sustainability criteria under which they are listed in Tables 4: 1) Cost; 2) Time; 3) Circular Economy; 4) Energy and Atmosphere; 5) Material and Resources; 6) Environmental Impacts; 7) Indoor Environmental Quality; and 8) Design and Innovation.

Question 2: Part B – For Building Owners

On a 5 point scale, rate your priority in selecting sustainable walls for four alternatives (Tables 3) in relation to the sustainability criteria under which they are listed in Tables 4: 1) Cost; 2) Time; 3) Circular Economy; 4) Energy and Atmosphere; 5) Material and Resources; 6) Environmental Impacts; 7) Indoor Environmental Quality; and 8) Design and Innovation.

Table 3:Wall (4 Alternatives)**Conventional consstruction**

Alt	Name	MasterFormat	Manufacturer	URL
	Wall			
W _{Alt1}	Folding Glass Partition Wall	10 22 43	Nana Wall System Inc.	https://www.nanawall.com/
W _{Alt2}	Partitions - Drywall w/ Wood StudX gypsum board on each side	09 29 00	CertainTeed	https://certainteed.concora.com/
W _{Alt3}	Exterior Wall_Quik-Brik 4x4x16 masonry unit	04 20 00	Oldcastle Architectural, Inc.	https://www.oldcastlearchitectural.ca/
W _{Alt4}	Exterior Wall_Harvard-Brik Std_8x4x16	04 20 00	EchelonMasonry.com	https://www.echelonmasonry.com/

Modular construction

Alt	Name	MasterFormat	Manufacturer	URL
	Wall			
W _{Alt1}	Prefabricated Penalization System Installed over a Proprietary Light-Gauge Metal Pan	07 24 13	Tremco CPG	https://www.dryvit.com/
W _{Alt2}	Modular Wall System (OMNIFLEX 300) 3.25" thick modular wall system,	13 1 2 00	Porta-Fab Corporation	https://www.portafab.com/
W _{Alt3}	Modular Wall System Series 300_3.25" thick on-loadbearing, demountable	13 12 00	Porta-Fab Corporation	https://www.portafab.com/
W _{Alt4}	Elevare™ Stacking Double Glazed High Wall Glass Partition Systems	10 22 19	Avanti Systems USA	https://www.avantisystemsusa.com/

3D concrete printing

Alt	Name	MasterFormat	Manufacturer	URL
	Industry Base 3D Printing Wall Material			
W _{Alt1}	<i>Sikacrete®-752 3D</i> (Portland Cement, Selected Aggregates and Additives)		Sika Group	https://www.sika.com/
W _{Alt2}	<i>3D-M68 Mortar</i> (Cementitious Materials, Admixtures, Additives and Water)		LATICRETE International, Inc.	https://laticrete.com/
W _{Alt3}	<i>BOD2 Printing Material</i> (Cement, Sand, Gravel, Recycled Roofing Tiles, Water, Admixture (Glenium sky 631) and Crackstop Fibers)		COBOD International	https://cobod.com/
W _{Alt4}	<i>Tector 3D Build</i> (Cementitious materials, Natural hydraulic lime, Admixtures, and Additives)		LafargeHolcim	https://www.holcim.com/

Table 4: Walls (sustainability criteria)

Wall	Wall alternative 1 (W_{Alt1})					Wall alternative 2 (W_{Alt2})					Wall alternative 3 (W_{Alt3})					Wall alternative 4 (W_{Alt4})				
Criteria	Very high	high	Moderate	low	very low	Very high	high	Moderate	low	very low	Very high	high	Moderate	low	very low	Very high	high	Moderate	low	very low
	5	4	3	2	1	5	4	3	2	1	5	4	3	2	1	5	4	3	2	1
Economic (S1)																				
Cost (C1)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Time (C2)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
Circular Economy (C3)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Environmental (S2)																				
Energy and Atmosphere (C4)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Material and Resources (C5)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Environmental Impacts (C6)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Social (S3)																				
Indoor Environmental Quality (C7)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Design Innovation (C8)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

2. Sustainability criteria for Conventional construction flooring

Question 1: Part A – For Building Designers

On a 5 point scale, rate your opinion on design consideration in the selection of sustainable flooring for four alternatives (Tables 5) in relation to the sustainability criteria under which they are listed in Tables 6: 1) Cost; 2) Time; 3) Circular Economy; 4) Energy and Atmosphere; 5) Material and Resources; 6) Environmental Impacts; 7) Indoor Environmental Quality; and 8) Design and Innovation.

Question 2: Part B – For Building Owners

On a 5 point scale, rate your priority in selecting sustainable flooring for four alternatives (Tables 4) in relation to the sustainability criteria under which they are listed in Tables 5: 1) Cost; 2) Time; 3) Circular Economy; 4) Energy and Atmosphere; 5) Material and Resources; 6) Environmental Impacts; 7) Indoor Environmental Quality; and 8) Design and Innovation.

Table 5: flooring (4 Alternatives)**Conventional construction**

Alt	Name	MasterFormat	Manufacturer	URL
	Flooring			
F _{Alt1}	Flooring_36" x 3" Da Vinci Limed Silk Oak RP96 wood plank	09 68 13	Karndean Designflooring USA	https://www.karndean.com/
F _{Alt2}	Flooring_Resilient Luxury Vinyl Tile/Plank	09 65 19	Tarkett North America	https://www.tarkettna.com/
F _{Alt3}	Luxury vinyl planks (LVPs)	09 68 13	Armstrong Flooring Canada	https://www.armstrongflooring.com
F _{Alt4}	Resinous Flooring and Coatings	09 67 23	Dex-O-Tex® flooring	https://dex-o-tex.com/

Modular construction

Alt	Name	MasterFormat	Manufacturer	URL
	Flooring			
F _{Alt1}	Flooring_Flex-Aire Modular® Cushion 24" x 24" Tile	09 68 13	J&J Flooring Group LLC	https://www.jjflooringgroup.com/
F _{Alt2}	Flooring_Resilient Luxury Vinyl Tile/Plank	09 65 19	Tarkett North America	https://www.tarkettna.com/
F _{Alt3}	Flooring_Engineered Prefinished Hardwood Flooring with Tongues and Grooves	09 64 29	Mirage Flooring	http://www.miragefloors.com/
F _{Alt4}	Flooring_Solid Prefinished Hardwood Flooring with Tongues and Grooves	09 64 29	Mirage Flooring	http://www.miragefloors.com/

Table 6: Flooring (sustainability criteria)

Flooring	Flooring alternative 1 (F_{Alt1})					Flooring alternative 2 (F_{Alt2})					Flooring alternative 3 (F_{Alt3})					Flooring alternative 4 (F_{Alt4})				
Criteria	<i>Very high</i>	<i>high</i>	<i>Moderate</i>	<i>low</i>	<i>very low</i>	<i>Very high</i>	<i>high</i>	<i>Moderate</i>	<i>low</i>	<i>very low</i>	<i>Very high</i>	<i>high</i>	<i>Moderate</i>	<i>low</i>	<i>very low</i>	<i>Very high</i>	<i>high</i>	<i>Moderate</i>	<i>low</i>	<i>very low</i>
	5	4	3	2	1	5	4	3	2	1	5	4	3	2	1	5	4	3	2	1
Economic (S1)																				
Cost (C1)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Time (C2)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Circular Economy (C3)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Environmental (S2)																				
Energy and Atmosphere (C4)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Material and Resources (C5)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Environmental Impacts (C6)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Social (S3)																				
Indoor Environmental Quality (C7)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Design and Innovation (C8)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

3. Sustainability factors for conventional construction ceiling

Question 1: Part A – For Building Designers

On a 5 point scale, rate your opinion on design consideration in the selection of sustainable ceiling for four alternatives (Tables 7) in relation to the sustainability criteria under which they are listed in Tables 8: 1) Cost; 2) Time; 3) Circular Economy; 4) Energy and Atmosphere; 5) Material and Resources; 6) Environmental Impacts; 7) Indoor Environmental Quality; and 8) Design and Innovation.

Question 2: Part B – For Building Owners

On a 5 point scale, rate your priority in selecting sustainable ceiling for four alternatives (Tables 7) in relation to the sustainability criteria under which they are listed in Tables 8: 1) Cost; 2) Time; 3) Circular Economy; 4) Energy and Atmosphere; 5) Material and Resources; 6) Environmental Impacts; 7) Indoor Environmental Quality; and 8) Design and Innovation.

Table 7: Ceiling (4 Alternatives)
Conventional construction

Alt	Name	MasterFormat	Manufacturer	URL
	Ceiling			
C _{Alt1}	ACOUSTIBuilt Seamless Acoustical Ceiling System	09 54 00	Armstrong World Industries	https://www.armstrongceilings.com/
C _{Alt2}	Micro-perforated Metal Acoustic Ceiling Panel	09 54 00	Acoustical Surfaces, Inc.	https://www.acousticalsurfaces.com/
C _{Alt3}	Mars™ High-NRC Logix™ Acoustical Panels	09 51 00	USG Corporation	https://www.usg.com/
C _{Alt4}	24"x 24" drop Mineral Fiber ceiling panels designed for 15/16" grid systems.	09 51 10	Armstrong World Industries	https://www.armstrongceilings.com/

Modular construction

Alt	Name	MasterFormat	Manufacturer	URL
	Ceiling			
C _{Alt1}	Wood Ceiling Panel USG True Wood Modular Grilles 12"x98"	09 51 26	USG Corporation	https://www.usg.com/
C _{Alt2}	Integrated Ceiling Assemblies	09 54 00	Armstrong Inc	https://www.armstrongceilings.com/
C _{Alt3}	Acoustical_Suspension_System-USG-Donn_Brand-DX-DXL-Tee: DX/DXL24 - 15/16" - Square Edge	09 29 00	USG Corporation	https://www.usg.com/
C _{Alt4}	Ceiling_Linear Wood Ceiling Panels 12"x10'	09 51 10	Geometrik Manufacturing Inc	https://geometrik.com/

Table 8: Ceiling (sustainability criteria)

Ceiling	Ceiling alternative 1 (CA1)					Ceiling alternative 2 (CA2)					Ceiling alternative 3 (CA3)					Ceiling alternative 4 (CA4)				
Criteria	Very high	high	Moderate	low	very low	Very high	high	Moderate	low	very low	Very high	high	Moderate	low	very low	Very high	high	Moderate	low	very low
	5	4	3	2	1	5	4	3	2	1	5	4	3	2	1	5	4	3	2	1
Economic (S1)																				
Cost (C1)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Time (C2)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Circular Economy (C3)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Environmental (S2)																				
Energy and Atmosphere (C4)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Material and Resources (C5)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Environmental Impacts (C6)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Social (S3)																				
Indoor Environmental Quality (C7)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Design and Innovation (C8)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

4. Sustainability factors for conventional construction ceiling

Question 1: Part A – For Building Designers

On a 5 point scale, rate your opinion on design consideration in the selection of sustainable ceiling for four alternatives (Tables 7) in relation to the sustainability criteria under which they are listed in Tables 8: 1) Cost; 2) Time; 3) Circular Economy; 4) Energy and Atmosphere; 5) Material and Resources; 6) Environmental Impacts; 7) Indoor Environmental Quality; and 8) Design and Innovation.

Question 2: Part B – For Building Owners

On a 5 point scale, rate your priority in selecting sustainable ceiling for four alternatives 7) in relation to the sustainability criteria under which they are listed in Tables 8: 1) Cost; 2) Time; 3) Circular Economy; 4) Energy and Atmosphere; 5) Material and Resources; 6) Environmental Impacts; 7) Indoor Environmental Quality; and 8) Design and Innovation.

Table 9: Doors (4 Alternatives)
Conventional construction

Alt	Name	MasterFormat	Manufacturer	URL
	Doors			
D _{Alt1}	1 3/8" - Raised Panel wooden single door K5660 Mission	08 14 33	Karona, Inc.	http://www.karonadoor.com/
D _{Alt2}	Door_AcousticSteel_Ambico_Double-Flush	08 14 33	Ambico Limited	https://www.ambico.com/
D _{Alt3}	Climate Control Efficiency Door-Dbl_Kawneer	08 32 13	Kawneer Global	https://www.kawneer.com/
D _{Alt4}	Door_Folding_LaCantina_Aluminum-Thermal-Series	08 33 00	LaCantina Doors, Inc	https://www.lacantinadoors.com/

Modular construction

Alt	Name	MasterFormat	Manufacturer	URL
	Doors			
D _{Alt1}	Wood Sound Control Door and Frame Assemblies	08 34 73	AMBICO Limited	https://www.ambico.com/
D _{Alt2}	Door_Entrance Kolbe Ultra Series Entrance Door-Outswing-4Wide	08 14 33	Kolbe & Kolbe Millwork Co., Inc.	http://www.kolbe-kolbe.com/
D _{Alt3}	Sliding Aluminum-Framed Glass Door Kawneer Series AA™3200 Thermal Sliding Doors	08 32 13	Kawneer Global	https://www.kawneer.com/
D _{Alt4}	Rolling Doors_StormDefender Tornado & Hurricane Protection	08 33 00	Cornell Innovation Door Solutions	https://www.cornelliron.com/

Table 10: Door (sustainability criteria)

Door	Door alternative 1 (<i>D_{Alt1}</i>)					Door alternative 2 (<i>D_{Alt2}</i>)					Door alternative 3 (<i>D_{Alt3}</i>)					Door alternative 4 (<i>D_{Alt4}</i>)				
Criteria	<i>Very high</i>	<i>high</i>	<i>Moderate</i>	<i>low</i>	<i>very low</i>	<i>Very high</i>	<i>high</i>	<i>Moderate</i>	<i>low</i>	<i>very low</i>	<i>Very high</i>	<i>high</i>	<i>Moderate</i>	<i>low</i>	<i>very low</i>	<i>Very high</i>	<i>high</i>	<i>Moderate</i>	<i>low</i>	<i>very low</i>
	5	4	3	2	1	5	4	3	2	1	5	4	3	2	1	5	4	3	2	1
Economic (S1)																				
Cost (C1)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Time (C2)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Circular Economy (C3)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Environmental (S2)																				
Energy and Atmosphere (C4)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Material and Resources (C5)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Environmental Impacts (C6)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Social (S3)																				
Indoor Environmental Quality (C7)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Design and Innovation (C8)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

5. Sustainability criteria for conventional construction windows

Question 1: Part A – For Building Designers

On a 5 point scale, rate your opinion on design consideration in the selection of sustainable windows for four alternatives (Tables 11) in relation to the sustainability criteria under which they are listed in Tables 12: 1) Cost; 2) Time; 3) Circular Economy; 4) Energy and Atmosphere; 5) Material and Resources; 6) Environmental Impacts; 7) Indoor Environmental Quality; and 8) Design and Innovation.

Question 2: Part B – For Building Owners

On a 5 point scale, rate your priority in selecting of sustainable windows for four alternatives (Tables 11) in relation to the sustainability criteria under which they are listed in Tables 12: 1) Cost; 2) Time; 3) Circular Economy; 4) Energy and Atmosphere; 5) Material and Resources; 6) Environmental Impacts; 7) Indoor Environmental Quality; and 8) Design and Innovation.

Table 11: Windows (4 Alternatives)**Conventional construction**

Alt	Name	MasterFormat	Manufacturer	URL
	Window			-
W _{Alt1}	Window-Fire-Rated Narrow Profile Steel fixed Windows_Designer Series	08 41 23	Technical Glass Products	https://technicalglass.com/
W _{Alt2}	Window- _Double_Hung-Kawneer-8450TL	08 51 13	Kawneer Global	https://www.kawneer.com/
W _{Alt3}	Window Invent XLT_Series Wausau_Architectural_Window	08 51 13	Wausau Group Inc.	http://www.wausauwindow.com/
W _{Alt4}	Windows Wausau 4000i And 4000i-Dt Behavioral Care Series	08 51 13	Wausau Group Inc.	http://www.wausauwindow.com/

Modular construction

Alt	Name	MasterFormat	Manufacture	URL
	Window			-
W _{Alt1}	Window_Vinyl Windows Transom-Simonton-ProFinish-Contractor_Master_Series	08 53 13	Simonton Windows, Inc.	https://www.simonton.com/
W _{Alt2}	Window_Aluminum Window Wall Systems, Fixed_Kawneer_AA4325_43250	08 44 13	Kawneer Global	https://www.kawneer.com/
W _{Alt3}	Window_Fixed_VistaLuxe Collection Direct Set Corner Unit-Double Wood_Pane Nosing	08 52 00	Kolbe & Kolbe Millwork Co., Inc.	http://www.kolbe-kolbe.com/
W _{Alt4}	Windor_Pressure-Resistant Bi-fold Windows	08 55 00	Sierra Pacific Industries	http://www.sierrapacificwindows.com/

Table 12: Windows (sustainability criteria)

Window	<i>Window alternative 1 (W_{Alt1})</i>					<i>Window alternative 2 (W_{Alt2})</i>					<i>Window alternative 3 (W_{Alt3})</i>					<i>Window alternative 4 (W_{Alt4})</i>				
Criteria	<i>Very high</i>	<i>high</i>	<i>Moderate</i>	<i>low</i>	<i>very low</i>	<i>Very high</i>	<i>high</i>	<i>Moderate</i>	<i>low</i>	<i>very low</i>	<i>Very high</i>	<i>high</i>	<i>Moderate</i>	<i>low</i>	<i>very low</i>	<i>Very high</i>	<i>high</i>	<i>Moderate</i>	<i>low</i>	<i>very low</i>
	5	4	3	2	1	5	4	3	2	1	5	4	3	2	1	5	4	3	2	1
Economic (S1)																				
Cost (C1)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Time (C2)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Circular Economy (C3)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Environmental (S2)																				
Energy and Atmosphere (C4)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Material and Resources (C5)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Environmental Impacts (C6)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Social (S3)																				
Indoor Environmental Quality (C7)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐	☐
Design and Innovation (C8)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Table 13: Sample Interview Response

Sustainability Factor	Walls				Flooring				Ceiling				Doors				Windows			
	Alt ₁	Alt ₂	Alt ₃	Alt ₄	Alt ₁	Alt ₂	Alt ₃	Alt ₄	Alt ₁	Alt ₂	Alt ₃	Alt ₄	Alt ₁	Alt ₂	Alt ₃	Alt ₄	Alt ₁	Alt ₂	Alt ₃	Alt ₄
Modular construction method																				
Cost (C ₁)	5	3	4	4	4	5	3	2	3	3	5	4	2	4	3	5	3	2	5	4
Time (C ₂)	4	5	5	3	4	4	3	3	3	3	4	5	3	5	4	4	3	3	4	4
Circular Economy (C ₃)	4	3	3	5	4	5	3	3	4	4	5	5	5	4	3	3	2	3	4	5
Energy and Atmosphere (C ₄)	5	4	4	3	4	5	3	3	3	3	5	4	2	4	3	5	3	2	5	4
Material and Resources (C ₅)	5	4	4	3	4	4	5	5	3	4	5	5	3	4	4	5	3	4	5	4
Environmental Impacts (C ₆)	2	3	3	4	5	4	3	3	3	4	4	5	3	4	4	5	3	3	5	4
Indoor Environmental Quality (C ₇)	5	3	4	3	4	5	3	2	3	3	5	5	2	4	3	5	3	3	5	4
Design Innovation (C ₈)	5	4	4	3	4	5	3	3	3	4	5	4	3	4	3	5	2	3	5	4
Conventional construction method																				
Cost (C ₁)	2	3	5	4	3	5	4	2	5	3	4	2	2	4	5	3	2	3	5	4
Time (C ₂)	4	5	3	2	2	5	4	3	4	3	5	2	4	5	4	2	2	3	4	5
Circular Economy (C ₃)	2	3	5	4	3	4	2	5	4	2	5	3	4	3	5	2	3	2	4	5
Energy and Atmosphere (C ₄)	2	3	5	4	4	5	3	3	4	2	5	3	2	4	5	3	2	3	5	4
Material and Resources (C ₅)	2	3	5	4	2	4	5	3	5	3	4	2	4	3	5	2	2	5	4	3

Environmental Impacts (C ₆)	5	2	2	3	3	5	4	2	5	3	4	2	2	5	5	3	3	4	5	2
Indoor Environmental Quality (C ₇)	3	4	5	4	3	4	5	2	5	2	4	3	2	4	5	3	2	4	5	3
Design Innovation (C ₈)	4	5	3	3	2	4	5	3	5	3	5	2	3	4	5	2	3	4	5	2
3D printing construction method																				
Cost (C ₁)	2	3	4	5	3	5	4	2	5	3	4	2	2	4	5	3	2	3	5	4
Time (C ₂)	3	3	5	4	2	5	4	3	4	3	5	2	4	5	4	2	2	3	4	5
Circular Economy (C ₃)	3	2	4	5	3	4	2	5	4	2	5	3	4	3	5	2	3	2	4	5
Energy and Atmosphere (C ₄)	2	3	4	5	4	5	3	3	4	2	5	3	2	4	5	3	2	3	5	4
Material and Resources (C ₅)	3	2	5	4	2	4	5	3	5	3	4	2	3	3	5	2	2	5	4	3
Environmental Impacts (C ₆)	2	2	4	5	3	5	4	2	5	3	4	2	2	5	4	3	3	4	5	2
Indoor Environmental Quality (C ₇)	3	2	4	5	3	4	5	2	5	2	4	3	2	4	5	3	2	4	5	4
Design Innovation (C ₈)	3	2	5	4	2	4	5	3	5	3	5	2	3	4	5	2	3	4	5	2