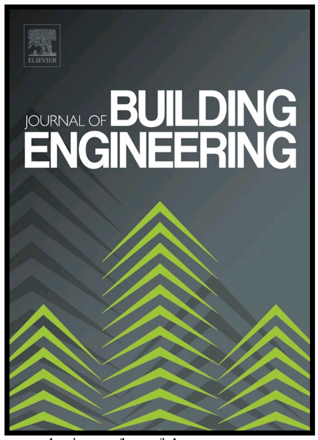

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PII: S2352-7102(18)30720-4
DOI: https://doi.org/10.1016/j.jobe.2018.11.006
Reference: JOBE633

To appear in: *Journal of Building Engineering*

Received date: 2 June 2018
Revised date: 9 November 2018
Accepted date: 9 November 2018

Cite this article as: Seyed Amirhosain Sharif and Amin Hammad, Simulation-Based Multi-Objective Optimization of Institutional Building Renovation Considering Energy Consumption, Life-Cycle Cost and Life-Cycle Assessment, *Journal of Building Engineering,* https://doi.org/10.1016/j.jobe.2018.11.006

Simulation-Based Multi-Objective Optimization of Institutional Building Renovation Considering Energy Consumption, Life-Cycle Cost and Life-Cycle Assessment

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ABSTRACT

Buildings are responsible for a significant amount of energy consumption resulting in a considerable negative environmental impact. Therefore, it is essential to decrease their energy consumption by improving the design of new buildings or renovating existing buildings. Heat losses or gains through building envelopes affect the energy use and the indoor condition. Heating, Ventilation, and Air Conditioning (HVAC) and lighting systems are responsible for 33% and 25% of the total energy consumption in office buildings, respectively. However, renovating building envelopes and energy consuming systems to lessen energy losses is usually expensive and has a long payback period. Despite the significant contribution of research on optimizing energy consumption, there is limited research focusing on the renovation of existing buildings to minimize their Life Cycle Cost (LCC) and environmental impact using Life Cycle Assessment (LCA). This paper aims to find the optimal scenario for the renovation of institutional buildings considering energy consumption and LCA while providing an efficient method to deal with the limited renovation budget. Different scenarios can be compared in a building renovation strategy to improve energy efficiency. Each scenario considers several methods including the improvement of the building envelopes, HVAC and lighting systems. However, some of these scenarios could be inconsistent and should be eliminated. Another consideration in this research is the appropriate coupling of renovation scenarios. For example, the HVAC system must be redesigned when renovating the building envelope to account for the reduced energy demand and to avoid undesirable side effects. A genetic algorithm (GA), coupled with an energy simulation tool, is used for simultaneously minimizing the energy consumption, LCC, and environmental impact of a building. A case study is developed to demonstrate the feasibility of the proposed method.

KEYWORDS: Energy Analysis and Simulation, Simulation-Based Multi-Objective Optimization, Life-Cycle Assessment, Life Cycle Cost, Energy Consumption, Renovation.

1. INTRODUCTION

Recent environmental and financial concerns have revealed an immediate need for the recovery of the sustainability level of buildings. This need is more critical for existing buildings (U.S. Environmental Protection Agency, 2011). The construction sector is being pushed by different governmental and non-governmental organizations to implement sustainable innovation for its products and processes (Straube and Burnett, 2005).

Buildings are responsible for about 40% of the total secondary energy use (Statistics Canada, 2008). The potential for decreases in energy consumption and Greenhouse Gas Emissions (GHG) associated with buildings is remarkable (Tuominen et al., 2012). Owners have faced increasing needs for minor repairs, as well as partial or major renovations of their buildings. However, they usually suffer from limited budgets or other constraints.

The objective of this research is to propose a method for optimizing the selection of renovation strategies for existing institutional buildings by minimizing energy consumption, Life Cycle Cost (LCC) and negative environmental impacts, while respecting limited renovation budgets. This method considers three main areas of building renovation, which are the building envelope, HVAC system, and lighting system; each of which has a noteworthy influence on building energy performance.

Different renovation scenarios can be compared to find the optimum scenario based on the renovation strategy. The proposed Simulation-Based Multi-Objective Optimization (SBMO) framework takes advantage of Building Information Modeling (BIM) coupled with simulation. There are different strategies for building renovation that focus on energy efficiency. Each scenario is created from combination of several methods within the applicable strategy. Methods are including related factors to the building envelope, HVAC, and lighting system. However, the inconsistent scenarios should be removed. For example, when double-glazed windows are implemented, the building becomes more airtight, so the infiltration rate is decreased considerably. Therefore, the HVAC system should be rescheduled or renovated to reflect the new energy demand and to avoid unwanted side effects.

2. LITERATURE REVIEW

Buildings have a long life-cycle. During this extended period, operational energy systems, such as HVAC system, equipment, and lightings, are responsible for tremendous amount of total building energy consumption (Juan et al., 2010). Throughout the life-cycle of a building, the processes of construction and allocation of resources should be selected with consideration of environmental responsibility. This extended period starts from design and continues to construction, operation, maintenance, renovation and concludes with demolition (U.E.P.A., 2011). The renovation of the building's envelope significantly affects the future heating and cooling strategies (ASHRAE Design Guide, 2014). The patterns of energy demands will change after the renovation of the building envelope.

The construction sector is relevant to sustainability because of the tremendous amount of energy consumption of construction products and also the benefits to society of the active role of this industry in achieving the aims of the sustainable development plans. In this context, existing buildings have a very substantial role, which must be highlighted because of the potential for energy saving and the availability of regulatory incentives and regulations (Itard and Meijer, 2008). Therefore, it is vital to properly renew existing buildings in a manner that they will consume minimum energy and produce less adverse environmental impacts, all with reasonable renovation budgets and improving the aesthetic quality of the building façades.

2.1. Building Envelope Renovation Scenarios

In existing buildings, heat losses or gains through building envelopes affect the energy use and the indoor condition, and produce a significant amount of energy depletion. Therefore, renovating the external walls and fenestrations has a considerable impact on reducing energy consumption (Straube et al., 2005). This kind of renovation should improve the thermal performance of the building and increase the property's value within reasonable renovation budget. Depending on the renovation objectives of each project, various results could be achieved. There are several factors which must be considered to develop renovation scenarios, including renovation methods, and building envelope materials and components (Konstantinou, 2014).

2.1.1 Renovation Methods

Renovation methods can be classified based on the way building components are replaces, improved or added and their consequence on the building envelope performance. Furthermore, the combination of the renovation methods is also possible. The reviewed literature identified certain renovation methods, i.e. Replace, Add-in, Wrap-it, Add-on, and Cover-it. These methods represent a systematic approach to the development of the renovation scenarios (Galiotto et al. 2015; Konstantinou 2014).The list of renovation scenarios cannot be comprehensive because the opportunities for combining different renovation methods are unlimited. Therefore, their classification by identifying the basic principle to help decide on the type of renovation method and emphasizing the advantages and disadvantages in each case is the first important step for the development of a renovation scenario.

2.1.2 Building Envelope Materials

The selection of building envelope materials is usually very problematic due to several issues, namely, cost, implementation, performance, and environmental issues. Several categories (i.e. insulation, glazing, fenestration, window frames, sealants, finishing, and cladding) should be considered to renovate a building envelope.

2.1.3 Building Envelope Components

The use of innovative technologies and materials has been greatly improved in recent years, and can lead to improvements in building energy efficiency. However, there are several barriers to their adoption, such as building integration problems. The main approaches are shifting from *static* to *responsive* and *dynamic* methods (e.g., Responsive Building Elements (RBE), and Multifunctional Façade Modules (MFM)) (Loonen et al., 2014). There are several innovative products, such as Phase Change Material (PCM), dynamic insulation, photovoltaics, electrochromic windows, which facilitate sustainable buildings (Kolokotsa et al., 2011).

2.2. HVAC Systems and Control Strategies

Previous research shows that the most substantial energy saving potential can be achieved by improving the building service systems and the energy source (Alev et al., 2014). Due to the gap between predictions and actual measurements of energy performance of buildings , there is a rise in the area of research focusing on the effect of building envelopes and HVAC optimization on buildings' energy consumption. The HVAC system must be redesigned when renovating the envelope of the building to reflect the new energy demand and to avoid unwanted side effects.

HVAC control systems have an important impact on energy management. The primary task of HVAC control is optimizing operation systems, sequencing of system components, avoiding excessive cycling of system components and the conflicts between them (ASHRAE Design Guide, 2014). Adjustments in control strategies are critical and are sometimes the only possible way to manage the energy consumption. Furthermore, buildings use mechanical and/or natural ventilation. In renovation projects, however, the full integration between these two methods must be considered.

2.3. Lighting Systems

The lighting system affects the internal heat gain. Therefore the lighting control should be addressed in the renovation project (DiLouie, 2008). A considerable number of studies have focused on the selection of the most appropriate lighting systems for buildings renovation (e.g., energy efficient fluorescent, high-pressure sodium light, motion-activated lighting, Light-Emitting Diode (LED) lighting, and induction lighting). However, budget limitations, environmental issues, and applicability are the major factors that must be considered when selecting a new lighting system. Daylighting has impact on the electrical energy consumption; therefore, in the simulation of the case study daylighting factor was considered.

2.4. Buildings Life Cycle Cost (LCC)

Sustainable buildings usually have higher initial capital investment than conventional ones (Kibert, 2008). However, during the life-cycle of the project, the extra spending incurred in the original capital cost of sustainable buildings can be recovered within a relatively short period because of several factors, such as the reduction in the energy consumption (Kibert, 2008). Furthermore, there is a strong correlation between optimizing energy performance and the LCC as choosing different materials and components for renovation has a significant impact on LCC. On the other hand, when it comes to improving environmental sustainability, finding a correlation between optimizing energy performance and sustainability is a challenge (Sharif and Hammad, 2017). As a result, finding a balance between these important concepts is crucial to improving a building's energy performance.

2.5. Life Cycle Assessment (LCA)

GHG emissions from construction and energy consumption in buildings result in a tremendous negative environmental impact. LCA is a comprehensive and systematic approach to evaluating environmental impacts of a product or process during its entire life cycle (Cabeza et al., 2014). LCA can incorporate the selection of environmentally preferable materials and the optimization and evaluation of the construction processes (Asdrubali et al., 2013). In LCA, the environmental impacts of the building, such as equivalent CO_2 emissions, are analyzed in all steps of the life cycle of the building. These steps are grouped into pre-use (product) phase, construction and installation phase, use phase, and End-of-Life (EoL) phase. Figure 1 shows the system boundaries of the assessments. Furthermore, current LCA studies comprise Embodied Energy (EE) and Operational Energy (OE) consumption during building life cycle. These studies usually consider maintenance during the O&M phase (Anand and Amor 2017; Cabeza et al. 2014). Three methods can be implemented for LCA: Process analysis and Input-Output (I-

O) analysis, which are traditional Life Cycle Inventory (LCI) methods, and hybrid analysis (Crawford, 2008). These methods have different assumptions regarding the system boundaries (Chang et al., 2016).

The application of LCA in the building sector has become a focus of research in the last ten years (Buyle et al. 2013; Asdrubali et al. 2013).The number of published research papers about LCA related to buildings has more than doubled in the last five years (Anand and Amor, 2017). However, previous studies used LCA to compare only one aspect of the building separately, for instance, building envelope or explicit materials or building systems and control. There is limited research combining all aspects of the building simultaneously (e.g., Alshamrani et al. 2014; Vandenbroucke et al. 2015). Wang et al.

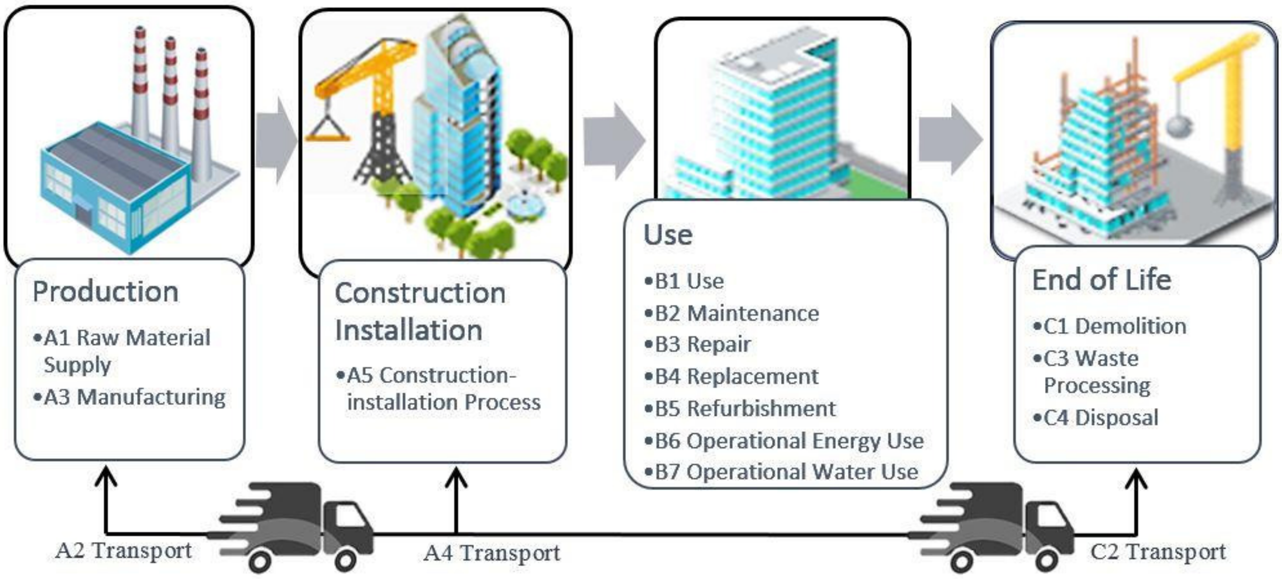


Figure 1. LCA system boundary of the assessments (Adapted from EN 15978:2012 and EN 15804:2014 standards).

(2005) and Asdrubali et al. (2013) focused on the design process, measuring or forecasting energy use for buildings and considering life-cycle environmental impacts. In this research the LCA is defined based on the Global Warming Potential (GWP), which is CO_2 equivalent and the Total Energy Consumption (TEC).

2.6. Optimization Approach in Buildings

According to the reviewed studies, simulation and optimization methods have been applied in the building industry for various purposes, such as improving energy performance, simulating and optimizing the energy consumption, improving the design of new buildings, and predicting future energy performance (Evins, 2013; Nguyen et al., 2014). Optimization is the process of finding one or more solutions that consider all constraints and minimize (or maximize) one or more objective functions (Branke et al., 2008). The selection of the optimization technique depends on two main factors: the search method and the parameters to be optimized. There are three categorizations for optimization, which are based on the uncertainty in the decision variables, the number of parameters to be optimized (objective functions) and the value of the objective functions. If the value of the objective function can be estimated with certainty, the optimization is considered deterministic. Otherwise, the optimization is categorized as stochastic. If the optimization problem has only one single objective, it is called *single-objective optimization*; otherwise, it is called *multi-objective optimization* (Cohon, 1978). Multi-objective optimization problems often involve conflicting objectives (Nakayama et al., 2009).

Also, Goldberg (1989), categorized optimization methods into three main groups including enumerative, systematic (gradient-based or calculus-based) and stochastic (random or gradient-free). Enumerative methods, which have simple principle, utilize algorithms that evaluate the objective function at every point in the search space sequentially and perform exactly that an exhaustive search. Enumerative methods have two limitations: the lack of real-world applicability and the magnitude of the search space, which can only be *finite* or *discretized* infinite. Therefore, the enumerative method is not commonly used in building optimization studies because the search space in the subject of the building optimization is usually too large for this method (Chantrelle et al., 2011).

Systematic methods, are more common in building optimization; for instance, to optimize the thickness of the insulation considering derivative methods (Diwekar, 2013; Bolattürk, 2008). Optimization of the passive thermal performance of buildings considering building envelopes was done by Bouchlaghem and Letherman (1990). The researchers coupled the simplex method and the non-random complex method to develop a thermal prediction program (Bouchlaghem and Letherman 1990).

Gradient-based methods are vulnerable by being dependent on the initial prediction, regularity of the objective function, and exposure to be trapped at local minimums when traversing parameter(s) . Furthermore, building optimization is very complex and could be considered as a nonlinear topic, which can be evaluated utilizing a building simulation program in some situations (Wetter and Wright, 2004). Therefore, systematic methods are not preferred for complex building renovation studies. While stochastic (gradient-free) methods, i.e. ant colony algorithm, simulated annealing, particle swarm optimization, and Genetic Algorithm (GA), which are based on random approaches, are more applicable (Delgarm et al., 2016; Nguyen et al., 2014). Furthermore, stochastic (gradient-free) methods can be easily integrated with building assessment tools because they do not require a hypothesis about the regularity of the objective functions. GA is one of efficient and widely recognized stochastic methods and was developed by Holland (Holland, 1975; Deb et al., 2002).

An overview of recent simulation and/or optimization papers on building renovation is given in Table 1 and compared with the current study in terms of methods, renovation parameters, objective functions, and selected tools. These papers have some overlaps with the current study. However, none of them has brought together all decision variables, i.e. envelope, HVAC, and lighting, and objective functions, i.e. TEC, LCC, and LCA for optimizing the renovation of the existing buildings. For instance, Chantrelle et al. (2011), used Non-dominated Sorting Genetic Algorithm (NSGA-II) optimization method (MultiOpt tool) and TRNSYS and COMIS as simulation tools to optimize energy use, comfort, and investment. Jin and Overend (2012), identified optimal façade solutions for a renovation project using EnergyPlus simulation and assessing the trade-off between cost, energy use and user productivity. Several recent studies considered a reference building for comparing and reviewing appropriate optimization strategies for existing buildings, but in this way, the characteristics of the reference building and the case study should be similar, which is not possible in all circumstances (Ascione et al. 2017; de Vasconcelos et al. 2015).

2.7. Integrating BIM with energy simulation, LCC, and LCA

Evaluating the energy consumption and environmental impacts of a project using simulation has attracted tremendous interest in recent years (Abaza, 2008). Different energy simulation and analysis tools have been established during the past 50 years (Jalaei and Jrade, 2014). BIM tools, such as Revit, have the potential to connect with energy analysis applications (Eastman et al., 2008). Furthermore, energy and daylighting simulation were added to new versions of BIM tools. Research on energy use and environmental issues using these tools offers a striking opportunity to make cost-effective choices, which have a positive effect on the building LCC and facilitate achieving the energy performance goals. BIM models can provide input data for energy simulation and present the results (Kumar, 2008). On the other hand, LCA tools have the capacity to process and analyze the environmental issues of the building. BIM tools (e.g. Revit) have been recently developed with environmental analysis add-ins.

The integration of BIM and LCA was proposed in several studies, such as Häkkinen and Kiviniemi, (2008). They developed a three-step method for integration. Their method initially linked separate tools through file exchange. Consequently, the required functionality was added to the existing BIM tool. Jalaei and Jrade (2014) proposed a methodology to integrate BIM, LCA, and Management Information Systems (MIS), which can be used to implement sustainable design for buildings at the conceptual phase and to consider their environmental influences.

ATHENA Impact Estimator (referred to as ATHENA in this paper) is frequently used by the North American construction industry due to its ability to assess the whole building and its components (Athena Impact Estimator, 2017). ATHENA modeling capacity includes building's envelope, structure, and interior partitions and doors. Based on the availability of data, LCA modeling can also calculate the operating energy consumption of the whole building. It is worthwhile to mention that LCA is not a method to estimate a building's annual operational energy (Athena Impact Estimator, 2017). ATHENA allows side-by-side comparisons for different renovation strategies.

Author	Title	Method		Decision Variables				Objective Functions				Tool
				Env	HVAC	Li	Comments	TEC	LCC	LCA	Comments	
Abdallah & Elrayes 2015	Optimizing the selection of building upgrade measures to minimize the operational negative environmental impacts	S O	NSGA-II	-	✓	✓	GHG emissions, refrigerant impacts, mercury-vapor emissions, lighting pollution, water use	-	✓	✓	Upgrade cost and building environmental impacts index	eQUEST
Asadi et al., 2014	Multi-objective optimization for building retrofit	S O	NSGA-II (MOGA)	✓	✓	-	EW and R insulation material, W, solar collector, HVAC	✓	-	-	EC, retrofit cost, and thermal discomfort hours	TRNSYS and ANN in MATLAB
Ascione et al., 2017	Cost-optimal analysis, Robust assessment of cost-optimal energy retrofit (CASA)	S O	NSGA-II (MOO) and ANN	✓	✓	-	Geometry, envelope, operation, and HVAC	✓	✓	-	EC, thermal comfort and global cost	EnergyPlus and MATLAB
Ascione et al., 2011	Energy retrofit of historical buildings	S	Dynamic energy simulation	✓	✓	✓	W, thermal insulation of the envelope, HVAC, control set-point, Li (Specific options)	-	-	-		EnergyPlus
Bolattürk , 2008	Optimum insulation thicknesses for building walls with respect to cooling and heating degree-hours	O		✓	-	-	Insulation material for building EWs	-	✓	-	Insulation thicknesses, energy savings, payback period using LCCA	
Chantrelle et al., 2011	Development of a multicriteria tool for optimizing the renovation of buildings	S O	NSGA-II (MOGA)	✓	✓	-	Building envelopes, heating and cooling loads and control strategies	-	-	✓	Energy consumption, cost, thermal comfort, and life-cycle environmental impact	MultiOpt, TRNSYS, COMIS
Flores-Colen, de Brito, 2010	A systematic approach for maintenance budgeting of buildings façades	S		✓	-	-	Five façades' claddings; (service life, performance, quality, maintenance operations, frequency, and costs)	-	✓	-	Budget allocation and performance of buildings during their LCC using EUAC	Simulation of performance degradation models
Magnier and Haghighat , 2010	MOO of building design using TRNSYS simulations, GA, and ANN	O S	NSGA-II, GAINN	✓	✓	-	HVAC system settings, thermostat programming, and passive solar design	✓	-	-	Thermal comfort (Predicted Mean Vote) and energy consumption	TRNSYS and MATLAB
Huang et al., 2014	Thermal properties optimization of envelope in energy-saving renovation of existing buildings	O	Math Model	✓	-	-	Shape factor, WWR, W, and wall (thermal insulation thickness of envelope and thermal properties)	-	✓	-	Energy-saving renovation costs, performance of the windows and requirements for the insulation layer	
Author	Title	Method		Env	HVAC	Li	Comments	TEC	LCC	LCA	Comments	Tool
				Decision Variables				Objective Functions				

Jin and Overend, 2012	Façade renovation for a public building based on a whole-life value approach	O S	MOO	✓	-	-	Façade materials and products	-	✓	✓	Cash payback period, carbon payback period, and occupant productivity	EnergyPlus and MATLAB
Juan et al., 2010	A hybrid decision support system for sustainable office building renovation	O S	Hybrid GA and A* (GAA*)	✓	✓	-	Sustainable site, energy efficiency, water efficiency, material and resources, and indoor environment quality	✓	-	✓	Renovation cost, building quality, and environmental impacts	GAA* and ZOGP, MIT Design Advisor
Loonen et al., 2014	Simulation-based support for product development of innovative building envelope components	S	SA and structured parametric studies	✓	-	-	W position, orientation and WWR, room depth, wall insulation, and thickness of thermal mass layer	✓	-	-	Total energy savings, daylight illuminance, glare discomfort, and overheating hours	TRNSYS and DAYSIM
Ouyang et al., 2009	Economic analysis of energy-saving renovation measures for urban existing residential buildings in China based on thermal simulation and site	S	Thermal simulation	✓	-	-	Layout, orientation, shape, WWR, heat transmission, shadow, airproof degree of W, thermal inertia of R, EW, partition wall, exterior door, floor, ground floor, absorption of R and EW surface,& green vegetation	-	✓	-	Economic benefit using LCC method	DOE-2
Palonen et al., 2009	A genetic algorithm for optimization of building envelope and HVAC system parameters (Design)	S O	NSGA-II and Hooke-Jeeves	✓	✓	-	additional insulation thickness of the existing insulation material (EW, R and floor), U-value of W, and type of heat recovery	-	✓	-	Investment cost (insulations and windows) and ventilation heat recovery	GenOpt, NSGA-II and Omni-optimizer, MINLP
Penna et al., 2015	MOO of Energy Efficiency Measures in existing buildings	S O	NSGA-II	✓	✓	-	Insulation of the walls, R, and floor, G, heating generator, MVS, thermal bridges and air tightness of the building	✓	✓	-	Energy efficiency and global costs, (EP, WDT, NPV)	TRNSYS
Schwartz et al., 2015	Multi-objective GA for the minimisation of the life cycle carbon footprint and LCC	S O	GA	✓	-	-	Panel, EW, internal wall, W, interior floor,concrete frame, and street celling and floor	-	✓	✓	LCA vs. LCC and embodied vs. operational carbon emissions	Sketchup, Bath ICE, and EnergyPlus
Current Study, 2018	SBMO of instutional building renovation considering TEC, LCC, and LCA	S O	NSGA-II	✓	✓	✓	R, EW, FT, W, WWR, HVAC, COS, HOS, Li, EWO	✓	✓	✓	TEC, LCC, and LCA pairwise	Design-Builder

Table 1. Overview of recent simulation and/or optimization literature on building renovation.

A*:	Best-first algorithm	EWO:	External Window Open	MVS:	Mechanical ventilation system	SA:	Sensitivity Analyses
EC:	Energy Consumption	EUAC:	Equivalent Uniform Annual Cost	NPV:	Net Present Value	W:	Window
EP:	Energy Performance	FT:	Façade Type	O:	Optimization	WDT:	Weighted Discomfort Time
Env:	Envelope	Li:	Lighting	R:	Roof	WWR:	Window to Wall Ratio
EW:	External wall	MINLP:	mixed integer (Nonlinear) programming	S:	Simulation	ZOGP:	Zero-one goal programming

3. METHODOLOGY

The model is developed in four main phases as shown in Figure 2: (1) model input data collection; (2) databases development; (3) definition of the renovation strategies; and (4) simulation-based multi-objective optimization. The first phase aims to define the model input data collection methods. Consequently, the common methods that shape each scenario should be investigated and added to the available databases. Having these databases related to the BIM tool helps the designer to select sustainable renovation strategies for buildings in the BIM environment easily and efficiently. The databases are used to store different data for three main categories, which are building envelope, building HVAC and lighting systems, and economic and environmental data. These steps are presented in the first and second phases of Figure 2. Subsequently, the renovation team defines an energy performance goal, which is used for developing the building renovation strategies (Phase 3). It is worthwhile to mention that each strategy consists of different scenarios for renovation, taking into account different building methods. The major task of Phase 4 is to produce near-optimum solutions considering energy performance, LCC and, LCA concurrently. The Simulation-Based Multi-Objective Optimization (SBMO) model is implemented to calculate the Pareto front. Then, the environmental analysis tool is implemented to cross-check the results of the LCA optimization. Finally, the results of the Pareto front form the content for the recommendation and results report. The Pareto front of a multi-objective optimization represents the non-dominated optimum solutions, which show the trade-off between the objective functions based on different renovation scenarios. The development procedure is explained in detail through the following four phases.

3.1. Model Input Data Collection (Phase 1)

Phase 1 has two steps: (1) provide the model input data, and (2) develop BIM model. This model will be used to save input data related to building components from the project Material Take-Off (MTO) table and other sources of data. To calculate environmental impacts of the components of the building, energy consumption needs to be measured or calculated. The TEC of building equipment is calculated based on the characteristics of the equipment and its operational schedule. Furthermore, other related data about the building characteristics should be gathered to create a comprehensive understanding of the Existing Situation (ES). These data are used to assess the current status of the building and to create a baseline model for calibration and comparison of results. A sample of the input data that summarizes the building features is shown in Table 5, which will be explained in the case study. The simulation software, which is linked to the BIM model, simulates the TEC of the building in detail. Data from energy bills and other reliable databases are used to validate the results. Building characteristics are imported into the energy model using the BIM Tool. This model contains thermos-physical properties of the building envelope, data from HVAC system and lighting, and other necessary information about the building. Figure 3 shows the building components considered in this study (green boxes).

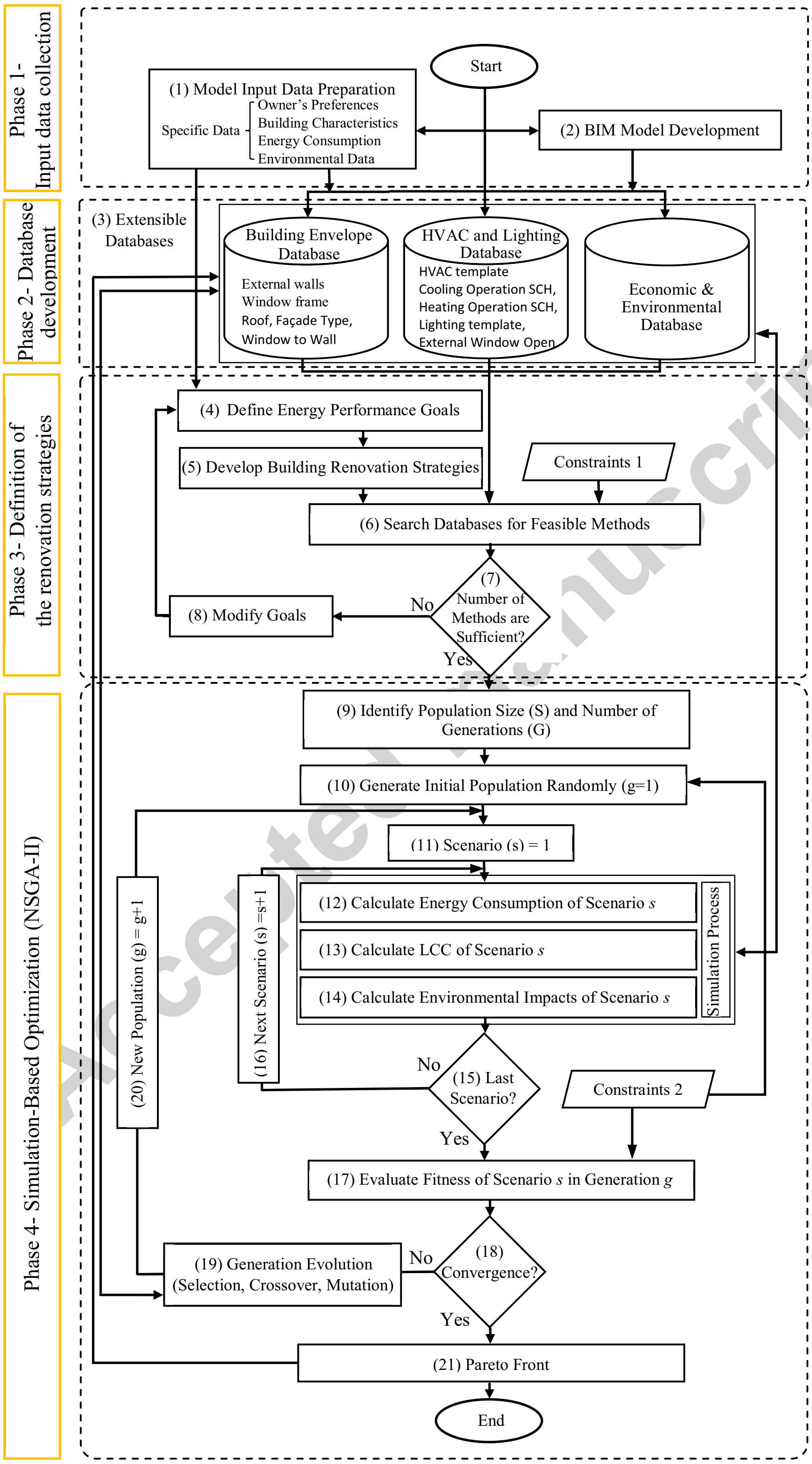


Figure 2. Model development phases

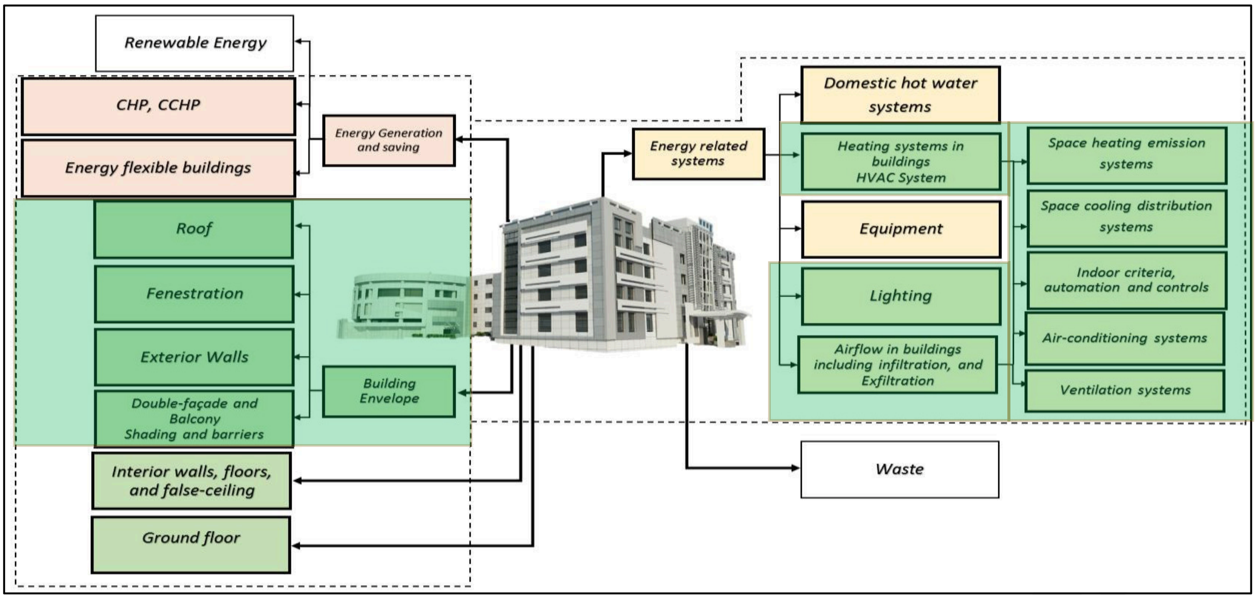


Figure 3. Building components considered in the research (Green boxes)

3.2. Database Development and Integration (Phase 2)

Phase 2 has only step (3), which is developing the extensible databases, including building components for the renovation project. The model's relational databases are developed to combine and relate different building components, renovation techniques, and other useful data. Each combination of the methods creates a renovation scenario.

3.3. Definition of the Renovation Strategies (Phase 3)

A detailed explanation of how to define renovation strategies is not the main goal of this study. However, reviewing its theoretical concepts provides us with a general understanding of how strategies are categorized. This is important because this study delves further into how to combine methods and create renovation scenarios using SBMO. Needless to say, this phase plays a major role in SBMO's success. In this phase, the most important tasks are to define or modify the scope of the renovation project and allocate the appropriate methods for each strategy.

To define the renovation strategies, this phase concentrates on developing a model to combine all data gathered from previous steps and integrate them to find, in general, which kind of renovation is applicable for the project considering the renovation budget limitations, owner's preferences, and certificate specifications (Constraints 1). This phase has five steps: (4) define energy performance goals. (5) Develop building renovation strategies. In the first step all collected data are evaluated quantitatively or qualitatively, and then the strategy of the renovation is finalized through group work between the decision-maker, facility management, and the owners who have agreed on the goal. It is essential to consider the owner's preferences early in the renovation design and plan interdisciplinary collaboration between all participants in the project (Galiotto et al. 2015). In this study, the decision making process is considered as a collaboration between the decision-makers and the facility management, who is the representative of the owner. The outcomes clarify the general scope of the renovation, whether it is a major renovation or a minor repair. Table 2 provides an example of the classification of renovation strategies. (6) Search the databases to find feasible methods to create renovation tasks and methods tables for building envelope and systems (e.g. Tables 3 and 4). Each scenario consists of different methods of the building envelope and building energy systems. The goal is to allocate appropriate methods to pre-defined renovation strategies. The classification of renovation methods varies case-by-case and are depends on different factors. (7) Assessing that there are enough renovation methods available for each strategy, this step is iteratively repeated until all feasible methods are allocated. (8) If the goals have not been achieved the goals should be modified. To achieve the goal of the renovation project, three renovation strategies are developed. These strategies start from minor and conclude with a major renovation. The concept of each strategy is accumulative.

Minor renovation strategy (S01)

This strategy is proposed to address only minor repair maintenance in case of limited renovation budget or if the building is a heritage building. *Add-in* and *wrap-it* methods are proposed for this strategy. The goal is to repair or upgrade defective parts from the inside. Renovation in this stage usually does not add new elements. Adjustments in control strategies for HVAC and lighting are also considered in this strategy. Furthermore, full integration between mechanical and natural ventilation must be considered.

Medium renovation strategy (S02)

This strategy has more intervention than S01. In this strategy, minor replacements for defective elements and old parts are applicable. *Add-in/ Wrap-it/ Replace* methods can be applied in this strategy. This strategy is more expensive, and the results are more promising in terms of energy efficiency. Moreover, replacing the HVAC and lighting equipment with minor effect on building characteristics could be suggested, considering the cost of renovation. Monitoring systems for HVAC and lighting are proposed in this strategy. Additionally, building automation and control could be proposed in this strategy.

Major renovation strategy (S03)

This strategy is the most comprehensive. With this strategy old façade elements or outdated elements are upgraded. The renovation can be extended to the load-bearing structure. New structures can be added on to the existing building, cover parts or entire internal and external courtyards and atria; the function of some parts may be changed. A major renovation of HVAC and lighting is applicable in this strategy.

3.4. Define Renovation Tasks and Methods

Different methods related to the following variables have been considered (i.e. Roof types (*R*), External Wall types (*EW*), Façade Types (*FT*), Glazing template (*G*), Window frame types (*W*), and Window to Wall Ratio (*WWR*, 30-70%), HVAC systems (*HVAC*), the Cooling and Heating Operation schedules (*COS, HOS*), and Lighting systems (*Li*)). Furthermore, three continuous variables are defined for determining ventilation methods: the External Window Open percentage (*EWO*) in the range of 0-70%, Mechanical Ventilation Rate (*MVR*) with 10 options, and Airtightness (*A*) with 4 options for each zone.

ASHRAE Design Guide recommends several systems, each of which can save up to 50% of energy consumption for office buildings (ASHRAE Design Guide, 2014). Several methods and systems are identified as the most commonly used in the energy renovation of buildings: Electric radiators, air to water heat pumps, split with no fresh air, hot water boilers, and exhaust heat recovery systems are commonly selected by the decision-makers. Building systems considered are in two ways: first, renovation of HVAC systems and secondly, operational setting-related methods, such as heating and cooling operation schedules. Percentage *EWO* also included, measuring ventilation rate. Additionally, Mechanical Ventilation Rate (*MVR*) and airtightness (*A*) parameters are proposed for minor renovation strategies.

Finally, different lighting methods are considered in the model. Furthermore, different lighting operation schedules address the control strategies (Table 4). Renovation methods are categorized in Table 2 and the particular renovation tasks alongside the renovation methods for buildings envelope and HVAC/lighting systems, from minor to major renovation strategy, are explained in Tables 3 and 4, respectively. Due to the cumulative concept of renovation strategies, for a major renovation, the proposed model takes into account all methods that are considered to be minor to major. For example, a medium renovation strategy for fenestration in Table 3 contains all tasks from S01 and S02 strategies and comprises 13 methods: *G01, G02, G05, G06, G07, FT01, FT02, FT05, FT06, Li01, W05, WWR*, and *EWO*. The role of natural daylight is not the main focus of this study; however, as shown in Table 3, several variables of the renovation methods of the building envelop (i.e. *W, FT*, and *WWR*) have indirect correlation with natural daylight within the optimization. In addition, three operation schedules (*Li01*) are considered for lighting as renovation methods (Table 2). Furthermore, different renovation methods are considered for glazing, which have effects on the daylighting (i.e. *G05, G06*, and *G07*).

3.5. SBMO for Energy performance, LCC, and LCA (Phase 4)

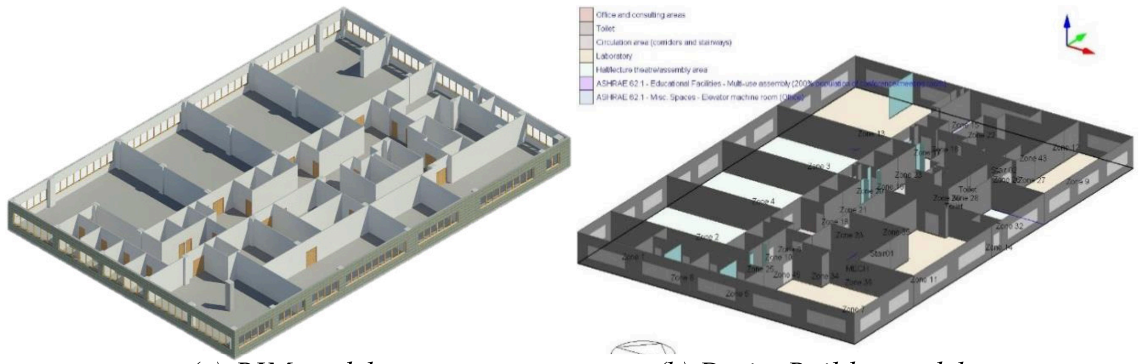
The BIM tool is used to export data to the SBMO. The SBMO uses the Non-dominated Sorting Genetic Algorithm (NSGA-II) optimization method. NSGA-II is implemented by developing the initial population of size *N* in the first generation. Phase 4 has 14 steps: (9) the decision-maker sets the population size *(P)* and the number of generation (*G*). (10) Then, the initial population is generated randomly. (11) SBMO uses an energy simulation tool to calculate the TEC, LCC, and LCA for each solution representing a combination of renovation scenarios. The input parameters to the optimization engine are divided into two main categories: building envelope and building systems. The optimization engine computes the objective functions, which are (12) TEC, (13) LCC, and (14) LCA for each scenario based on the selected values of the methods in each simulation run. (15) The system repeats the calculations using different input scenarios. (16) The integration of the simulation model and an optimization algorithm is performed through a systematic approach, which allows exploitation of the best features of these tools simultaneously. (17) The next step is to evaluate the fitness values of the scenarios in the generation. Some constraints are also applied to specify the boundaries of TEC and LCC (Constraints 2). (18) Convergence condition is evaluated in this step. (19) Consequently, the selection, crossover, and mutation operations are applied on the entire population. (20) This procedure is iteratively repeated for all members in all generations until the convergence happens or a predefined number of generations is reached. (21) The results of the optimizations are shaped into the Pareto front, which will be used to inform decision-makers of different renovation scenarios, as well as the trade-off relationships among the various scenarios.

4. IMPLEMENTATION AND CASE STUDY

The effect of building envelope and systems renovation is investigated in the last floor of a multipurpose university building at Concordia University (Montreal, Canada) with a net floor area of 1,708 m^2. It is modeled in Revit 2017 to create the BIM model with Level of Detail 300, as shown in Figure 4(a). The developed model is imported to DesignBuilder software (DesignBuilder, 2016) as shown in Figure 4(b). The zoning is used to define the function for each part to be able to apply the specific renovation scenarios for each zone (i.e. laboratory, office and consulting area). It is worthwhile to mention that the function of a zone has a significant impact on the selection of the renovation scenario. The allocation of building activities is explained in Table 5.

4.1. BIM Model Implementation

To have an accurate energy analysis of the case study, its BIM model must be transformed into an energy analytical model. First, all the spaces must be converted into *rooms*. *Rooms* designate thermal *zones* in DesignBuilder. By definition, a thermal zone is a space bounded by its roof, walls, and floor,



(a) BIM model *(b) DesignBuilder model*

Figure 4. Case Study Model

and is the initial unit for calculating heat loads. Bounding elements describe the extent of a *room*. After defining *rooms* for analyzing the building's energy, bounding elements are transformed to 2D surfaces demonstrating their actual geometry. It is vital to define the position of the adjacent rooms in the analytical model.

ID	**Renovation methods (# of Options)**	**ID**	**Renovation methods (# of Options)**
R	**Roof (20)**	HVAC	**HVAC (29)**
R01	Insulation (5)	HVAC01	Air to Water Heat Pump (ASHP) (2)
R02	Flat roof - 19 mm asphalt (3)	HVAC02	Fan Coil Unit (4-Pipe) (4)
R03	Combined semi-exposed Uninsulated (3)	HVAC03	Packaged Thermal Air Conditioner, PTAC (2)
R04	Combined flat roof (3)	HVAC04	Packaged Thermal Heat Pump, PTHP(1)
R05	Combined semi-exposed (3)	HVAC05	Radiator heating (4)
R06	Photovoltaic (1)	HVAC06	Split (2)
R07	Innovative roofs (2)	HVAC07	Radiators Electric, Nat. Vent. (1)
EW	**External wall (38)**		
EW01	Brick air, concrete block (6)	HVAC08	VAV, Air-cooled Chiller (6)
EW02	Brick cavity with insulation (4)	HVAC09	VAV, Dual Duct (2)
EW03	Cavity wall (E&W) Part L (2)	HVAC10	VAV, Water-cooled Chiller (2)
EW04	Lightweight curtain wall (4)		
EW05	Semi-exposed wall (7)	HVAC20	Ventilation system with heat recovery (HR) (1)
EW06	Wall- Energy code standard (5)	RMV	Repair Mechanical Ventilation (2)
EW07	Wall- State-of-the-art (5)		
EW08	Advanced Insulation (2)		
EW09	Innovative walls (3)	HOS, COS	**Heating/ Cooling Operation Schedule (7)**
FT	**Facade type (22)**	H/C OS1	ON 24/7 (1)
FT01	100% fitted glazing (1)	H/C OS2	Max mode (3)
FT02	40% Vertical Glazing (1)	H/C OS3	Two season schedule (1)
FT03	Fixed windows (3)	H/C OS4	7:00 - 23:00 Mon – Fri (1)
FT04	Curtain wall, 85% glazed (1)	H/C OS5	6:00 - 18:00 Mon – Fri (1)
FT05	Horizontal strip, % glazed (6)		
FT06	Preferred height 1.5m (10)	Li	**Lighting (12)**
G	**Glazing template (103)**	Li01	Operation Schedule (3)
G01	Single glazing (25)	Li02	Canadian energy code (2)
G02	Double glazing (30)	Li03	LED (2)
G03	Triple glazing (25)	Li04	Fluorescent (3)
G04	BIPV (1)	Li05	High-pressure Mercury (1)
G05	Smart glazing systems (PCM) (4)	Li06	High-pressure sodium (1)
G06	Fixed Shading (15)		
G07	Shading adjustable (3)		**Ventilation/ Area control**
W	**Window frame types (5)**	EWO%	External window opens (0-70%)

W01	Aluminum window frame (2)	MVR	Mechanical Ventilation Rate (0-10, Increment: 0.2)
W02	Wooden window frame (2)	A	Airtightness (0-4, Increment: 1)
W03	UPVC window frame (1)	WWR%	Window to Wall ratio (30-70%)

Table 2. Renovation methods

ASHP:	Air to Water Heat Pump	HR:	Heat Recovery	PTAC:	Packaged Terminal Air Conditioner
BIPV:	Building Integrated Photo Voltaic	LED:	Light-Emitting Diode	PTHP:	Packaged Thermal Heat Pump
DOAS:	Dedicated Outdoor Air System	Max:	Maximum	UPVC:	Unplasticized polyvinyl chloride
FPID:	Fan-Powered Induction Unit	Nat. Vent.:	Natural Ventilation	VAV:	Variable air volume

Table 3. Renovation tasks and methods for building envelope

		Renovation tasks	Renovation methods	Type of Intervention
Roof	S01	Add insulation, unheated roof	**R01**- Insulation between rafters, lining or interior insulation	Add-in, Wrap-it
		Insulation entirely above deck, heated attic roof	**R01**- Insulation on attic floor or on roof	Add-in
	S02	Additional insulation on roof slab, waterproofing Internal insulation	**R01**- Insulation entirely above deck, waterproofing	Add-in
	S03	Increase roof surface reflectance and emittance	**R02**- Flat roof - 19 mm asphalt	Add-in
			R03- Combined Semi-exposed roof	Add-in
			R04- Combined flat roof	Add-in
			R05- Combined semi-exposed roof	Add-in
		Photovoltaic	**R06**- Photovoltaic	Add-in, Add-on
		Additional floor	**R02**- Additional Flat roof	Add-in, Add-on
		Green roof	**R07**- Green roof	Replace, Wrap-it
		Use innovative techniques	**R07**- Roof pond system	Replace, Cover-it
External wall	S01	Provide continuous air barrier	**A**- Airtightness (cavity insulation)	Add-in
		Increase thermal mass	**A**- Airtightness (internal insulation)	Add-in
		Cavity insulation	**EW01**- Brick air concrete block or (thermolite block insulation), **EW02**- Brick cavity with insulation, **EW03**- Cavity wall, **EW05**- Semi-exposed wall	Add-in, Add-on Replace
	S02	Exterior Insulation and Finishing Systems (EIFS) Use thermal storage, Trombe walls, interior mass	**EW06**- Wall- Energy code standard (LW Concrete block, LW super insulated, ICF), **EW07**- Wall- State-of-the-art (SIPS, Precast enclosure wall/ precast concrete sandwich panels, EIFS)	Wrap-it, Add-on, Replace Wrap-it
	S03	Use innovative techniques	**EW09**- BIPV wall	Wrap-it, Add-on
			EW08- Advanced Insulation (SHG, Dynamic insulation)	Wrap-it, Add-on
		Second Façade/ Single glazing	**EW04**- LW curtain wall, **FT04**- Curtain wall (Second Façade/ Single glazing, Ventilated façade)	Wrap-it, Add-on Replace
		Additional space/ Second façade integrated/ Ventilated façade	**EW09**- Second Façade/ Double glazing, **EW09**- Additional space/ Second façade integrated	Wrap-it, Add-on, Replace, Cover-it

Table 3. Renovation tasks and methods for building envelope (Cont.)

Fenestration	S01	Use glazing with low solar heat gain coefficient (SHGC)	**G01, G02**- Upgrade window (Single glazing, Double glazing) **FT01**- 100% fitted glazing, **FT02**- 40% Vertical glazing	Add-in
		Maximize the benefits of daylighting	**Li01**- Operation Schedule	NA
		Operable windows with screens so that air conditioning and heating are not necessary during transition periods	**Li01**- Operation Schedule	NA
			FT05- Horizontal strip glazing	Add-on, Replace
			FT06- Preferred height 1.5m	Add-on, Replace
	S02	Use skylights and north-facing clerestories to daylight interior zones	**G05**- Smart glazing systems (Transparent insulation, PCM)	Add-on
		Shading fixed	**EWO**- Operation Schedule, **G06**- Fixed shading	Add-on, Cover-it
		Enlarged windows	**WWR**- Window to Wall (Improve the window frame)	Add-in, Replace
		For buildings with operable windows, renovate building layout for effective cross-ventilation	**WWR**- Window to Wall	Add-on
			G07- Shading adjustable	Replace, Cover-it
		Shade building surfaces	**W05**- Secondary single glazing	Add-on, Cover-it
	S03	Shading adjustable	**G07**- Shading adjustable (Diffusing Shades, Electrochromic switchable, slatted blinds, PV/T hybrid solar window)	Add-in, Replace, Wrap-it
		Replace windows with double glazing	**G02**- Secondary double glazing	Cover-it, Wrap-it
			G02- Replaced Windows with double glazing	Replace
		Replace windows triple glazing	**G03**- Replaced Window with triple glazing or Quadruple LoE Film, **G07**- Replace with Ventilated double glazed window	Replace
		Minimize windows east and west, maximize north and south	**FT01**- 100% fitted glazing, **FT02**- Vertical glazing, **FT03**- Fixed windows, **FT05**- Horizontal strip glazing, **FT06**- Preferred height	Add-on, Replace, Cover-it
		Upgrade windows, use innovative components	**G04**- BIPV, **G05**- Smart glazing systems (Advanced glazing windows, PCM, Thermochromic, Electrochromic windows)	Replace, Wrap-it Add-in, Replace

EIFS:	Exterior Insulation and Finishing Systems	PV/T hybrid:	Photovoltaic thermal hybrid
ICF:	Insulated Concrete Forms	SHGC:	Solar Heat Gain Coefficient
LW:	Lightweight	SHG:	Solar Heat Gain Insulation
NA:	Not applicable	SIPS	Structural Insulated Panel Systems

Table 4. Control and renovation tasks and methods for HVAC and lighting systems

		Renovation tasks	Renovation methods
Ventilation	S01	Shut off outdoor air and night time out door air during unoccupied periods	**EWO**- Control strategy
		Use time-of-day scheduling, temperature setback, and setup, pre-occupancy purge	**H/COS**- Operation Schedule
		Seal all duct joints and seams (Ducts)	**MVR**- Mechanical ventilation
	S02	Use demand-controlled ventilation	**RMV**- Repair Mechanical ventilation, Natural ventilation
		Use air economizer	**MVR**- Mechanical ventilation
	S03	Minimize duct and fitting losses (Ducts)	**MVR**- Mechanical ventilation
		Change constant speed Vs. Variable speed fans	**RMV**- Repair Mechanical ventilation
HVAC	S01	Use control strategies that reduce energy use	**H/COS**- Operation Schedule
		Insulate ductwork	**RMV**- Repair Mechanical ventilation
	S02	Use high-efficiency fans	**HVAC20**- Ventilation system with HR
		Test, adjust and balance the air distribution system Use energy recovery to precondition outdoor air	**HVAC02**- Fan Coil Unit (4-Pipe) with District Heating + Cooling **HVAC03**- ASHP, Convectors, Nat Vent, PTAC Electric Heating, PTAC HW Heating,
		Select efficient energy recovery equipment	**HVAC04**- PTHP
		No ductwork outside the building envelope Divide building into thermal zones	**MVR**- Mechanical ventilation
	S03	Improve equipment efficiency	**HVAC02**- Fan Coil Unit (4-Pipe), Air-cooled Chiller, DOAS, Water Cooled Chiller, Water-side economizer, **HVAC03**- ASHP, Convectors, Nat Vent, PTAC Electric Heating, PTAC HW Heating, **HVAC04**- PTHP
		Enhance efficiency of HVAC systems	**HVAC05**- Radiator heating, Boiler HW (Mech. vent Supply + Extract, Mixed mode Nat Vent, Local comfort cooling, **HVAC07**- Radiators Electric
		Integrate systems, innovative and green systems	**HVAC06**- Split **HVAC01**- ASHP Hybrid with Gas Boiler, Nat Vent. **HVAC08**- VAV, Air-cooled Chiller, (Fan-assisted Reheat (Parallel PIU), HR, Outdoor air reset, mixed mode, Outdoor air reset, Steam humidifier, Air-side HR), **HVAC09**- VAV, Dual Duct, **HVAC10**- VAV, Water-cooled Chiller

Table 4. Control and renovation tasks and methods for HVAC and lighting systems (Cont.)

		Renovation tasks	Renovation methods
Lighting	S01	Use automatic controls to turn off lighting when not in use	**Li01**- Operation Schedule **Li02**- Canadian energy code
		Use separate controls for lighting in areas near windows	
	S02	Use efficient electric lighting system	**Li03**- LED with linear control, **Li04**- Fluorescent, High-frequency control, LINEAR dimming daylighting control, T5, **Li04**- Fluorescent, High-frequency control, with On/Off dimming daylighting control, T8, **Li05**- High-pressure Mercury **Li06**- High-pressure sodium
		Do not use incandescent lighting unless it will be infrequently used	
	S03	More efficient exterior lighting	

ASHP:	Air to Water Heat Pump	VAV:	Variable air volume
DOAS:	Dedicated Outdoor Air System	LED:	Light-Emitting Diode
FPID:	Fan-Powered Induction Unit	Max:	Maximum
HR:	Heat Recovery	PTAC:	Packaged Terminal Air Conditioner
Nat Vent:	Natural Ventilation	PTHP:	Packaged Thermal Heat Pump

4.2. Energy Analysis of the Existing Situation (ES)

To find the near optimal strategy for the renovation of the building, the mandatory data were added to the model. Table 5 shows a part of the input data, such as the building envelope materials, windows, operational schedule, allocation of building activities, building systems, temperature set points, and Domestic Hot Water (DHW), which are added to the energy simulation tool.

The energy tool calculates half-hourly temperatures, and heat flows from each zone. Additionally, the results demonstrate a comprehensive overview of the heat flows, systems loads, relative humidity, and total fresh air comfort conditions in each zone. The total site energy consumption estimate of the building components using the simulation tool is about 651,485 kWh, which is equal to 381 kWh/m^2; while the actual energy consumption based on the energy bills was measured to be 611,479 kWh, for the year 2014-2015, which reflects a 6.1% difference in the values. Comparing the results of the calculation with the energy bills shows that the results of the energy model are accurate with the acceptable level of discrepancy.

Table 5. Sample input data of the building characteristics.

Description	Characteristics
Roof surfaces	Flat roof U-value = 0.25 W/m^{2}K.
Exterior walls	Brick/ block exterior finishing (insulation to 1995 regulations)
Windows	Window to wall: 30% clear 6 mm glass, Double glazing in some parts, Preferred height: 1.5m, Spacing: 5m, Sill height: 0.8m, Frame and dividers: Steel and Aluminum
Airtightness	0.3 ACH constant rate, ON 24/7
Building operation Schedule	7:00- 23:00 Mon-Fri
Allocation of building Activities	Study spaces (classroom and atelier), office, mechanical and electrical room, restrooms, storage, and corridors.
Activity	Educational Facilities (multi use), Occupancy density (people/m^2): 1.0764, Winter clothing: 1.2 (clo), Summer clothing: 0.5 (clo)
HVAC system	Fan coil unit (4-Pipe), Air cooled chiller, Boilers and chillers are on 24/7, only the air systems shut off between 11:00 pm and 7:00 am
Temperature set	22°C cooling, 28°C cooling setback, 20°C heating, and 15°C heating set back
Heating	Natural Gas, Heating system seasonal CoP: 0.85, maximum supply air temperature: 45°C
Cooling	Electricity from grid, Cooling system seasonal CoP: 2.8- 3.2, minimum supply air temperature: 12°C
DHW	Electricity from grid, Dedicated hot water boiler, Delivery temperature: 65°C, main supply temperature: 10°C, CoP: 0.85, Consumption rate: 10-20 l/m^2-day

The results of the simulation shows that the heating system is sufficiently sized to make the load at design conditions as the air temperature never drops below the set point during the occupancy period and also never drops below the setback temperature of 15 ˚C. The model also shows that the air temperature increased to around 26 ˚C in the afternoon over several weeks, so the building is probably overheated, therefore some changes to the existing design or controls are required. Also, the results shows that the heating system has fluctuations especially in winter, which is confirmed by controlling the Zone Heating graph. Therefore, the system needs modification or repair to have more efficient outcomes. The fluctuation in the total fresh air graph explains that the variance in the infiltration rate seems significant and should be considered. Although the infiltration rate is set to a constant value and it is based on the reference temperature, changes in the variations in the indoor temperature should be studied.

4.3. Development of the Renovation Strategies

The formation of renovation strategies depends on different factors, such as the size of the project, results from the energy simulation of the case, and the severity of the building's problems, and renovation budget. In addition, the constraints of renovation scenarios provide the boundaries of the acceptable range of each method. The methods are also influenced by several factors, such as the availability of components in the market, the applicability of the method, and other requirements (i.e. the energy certification requirements, mandatory building renovation codes, and technical standards and regulations). Another factor vital for defining a renovation strategy, is the owner's preferences. For example, in the renovation, if the shape and size of certain windows are specified by the owner, these items should be considered 'as is' in the model (constraints 1). In this study, the requirements of facility management, which are mainly about the HVAC system and windows, are considered as owner's preferences. Selected renovation methods are from a wide range of predefined methods, and are assigned to different zones that are located next to the exterior of the building. An example of the definition of renovation strategies is shown in Table 6. Various options can be assigned to each strategy; however, a major renovation strategy usually involves medium and minor renovation methods along with its own methods. Based on the condition of the building and previously mentioned assessments, a major renovation strategy has been selected for this case study.

4.4. SBMO for Energy Performance, LCC, and LCA

In this section, the results of the SBMO are presented. The calculations were carried out on a computer with Intel® Core™ i7-3770 CPU@ 3.40 GHz processor and 8.00 GB RAM. Each optimization, on average, took 170 hours. Using SBMO provides the capability of testing renovation scenarios within their specified ranges to find out which combination of methods results in the near optimal solutions; therefore, the optimization usually requires running a significant number of simulations. The setting considered for the optimization algorithm in this research is 100 generations with a population size of 25 according to the DesignBuilder recommended setting . Due to the limitations of the software, multi-objective optimizations of TEC, LCC, and LCA are generated in pairs. In the first case, the TEC and LCC are considered as the two objective functions. In the second case, minimizing the TEC and the equivalent CO_2 emissions in the building's life cycle is studied. The model identified the near-optimal renovation scenarios for the case study building for all the specified renovation scenarios, as shown in Figures 5(a) and (b). The results include many combinations of the building's envelope, HVAC, and lighting renovation methods, considering different TEC that range from 229 MWh to 513 MWh, various LCC that range from CAD$3.6M to CAD$5.3M and LCA CO_2 equivalent from 3.9×10^6 Kg CO_2 eq to 20×10^6 Kg CO_2 eq for a period of 50 years.

	Design Variable	Minor (S01)			Medium (S02)			Major (S03)		
		Opt.	Min	Max	Opt.	Min	Max	Opt.	Min	Max
Building Envelop	Roof (R)	-	-	-	10	-	-	17	-	-
	External Wall (EW)	5	-	-	15	-	-	33	-	-
	Window frame (W)	4	-	-	4	-	-	6	-	-
	Façade Type (FT)	15	-	-	22	-	-	22	-	-
	Glazing template (G)	75	-	-	15	-	-	75	-	-
	Window to Wall (WWR)	-	30%	70%	-	30%	70%	-	30%	70%
Building Systems	HVAC template- (HVAC)	-	-	-	15	-	-	25	-	-
	Mechanical Ventilation rate (MVR)	-	0	10	-	-	-	-	-	-
	Cooling Operation Schedule (COS)	10	-	-	7	-	-	7	-	-
	Heating Operation Schedule (HOS)	10	-	-	7	-	-	7	-	-
	Airtightness (A)	-	0	4	-	-	-	-	-	-
	Lighting template (Li)	5	-	-	7	-	-	11	-	-
	External Window Open (WO)	-	0%	70%	-	0%	70%	-	0%	70%

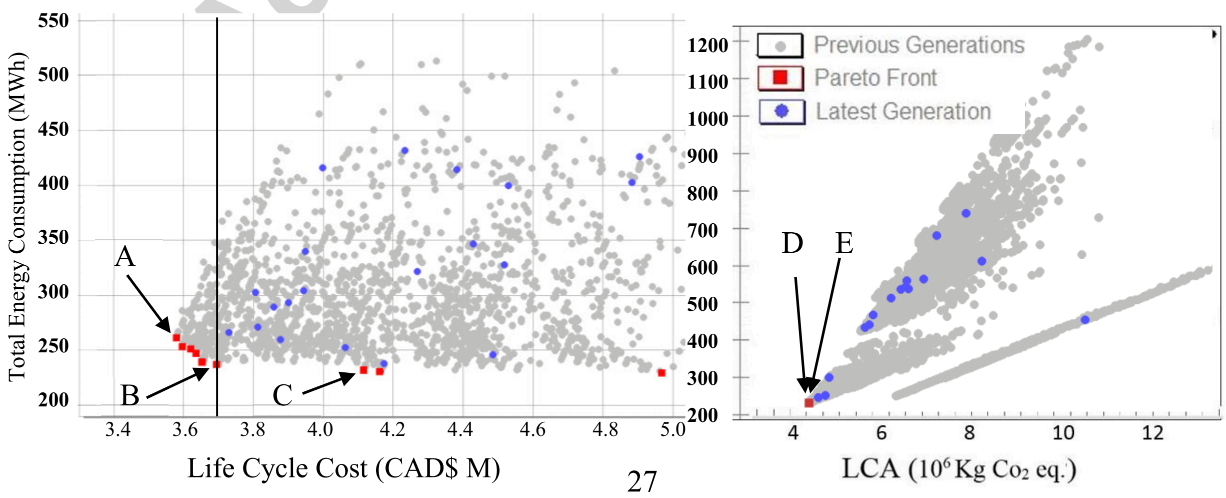
Table 6. Example of the definition of renovation strategies.

Opt.: the number of selected methods for each design variable.

Figure 5(a) shows the generated near-optimal solution of TEC and LCC for a major renovation strategy as explained in Section 4.4. In this figure, the Pareto front includes 22 near-optimal solutions. As can be observed, a decrease in the TEC can only be achieved by increasing the LCC. For instance, scenario A in Figure 5(a) has lower LCC of CAD$3.58 M, and it provides a reduction in the TEC (390,370 kWh/year) while in scenario C reduction in the TEC is higher (421,143 kWh/year) with higher LCC that is CAD$4.16M for the period of the study. Furthermore, scenario B, which is a moderate scenario offers more reduction in the TEC (414,695 kWh/year) with only CAD$115,000 increase in the LCC in comparison with scenario A. Therefore scenario B is selected and analyzed.

Figure 5(b) depicts the Pareto front result of TEC and LCA for the major renovation strategy. It shows that a reduction in LCA can only be attained by decreasing the TEC. In this figure, two optimal scenarios that favor each objective functions are revealed. However, the differences between these two scenarios are insignificant. Scenarios D and E have optimal environmental impacts (about 3.9×10^6Kg CO_2eq,) and low TEC (about 229,700 kWh). These two scenarios have very similar methods, the only differences are in EWO rates (34% vs. 8%) and the percentages of the glazed area in Façade types (10% vs. 20%).

The proposed results clarify the ability of the developed SBMO to create a wide range of near optimal solutions that offer optimal trade-offs among the three optimization objectives. Therefore, Decision-makers can explore results to find an optimal solution with an optimal balance among the objective functions while fulfilling predefined constraints. For instance, Figure 5(a) can be utilized to identify optimal solutions considering different TEC and LCC



(a) Total Energy Consumption vs. LCC (b) Total Energy Consumption vs. LCA

Figure 5. Two set of optimizations results

constraints. If the decision maker in this case study has a LCC constraint for CAD$3.7M to renovate the building for 50 years, it can be represented by a perpendicular line to the LCC axis, as shown in Figure 5(a). According to this specified constraint, Scenario B can be selected as the optimal solution that minimizes the LCC and TEC, simultaneously. Furthermore, the owner of the building can also be advised that an increase in the renovation budget from CAD$3.7M to CAD$5M does not have a significant effect on the reduction of TEC. The same investigation can be used to find out the least renovation scenario to achieve a specified environmental impact or required TEC. Figure 5(b) shows that the optimal solution for LCA is achieved only by reducing TEC to about 230,000 kWh/year. The action report that contains detailed information of all proposed building renovation methods for identified optimal scenarios A, B, C, D and E is shown in Table 8. A closer observation of the generated optimal results for Scenarios A and B in Table 8 and comparing these results with the original situation of the building (Table 5) reveal that in this renovation project; (1) *W, FT, WWR, HVAC* and *Li* should be modified, while only the insulation of the exterior walls should be improved and there is no need to change the roof. (2) TEC improvement of 24,325 kWh/year can be achieved (from scenarios A to B) by selecting different *EW* insulation, *FT, Li (*T5 to LED with linear control) and choosing different individual methods for *COS* and *HOS.* Comparison of scenarios A, B and D also shows that there are many similarities in proposed renovation methods such as *W, HVAC, Li,* and *WO.*

Scenarios D and E achieve the least LCA and TEC by recommending all possible methods that simultaneously cause the greatest reduction of negative environmental impacts and energy consumption simultaneously. The generated action report produced for scenario D recommends all applicable renovation methods for Scenario B, with some exceptions (i.e. *R, HVAC,* and *HOS* methods). Although they do not necessarily provide a similar TEC, differences are not significant.

4.5. Evaluation of Environmental Impacts Using ATHENA

Separate LCA was conducted to analyze the Pareto front results of the SBMO. In this section, the Operational Energy (OE) consumption and Embodied Energy (EE) of building components, construction, and demolition of Scenario B and ES are computed in ATHENA and compared with the results of DesignBuilder (Figure 6). There is a difference between these tools, due to differences in methods, databases, and reporting formats. SBMO uses DesignBuilder to calculate

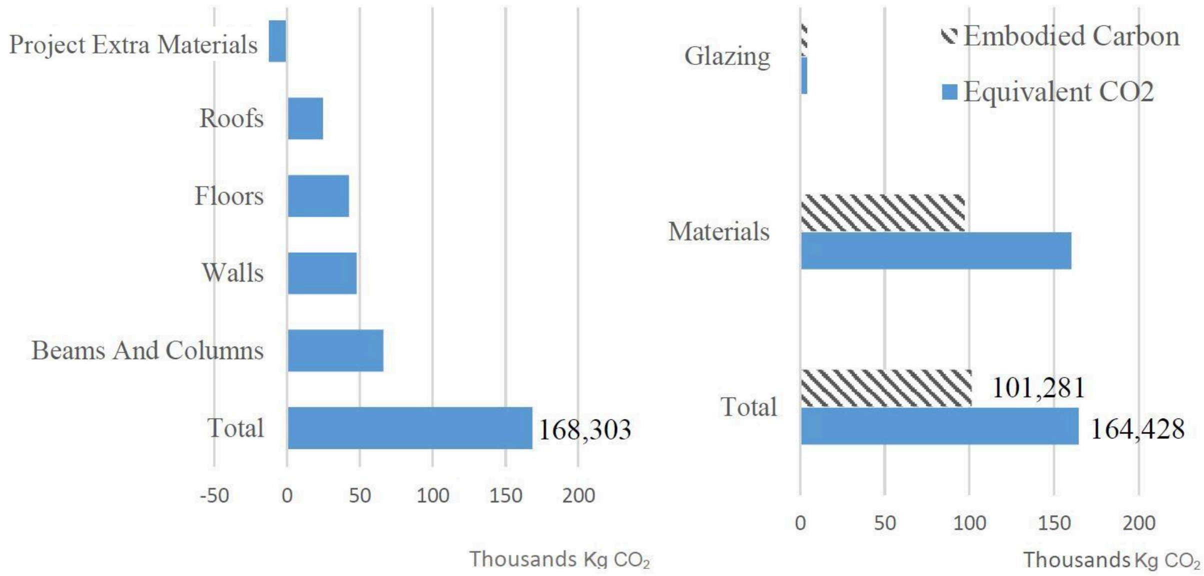
LCA based on bulk carbon data obtained from the Bath ICE and other data sources. The embodied carbon related to several building services, such as HVAC and lighting, is not considered in the final results. Furthermore, DesignBuilder reports embodied carbon and equivalent carbon separately; the latter considers the effects of other greenhouse gases as equivalent carbon. Furthermore, DesignBuilder calculates only operational energy . On the other hand, ATHENA calculates embodied and operational energy . It should be noted that both DesignBuilder and ATHENA do not capture all aspects of renovation projects. For example, although the comparison of the ES and the renovation scenario with respect to OE, EE, and LCA is possible, it still has some limitations. For instance, the impact of the components that have been removed in the renovation process is not included in the calculation.

The result of the LCA comparison between ATHENA and DesignBuilder is shown in Table 7, Figure 6 and Figure 7. Table 7 compares the TEC and GWP for Scenario B and ES. Figure 7(a) compares the total primary energy and fossil fuel for Scenario B. As illustrated in Figure 7(b and c), it is obvious that in Scenario B the EE consumption with a total of 719,418 kWh is higher than OE consumption (257,995 kWh) and the embodied GWP (E-GWP) with a total of 162,233 kg CO_2 eq is higher than operating GWP (O-GWP) with a total of 40,151 kg CO_2 eq for one year. Figure 6 shows a comparison between ATHENA and DesignBuilder for ES.

A careful comparison of ATHENA and DesignBuilder results shows that the OE consumptions is valid with a 2.7% difference in the values for ES, while in Scenario B, OE difference is higher (8.9%) for ATHENA because this scenario selects more efficient HVAC method, simplification of the HVAC in ATHENA, and differences in calculation methods. EE comparison is not possible because DesignBuilder only calculates OE. As shown in ATHENA part of Table 7, the 669,160 kWh of the OE consumed in the ES that has fallen to 257,994 kWh for Scenario B (Figure 7 (b)), mainly due to the new HVAC, EW, W, COS, HOS and lighting methods. The EE for ES is 722,083 kWh and itdecreased to 719,419 kWh for Scenario B (Table 7). Table 7 compares the ATHENA and DesignBuilder results for O-GWP and E-GWP for ES and Scenario B. Differences between equivalent CO_2 amount from DesignBuilder and E-GWP amount from ATHENA, which are comparable concepts, are negligible in both ES (2.3% higher for ATHENA) and Scenario B (4.2% higher for DesignBuilder). However, operational GWP comparison is not possible due to the limitations of DesignBuilder. Comparison between E-GWP for ES and Scenario B for ATHENA shows a slight decrease in Scenario B. A significant reduction in O-GWP from ES (114,456 kg CO_2 eq per year) to Scenario B (40,150 kg CO_2 eq per year) can be observed. There are two reasons for this: First, utilizing different renovation methods. Second, the majority of the components and materials used in Scenario B are in direct contact with the outdoor environment. It is worthy to mention that ATHENA library supports only a limited number of green materials and components that can be considered as a constraint of the software.

Table 7. Environmental impact sample report of the existing situation (ES) and Scenario B

		DesignBuilder		ATHENA		Differences
TEC kWh	Existing situation	OE	651,485	OE	669,160	2.7%
		EE	NA	EE	722,083	NA
	Scenario B	OE	236,790	OE	257,994	8.9% (HVAC)
		EE	NA	EE	719,419	NA
GWP kg CO_2 eq	Existing situation	O-GWP	NA	O-GWP	114,456	NA
		Equivalent CO_2	164,428	E-GWP	168,302	2.3%
		Embodied Carbon	101,281	NA	NA	NA
	Scenario B	O-GWP	NA	O-GWP	40,150	NA
		Equivalent CO2	169,110	E-GWP	162,233	4.2%
		Embodied Carbon	102,504	NA	NA	NA



(a) ATHENA IE results (b) DesignBuilder results

Figure 6. ES comparison of (a) Global Warming Potential LCA Measure (exported from ATHENA), (b) Embodied Carbon and Inventory (exported from energy simulation tool).

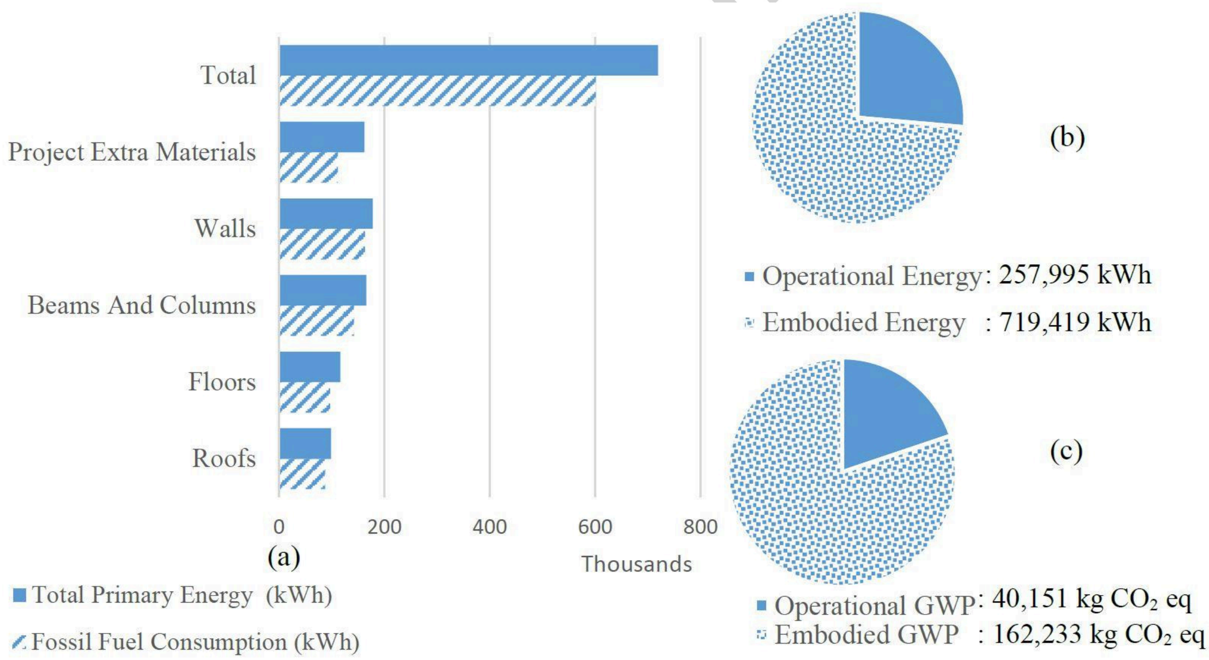


Figure 7. (a) Total Primary Energy and Fossil Fuel Consumption, (b) Operational vs. Embodied Energy consumption and (c) Operational vs. Embodied GWP, ATHENA results for Scenario B

Table 8. Detailed list of components implemented in the selected renovation scenarios.

	Method	TEC vs. LCC		
		Scenario A	Scenario B	Scenario C
Building Envelope	R	Project flat roof U-value = 0.25 W/m2K	Project flat roof U-value = 0.25 W/m2K	Combined semi-exposed Roof U-value = 0.25 W/m2K
	EW	Semi-exposed wall Typical reference LW (LW metallic Cladding 0.01 m+ XPS 0.09 m+ Gypsum Plastering 0.01m)	Wall - State-of-the-art - MW (Brickwork Outer 0.11m+ XPS 0.12m+ Concrete 0.1m+ Gypsum Plastering 0.01m)	Wall - State-of-the-art - MW (Brickwork Outer 0.11m+ XPS 0.12m+ Concrete (M) 0.1m+ Gypsum Plastering 0.01m)
	W	Project BIPV Wall	Project BIPV Wall	Project BIPV Wall
	FT	Fixed windows - H:1 m, W: 0.5	Preferred height 1.5m, 10% glazed	Fixed windows - H:1 m, W: 1m
	WWR (%)	42	42	38
Building Systems	HVAC	Radiators Electric, Natural Ventilation	Radiators Electric, Natural Ventilation	Radiators Electric, Natural Ventilation
	COS	Max Outdoor temp for Nat Vent: Always 100	6:00 - 18:00 Mon – Fri	Mixed mode temperature control
	HOS	Max Outdoor temp for Nat Vent: Always 100	On 24/7	Max Indoor temp for Nat Vent: Always 100
	Li	T5 (16mm diam) Fluorescent, triphosphor, high-frequency control	LED with linear control	LED with linear control
	EWO (%)	50	66	54
TEC (kWh)		261,115	236,790	230,342
LCC (CAD)		3,579,913	3,695,244	4,161,893

(a)

Method	TEC vs. LCA	
	Scenario D	Scenario E
R	Roof, Metal Building, R-19+10 (3.3+1.8), U-0.041 (0.232)	Roof, Metal Building, R-19+10 (3.3+1.8), U-0.041 (0.232)
EW	Wall - State-of-the-art - MW (Brickwork Outer 0.11m+ XPS 0.12m+ Concrete (M) 0.1m+ Gypsum Plastering 0.01m)	Wall - State-of-the-art - MW (Brickwork Outer 0.11m+ XPS 0.12m+ Concrete (M) 0.1m+ Gypsum Plastering 0.01m)
W	Project BIPV Wall	Project BIPV Wall
FT	Preferred height 1.5m, 10% glazed	Preferred height 1.5m, 20% glazed
WWR (%)	56	52
HVAC	Split no fresh air	Split no fresh air
COS	6:00 - 18:00 Mon – Fri	6:00 - 18:00 Mon – Fri
HOS	6:00 - 18:00 Mon – Fri	6:00 - 18:00 Mon – Fri
Li	LED with linear control	LED with linear control
EWO (%)	34	8
TEC (kWh)	229,694	229,777
LCA (Kg CO_2 eq)	3,921,015	3,916,236

(b)

XPS: XPS Extruded Polystyrene- CO_2 Blowing
LW: Lightweight
MW: Medium weight

5. CONCLUSIONS AND FUTURE WORK

Quantifying the environmental impacts and simulating the energy consumption of building's envelope and systems at the renovation phase are very critical for decision-makers for the selection of the best renovation scenarios that would lead to a more energy efficient building. This research presented a SBMO that is capable of optimizing the building renovation scenarios to minimize the TEC, LCC and the environmental impacts of existing buildings. The methodology is used by developing a model that simulates the process of renovating buildings by using the renovation data in energy analysis software to analyze TEC, LCC, and LCA, and identify the potential renovation scenarios that can be implemented based on the selected renovation method. Furthermore, an LCA tool is used to cross-check the results the environmental sustainability of the final decision.

A case study of one floor of an existing building was studied to assess the implementation of the developed model. LCA and TEC have strong linear correlation in comparison with the LCC and TEC. It is worthy to mention that the optimization in the first case has a larger number of Pareto solutions because energy consumption and LCC are conflicting objectives. Comparing the LCC per TEC for the Pareto solutions clarifies the efficiency of them. This comparison demonstrates that there is a better potential in reducing TEC in Scenario B than in Scenario A since with a slight increase in LCC, significant decrease in TEC is attained. Furthermore, the energy saving improvement from scenario A to B is 24,325 kWh/year, which is significant. It would be interesting as a future work to evaluate the sustainability of the proposed buildings renovation scenario based on Leadership in Energy and Environmental Design (LEED) rating system.

ACKNOWLEDGMENT

This research was made possible by "Fonds de recherche du Québec Nature et technologies" (FRQNT) award from the Quebec government and a scholarship from "Pierre Arbour Foundation".

REFERENCES

Abaza, H. (2008). An interactive design advisor for energy efficient building. Journal of Green Building, 3(1), 112–125.

Abdallah, M. and El-rayes, K. (2015). Optimizing the selection of building upgrade measures to minimize the operational negative environmental impacts of existing buildings. Building and Environment, 84, 32–43.

AIA, The American Institute of Architects (2007). Integrated Project Delivery: A Guide, ver. 1. Retrieved 1, 9, 2017, from http://www.aia.org/ipdg.

Alev, Ü., Eskola , L., Arumägi, E., and Jokisalo, J. (2014). Renovation alternatives to improve energy performance of historic rural houses in the baltic sea region. Energy and Buildings, 77, 58–66.

Alshamrani, O., Galal, K., and Alkass, S. (2014). Integrated LCA-LEED sustainability assessment model for structureand envelope systems of school buildings. Building and Environment, 80, 61-70.

Anand , C. and Amor, B. (2017). Recent developments, future challenges and new research directions in LCA of buildings: A critical review. Renewable and Sustainable Energy Reviews, 67, 408-416.

Asadi, E., Silva, M. G. da, Antunes, C. H., Dias, L., and Glicksman, L. (2014). Multi-objective optimization for building retrofit: A model using genetic algorithm and artificial neural network and an application. Energy and Buildings, Elsevier, 81, 444–456.

Ascione, F., Bianco, N., De Stasio, C., Mauro, G. M., and Vanoli, G. P. (2017). CASA, cost-optimal analysis by multi-objective optimisation and artificial neural networks: A new framework for the robust assessment of cost-optimal energy retrofit, feasible for any building. Energy and Buildings, Elsevier B.V., 146, 200–219.

Asdrubali, F., Baldassarri, C., and Fthenakis, V. (2013). Life Cycle Analysis in the construction sector: Guiding the optimization of conventional Italian buildings. Energy and Buildings, 64, 73- 89.

ASHRAE Design Guide (2014). Advanced energy design guide for small to medium office buildings. Book. Atlanta, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Athena Impact Estimator. (2017, 10 14). Athena Impact Estimator for Buildings V4.2 Software and Database Overview. Retrieved 10, 14, 2017, from https://calculatelca.com/software/impact-estimator/user-manual/

Bouchlaghem, NM. and Letherman, KM. (1990). Numerical optimization applied to the thermal design of buildings, Build Environ, 25(2),117–24.

Bolattürk A. (2008). Optimum insulation thicknesses for building walls with respect to cooling and heating degree-hours in the warmest zone of Turkey, Building and Environment, 43, 1055–1064.

Bowick, M., O'Connor, J., and Meil, J. (2014). Athena Guide to Whole-Building LCA in Green Building Programs,1–41.

Branke, J., Deb, K., and Miettinen, K. (Eds.). (2008). Multiobjective optimization: Interactive and evolutionary approaches (Vol. 5252). Springer Science & Business Media.

Buyle, M., Braet, J., and Audenaert, A. (2013). Life cycle assessment in the construction sector: A review. Renewable & Sustainable Energy Reviews, 26, 379–88.

Cabeza, L., Rincón, L., Vilariño, i., Pérez, G., and Castell, A. (2014). Life Cycle Assessment (LCA) and Life Cycle Energy Analysis (LCEA) of buildings and the building sector: A review. Renewable and Sustainable Energy Reviews, 29, 394-416.

CaGBC the Canadian Green Building Council (CaGBC). Retrieved 2, 14, 2017, from: https://www.cagbc.org/.

Chantrelle, F. P., Lahmidi, H., Keilholz, W., Mankibi, M. El, and Michel, P. (2011). Development of a multicriteria tool for optimizing the renovation of buildings. Applied Energy, Elsevier Ltd, 88(4), 1386–1394.

CBC News. (2016, 10 5). CBC News. Retrieved 2, 14, 2017, from: http://www.cbc.ca/news/canada/montreal/mcgill-concordia-quebec-buildings-university-1.3793180

Chang, Y., Huang, Z., Ries, R. j., and Masanet, E. (2016). The embodied air pollutant emissions and water footprints of buildings in China: a quantification using disaggregated input–output life cycle inventory model. Journal of Cleaner Production, 113, 274-284.

Cohon J. L (1978). Multi-objective Programming and Planning. New York: Academic Press.

Crawford, R. (2008). Validation of a hybrid life-cycle inventory analysis method. Journal of Environmental Management, 88, 496–506.

Deb, K., Partap, A., Agarwal, S., and Meyarivan, T. (2002). A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE Transactions on Evolutionary Computation, 6 (2), 182-197.

Deb K., (2001). Multi-objective optimization using evolutionary algorithms. [Book]. New York : John Wiley and Sons.

Delgarm, N., Sajadi, B., Kowsary, F., & Delgarm, S. (2016). Multi-objective optimization of the building energy performance: A simulation-based approach by means of particle swarm optimization (PSO). Applied Energy, 170, 293–303.

DesignBuilder Software Ltd. (2016). DesignBuilder. Retrieved 1, 1, 2016, from https://www.designbuilder.co.uk/

de Vasconcelos, A. B., Pinheiro, M. D., Manso, A., and Cabaço, A. (2015). A Portuguese approach to define reference buildings for cost-optimal methodologies. Applied Energy, 140, 316-328.

De Wilde, P. (2014). The gap between predicted and measured energy performance of buildings: A framework for investigation. Automation in Construction, 41, 40-49.

DiLouie, C. (2008). Lighting Controls Handbook. NY, Illuminating Engineering Society.

Diwekar U. (2013). Introduction to Applied Optimization. Springer Science and Business Media.

DOE-2, Retrieved 1, 5, 2016, from http://doe2.com

e-QUEST, Retrieved 11, 1, 2015, from http://doe2.com/equest/

Eastman, C., Teicholz , P., Sacks, R., and Liston, K. (2008). BIM handbook: a guide to building information modeling for owner, managers, designers, engineers, and contractors. New York, John Wiley& Sons.

Evins, R. (2013). A review of computational optimisation methods applied to sustainable building design. Renewable and Sustainable Energy Reviews, Elsevier, 22, 230–245.

Eurostat. (2010). Environment and Energy Europe in figures: Eurostat yearbook. Luxembourg: Office for Official Publications of the European Communities.

Flores-colen, I., and Brito, J. De. (2010). A systematic approach for maintenance budgeting of buildings façades based on predictive and preventive strategies. Construction and Building Materials, Elsevier Ltd, 24(9), 1718–1729.

Galiotto, N., Heiselberg , P., and Knudstrup, M.A. (2015). Integrated Renovation Process Overcoming Barriers to Sustainable Renovation. Journal of Architectural Engineering, 21(3), 04015007.

gbXML site. Retrieved 7, 7, 2015, from http://www.gbXML.org/. last reviewed, 12/12/2017.

Goldberg DE. (1989). Genetic algorithms in search, optimization and machine learning. Addison Wesley.

Giebeler, G., Krause, H., Fisch, R., Musso, F., Lenz, B., & Rudolphi, A. (2009). Refurbishment manual: maintenance, conversions, extensions. Walter de Gruyter.

Häkkinen, T. and Kiviniemi, A. (2008). Sustainable building and BIM, Melbourne, Australia.

Holland J. H. (1975) Adaptation in natural and artificial systems: an introductory analysis with applications to biology, control, and artificial intelligence [Book], USA: University of Michigan Press.

Huang, J., Lv, H., Gao, T., Feng, W., Chen, Y., and Zhou, T. (2014). Thermal properties optimization of envelope in energy-saving renovation of existing public buildings. Energy and Buildings, Elsevier B.V., 75, 504–510.

Intergovernmental Panel on Climate Change. (2007). Climate Change 2007: The Physical Science Basis. Switzerland, WMO.

International Alliance for Interoperability (IAI). (2006). IFC Model View Definition. Retrieved 1, 11, 2016, from http://www.blis-project.org/IAI-MVD/.

Itard, L. and Meijer , F. (2008). Towards a sustainable Northern European housing stock (Vol. 22). Amsterdam: Delft Center for Sustainable Urban Areas.

Jalaei, F. and Jrade, A. (2014). Integrating Building Information Modeling (BIM) and energy analysis tools with green building certification system to conceptually design sustainable buildings. Journal of Information Technology in Construction,19, 494-519.

Jin, Q., and Overend, M. (2012). Facade renovation for a public building based on a whole-life value approach. First Building Simulation and Optimization Conference, 417–424.

Juan, Y.K., Gao, P., and Wang, J. (2010). A hybrid decision support system for sustainable office building renovation and energy performance improvement. Energy and Buildings, 42, 290–297.

Kibert, C. J. (2008). Sustainable construction: green building design and delivery. New Jersey, Wiley, Hoboken.

Kolokotsa, D., Rovas, D., Kosmatopoulos, E., and Kalaitzakis, K. (2011). A roadmap towards intelligent net zero- and positive-energy buildings. Solar Energy, 85(12), 3067–3084.

Konstantinou, T. (2014). Façade refurbishment toolbox. Delft University of Technology, Faculty of Architecture and The Build Environment.

Kumar S. (2008). Interoperability between Building Information Modeling (BIM) and energy analysis programs, MSc thesis, University of southern California, USA.

Loonen, R., Singaravel, S., Trčka, M., Cóstola, D., and Hensen, J. (2014). Simulation-based support for product development of innovative building envelope components. Automation in Construction, 45, 86-95.

Nakayama H., Yun Y. and Yoon M. (2009). Sequential Approximate Multiobjective Optimization Using Computation Intelligence. [Book]. Berlin: Springer-Verlag Berlin Heidelberg.

Natural Resources Canada. (2015). Survey of Commercial and Institutional Energy Use (SCIEU), Buildings, Retrieved from Natural Resources Canada. Retrieved 1, 8, 2016, from https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/data_e/databases.cfm

Nguyen, A.-T., Reiter, S., and Rigo, P. (2014). A review on simulation-based optimization methods applied to building performance analysis. Applied Energy, Elsevier Ltd, 113, 1043–1058.

Ouyang, J., Ge, J., and Hokao, K. (2009). Economic analysis of energy-saving renovation measures for urban existing residential buildings in China based on thermal simulation and site investigation. 37, 140–149.

Palonen, M., Hasan, A., and Siren, K. (2009). A Genetic Algorithm For Optimization Of Building Envelope And Hvac System Parameters. 11th International IBPSA Conference, Building Simulation 2009, 159–166.

Penna, P., Prada, A., Cappelletti, F., and Gasparella, A. (2015). Multi-objectives optimization of Energy Efficiency Measures in existing buildings. Energy and Buildings, Elsevier B.V., 95, 57–69.

Schwartz, Y., Raslan, R., and Mumovic, D. (2015). Multi-objective genetic algorithms for the minimisation of the life cycle carbon footprint and life cycle cost of the refurbishment of a residential complex's envelope: a case study. SimAUD '15 Proceedings of the Symposium on Simulation for Architecture & Urban Design, 189–196.

Sharif, S. and Hammad, A. (2017). Simulation-based optimization of building renovation considering energy consumption and life-cycle assessment. International Workshop on Computing in Civil Engineering (IWCCE 2017). Seattle: University of Washington.

Statistics Canada, (2008). Retrieved 1, 9, 2015, from https://www45.statcan.gc.ca/2008/cgco_2008_000-eng.htm

Straube, J. and Burnett, E. (2005). Building Science for Building Enclosures (Book). Westford, Mass, Building Science Press Inc.

Tuominen, P., Klobut, K., Tolman, A., Adjei, A., and de Best-Waldhober, M. (2012). Energy savings potential in buildings and overcoming market barriers inmember states of the European union. Energy Build., 51, 48-55.

U.E.P.A. (2011). U.E.P.A. 2011 Green building-basic information. Retrieved 1, 1, 2015, from http://www.epa.gov/greenbuilding/pubs/about.htm.

U.S. Environmental Protection Agency. (2011). Strategic sustainability performance plan. U.S. Environmental Protection Agency.

USGBC US Green Building Council (USGBC), LEED is green building Retrieved 5, 5, 2017, from https://new.usgbc.org/leed.

Vandenbroucke , M., Galle, W., De Temmerman, N., Debacker, W., and Paduart, A. (2015). Using life cycle assessment to inform decision-making for sustainable buildings. Buildings, 5(2), 536-559.

Wang, W., Rivard, H., and Zmeureanu, R. (2005). An object-oriented framework for simulation-based green building design optimization with genetic algorithms. Advanced Engineering Informatics, 19, 5-23.

Wetter, M., and Wright, J. (2004). A comparison of deterministic and probabilistic optimization algorithms for nonsmooth simulation-based optimization. Building and Environment, 39(8), 989-999.

WCED. (1987). Our common future. World Commission on Environment and Developmen. New York: Oxford.

Wilde, P. (2014) The gap between predicted and measured energy performance of buildings: A framework for investigation, Automation in Construction, 41, 40-49.

Highlights:

- Developing a comprehensive simulation-based optimization method for building renovation.
- The method considers energy consumption, lifecycle cost and environmental impacts.
- The selection of the near-optimum renovation scenarios depends on the combination of methods and on case-specific constraints.