

Sustainable Energy Modeling for Office Buildings Through Energy Efficiency Strategies

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Abstract

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As older buildings are not compliant with modern energy standards such as ASHRAE or the National Building Code of Canada, they are generally less energy efficient than newer buildings. National Research Council data indicate that although the energy efficiency of commercial and institutional buildings improved by about 15% over the last two decades, total energy demand increased by about 19%, and would likely have exceeded 30% without modern materials and efficiency practices. In cold climates, office buildings have high heating-related energy use, making cost-effective retrofits essential.

This thesis evaluates the energy and economic impacts of retrofit strategies for office buildings in Montréal's cold climate (ASHRAE Zone 6A). Two representative office building archetypes were modeled using a physics-based bottom-up Building Energy Modeling (BEM) approach in DesignBuilder: (1) a modern, code-compliant office tower reflecting contemporary efficiency standards (Type A), and (2) an older office tower with a weaker envelope and less efficient building systems (Type B). A wide range of retrofit scenarios was simulated, including envelope upgrades, glazing improvements, ventilation and heat-recovery measures, lighting controls, and operational schedule optimization. Economic performance was assessed using Simple Payback Period (SPP) and Discounted Payback Period (DPP) to evaluate financial feasibility across different investment and energy-saving levels.

Results show that that combined retrofit packages consistently outperformed single-measure upgrades in both energy savings and economic value. These findings provide practical guidance for engineers, building owners, and policymakers seeking cost-effective and high-impact retrofit pathways for commercial office buildings in cold-climate regions such as Montréal.

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Dedication

This thesis is dedicated to my beloved sister, whose sacrifices and unconditional support sustained me throughout this journey, and to my parents, whose love, guidance, and lifelong encouragement shaped the path that led me here.

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Chapter 1 Introduction

1.1 Background and Research Motivation

The building sector is one of the largest contributors to global energy consumption and greenhouse gas emissions, accounting for nearly 30% of total energy use worldwide (World Business Council for Sustainable Development, 2023). Many old office buildings still operate with outdated envelopes (CaGBC, 2022), inefficient glazing systems (CaGBC, 2022), and older mechanical equipment. As cities move toward sustainability and carbon neutral goals, improving the energy performance of these existing buildings has become more necessary (IEA, 2021). According to the National Research Council data, the energy efficiency of commercial and institutional buildings has improved by about 15% in the period from 2000 to 2018, while in the same period the energy demand in those buildings has increased by about 19%. The energy consumption in those buildings would have increased to 33% without adopting any energy efficiency measures. Considering that, in this sector, \$3.4 billion was saved in energy cost and 6.0 Mt in Green House Gas Emission could be avoided in 2018 (NRC, 2026).

Montreal (ASHRAE Zone 6A) is a city that has a long winter and it has high energy consumption in heating section (Natural Resources Canada, 2022). So, if the building envelope or mechanical system is inefficient it can be losing more energy. One of the possible solutions is to improve the existing office buildings with efficient components to reduce energy consumption. To achieve efficiency in buildings, programs like, LEED have been introduced to encourage better building envelopes and more efficient Heating, Ventilation, and Air Conditioning (HVAC) systems (ASHRAE, 2016; National Research Council of Canada, 2017).

Building Energy Modeling (BEM) is a powerful tool for understanding how buildings use energy and for testing retrofit strategies before implementation (Reinhart & Cerezo Davila, 2016). BEM allows the creation of models with details and examines how different components such as walls, windows, HVAC systems, lighting, and occupancy schedules affect total energy demand (Hong et al., 2016).

To support large-scale and comparative retrofit analysis, building archetypes are often employed. Archetypes are representative models of groups of buildings that are constructed based on common characteristics (Gavalda, 2024). Accordingly, building patterns are classified in different ways, including patterns based on architecture era (CaGBC, 2022; NRC, 2020), performance-based patterns (DOE, 2020), climate-based patterns (Hong et al., 2016), building code-based patterns (ASHRAE, 2016), energy consumption-based patterns (Sokol et al., 2017), and construction and feature-based patterns (Cerezo Davila et al., 2016; Al Jadaa & McArthur, 2024)

Choosing which retrofit strategy is suitable is a difficult part for owners because it has a financial cost for them based on what retrofit they want to do; and there are a lot of upgrade options such as

facade improvements, window glazing changes, HVAC upgrades, lighting replacements, and control adjustments. So, choosing the right combination of retrofit is often confusing for them.

Despite the importance of retrofitting, there is still limited practical guidance on which retrofit strategies contain both high energy savings and short payback periods (Ma et al., 2012). Choosing the best retrofit strategy is often difficult for building owners because many different upgrade options exist, such as improving insulation, replacing windows, tightening the building envelope, upgrading HVAC systems, or changing lighting and operating schedules. Each of these measures has different costs and different levels of energy savings, which makes them uncertain (Zhang, 2020). Although certain retrofit actions can achieve considerable energy reductions, they often require high investment costs, while cheaper upgrades usually offer only small improvements and limited reductions in energy use (Maleki, 2009).

This study adopts an archetype-based approach to represent typical office buildings in Montréal's cold climate. Two representative office building archetypes were developed based on construction period and energy code compliance: a post-code modern office building (Type A) and a pre-code older office building (Type B). While the models are informed by real buildings through site observations and available documentation. They serve as representative reference models that allow systematic evaluation of retrofit strategies and comparison across different baseline conditions.

Better understanding of different retrofit strategies in both energy saving and cost can be useful for them and can help owners and engineers to make a better decision. By using energy models, it is possible to test retrofit scenarios before doing any action and have a good insight into financial investments and then decide which retrofit is suitable and has a rapid payback period.

1.2 Problem Statement and Research Questions

Compliance with energy standards such as National Energy Code of Canada for Buildings (NECB) and ASHRAE energy codes makes buildings more efficient. Because many of Montreal's office buildings are old, they are less efficient than these standards. Many of these structures were operated with poor insulation, single glazing, and outdated air conditioning systems, which increases the heating load. On the other hand, there are buildings in Montreal that are newer and built to energy standards, some even LEED certified at various levels, which are highly energy efficient but have a much higher capital cost.

Most existing studies either focus on individual technologies, provide general recommendations, or do not combine detailed building energy modeling with financial evaluation. So, owners cannot make a good decision on which retrofit strategy is better than others for office buildings that are located in cold climate. So, there is a need for research that evaluates energy retrofit solutions based on the categories of archetypes that are seen in office building. It is also important to

determine for which archetype groups what kind of retrofit can be effective and then compare different retrofit types and estimate which one has a better cost.

This study investigates two kinds of archetypes and tries to address this problem by modeling two representative office buildings in Montreal, simulating different retrofit scenarios, and analyzing their energy and economic performance to determine which strategies offer the best balance between efficiency and cost.

Although many retrofit technologies are available, there is still limited practical guidance on how to select retrofit strategies that balance energy savings, investment cost, and payback period, particularly for office buildings in cold climates. Many existing studies focus on individual retrofit measures or emphasize energy performance without sufficient economic evaluation. As a result, building owners and engineers often lack clear decision-support tools for prioritizing retrofit actions.

This study addresses the following research questions:

- What retrofit strategies can achieve the highest energy savings in Montréal office buildings?
- Which retrofit solutions remain economically viable with acceptable payback periods?
- How should retrofit priorities differ between older and newer office buildings?

1.3 Research Objectives

To support sustainability by reducing energy consumption, the objectives of the present research are identified as follows.

- To develop a method to reduce energy consumption in a building to support sustainability
- To Identify efficient retrofit strategies in office buildings by minimizing energy consumption
- To identify economically viable retrofit strategies to minimize payback time
- To offer useful guidelines for decision-makers

1.4 Organization of the Thesis

This thesis is organized into five main chapters.

Chapter 1 introduces the research background and motivation, defines the problem statement, outlines the research objectives, and explains the overall structure of the thesis.

Chapter 2 reviews the existing literature related to building energy modeling, building archetypes, retrofit strategies, and previous studies focusing on energy efficiency and economic performance of office buildings.

Chapter 3 presents the research methodology in this study. It describes the research framework, data collection process, definition of modeling parameters, selection of building cases, development of energy models using Design Builder, retrofit scenario design, and economic evaluation methods.

Chapter 4 discusses the analysis and results of energy simulations. It presents the baseline performance of the selected office buildings and evaluates the energy and economic impacts of the proposed retrofit scenarios.

Chapter 5 concludes the thesis by summarizing the key findings, shows the scientific contributions of the research, and discussing the limitations of the study along with recommendations for future research.

Chapter 2 Literature Review

2.1 Energy Modeling Scales in the Built Environment

Energy modeling in the built environment can be categorized into two primary scales:

(1) Building Energy Modeling (BEM) and (2) Urban Building Energy Modeling (UBEM). (Reinhart & Davila, 2016).

Building Energy Modeling (BEM) and Urban Building Energy Modeling (UBEM) are tools to evaluate and predict energy performance at both the individual building and urban scales. BEM analyzes the energy use of an individual building by considering its envelope, mechanical systems, and occupancy. UBEM expands this approach to model the total energy use of multiple buildings across a neighborhood or city (Piro et al., 2023).

Building Energy Modeling (BEM) is a computer simulation of energy performance within a single building. BEM provides a detailed way to compare alternative designs, retrofit scenarios, and operational strategies. Widely used simulation tools such as EnergyPlus, TRNSYS, and DesignBuilder can estimate a building's energy consumption, comfort performance (Reinhart & Davila, 2016).

Urban Building Energy Modeling (UBEM) combining many individual BEM models or using the archetypes category applies the same principle in a city scale. UBEM models the built environment as a connected energy system that includes buildings, infrastructure, and environmental factors (Ferrando et al., 2021); while BEM focuses on the individual building as a system (Ali et al., 2021). Figure below shows the two main scales of energy modeling in the built environment. Building Energy Modeling (BEM) focuses on the performance of a single building, while Urban Building Energy Modeling (UBEM) extends this approach to the urban scale, analyzing energy use across districts or entire cities.

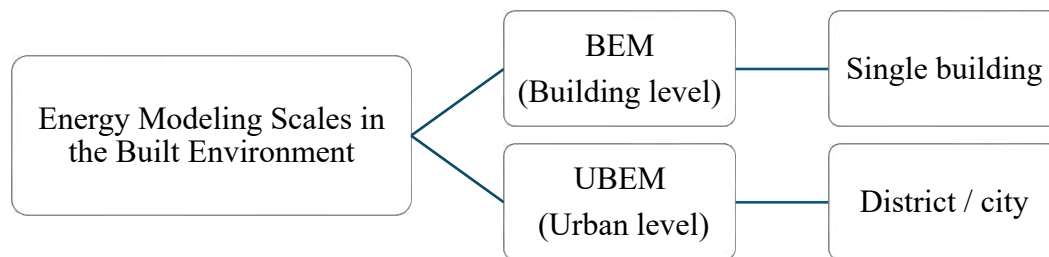


Figure 2.1 Energy Modeling Scales in the Built Environment (Driven Reinhart & Davila, 2016)

2.2 Classification of Building Energy Models and Urban Building Energy Models

There are several methods that are used to model energy consumption, and these methods are divided into three main groups: top-down models, bottom-up models, and hybrid models.

- Top-down model depends on large scale data like population, and total energy use, energy prices, or city-wide fuel use (Swan & Ugursal, 2009). Although this method is effective for large scale forecasting, it cannot show the physical features or operational patterns of individual buildings (Li et al., 2017). For this reason, top-down methods estimate city-wide energy demand using city scale statistics, not physical features so they can be useful in UBEM models.
- Bottom-up model calculates energy demand using building level details like construction materials, heating and cooling systems, internal loads, and how occupants use space (Swan & Ugursal, 2009). Because of bottom-up methods provide this level of detail of building can be considered for BEM. These models are usually divided into two groups:
 - (1) Statistical models that use meter readings records, survey data or machine-learning methods to relate building features to energy consumption (Swan & Ugursal, 2009).
 - (2) Engineering or physics-based models, which estimate energy performance using thermodynamic calculations and dynamic simulation programs such as DesignBuilder, EnergyPlus or TRNSYS. Physics-based bottom-up models are the most accurate for evaluating retrofit options and design choices because they explicitly model heat flows, system behaviour, and environmental conditions (Kavgic et al., 2010).
- Hybrid methods combine the strengths of both top-down and bottom-up models to better accuracy (Li et al., 2017). This kind of modeling is useful for UBEM models because UBEM looks at energy use for whole areas like neighborhoods or cities and therefore needs both building details and city-wide information (Ali et al., 2021).

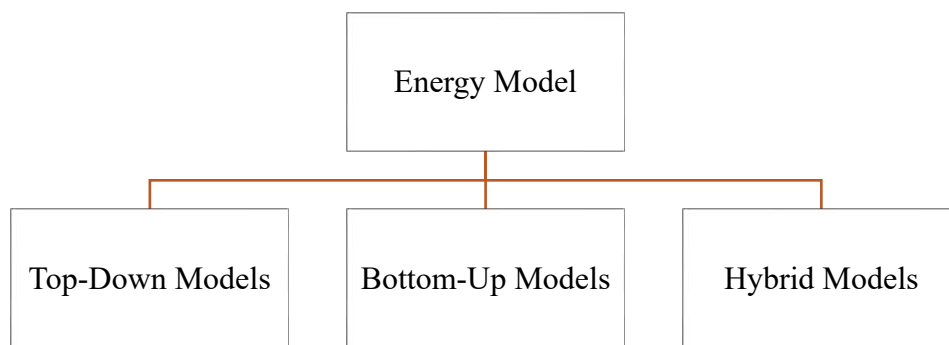


Figure 2.2 Classification of Energy Modeling (Swan & Ugursal, 2009; Li et al., 2017; Kavgic et al., 2010)

Figure 2.2 shows these classifications: Top-down (Li et al., 2017), Bottom-up (Ferrando et al., 2021; Kavgic et al., 2010) and Hybrid (Li et al., 2017; Ali et al., 2021)

2.3 Building Archetype Concept and Classification

Archetypes are typical building models that show characteristics of a group of buildings with similar features, based on things like construction age, function, geometry, or energy system (Deru et al., 2011). Archetypes are example buildings that stand in for many similar buildings.

Building archetypes has an important role in both Building Energy Modeling (BEM) and Urban Building Energy Modeling (UBEM) because they let researchers study many buildings at once without needing detailed data for each one separately.

Instead of collecting full geometric, material, and operational data for thousands of buildings, archetypes provide typical models that show groups of buildings with similar characteristics. This saves time, reduces effort, and keeps the results reliable.

Archetypes can be selected by using several parameters, including energy code level (Deru et al., 2011), construction period or vintage (Hong et al., 2016), building function or use (Ali et al., 2021), typical energy consumption levels, geometric form (Ferrando et al., 2021), and climate zone (Deru et al., 2011).

Figure 2.3 below shows different ways to group buildings into archetypes for use in Building Energy Modeling (BEM) and Urban Building Energy Modeling (UBEM). It groups buildings according to their shared building features, age, type, energy use, shape, code level, and climate zone. Many large numbers of buildings can be represented using a small set of representative examples.

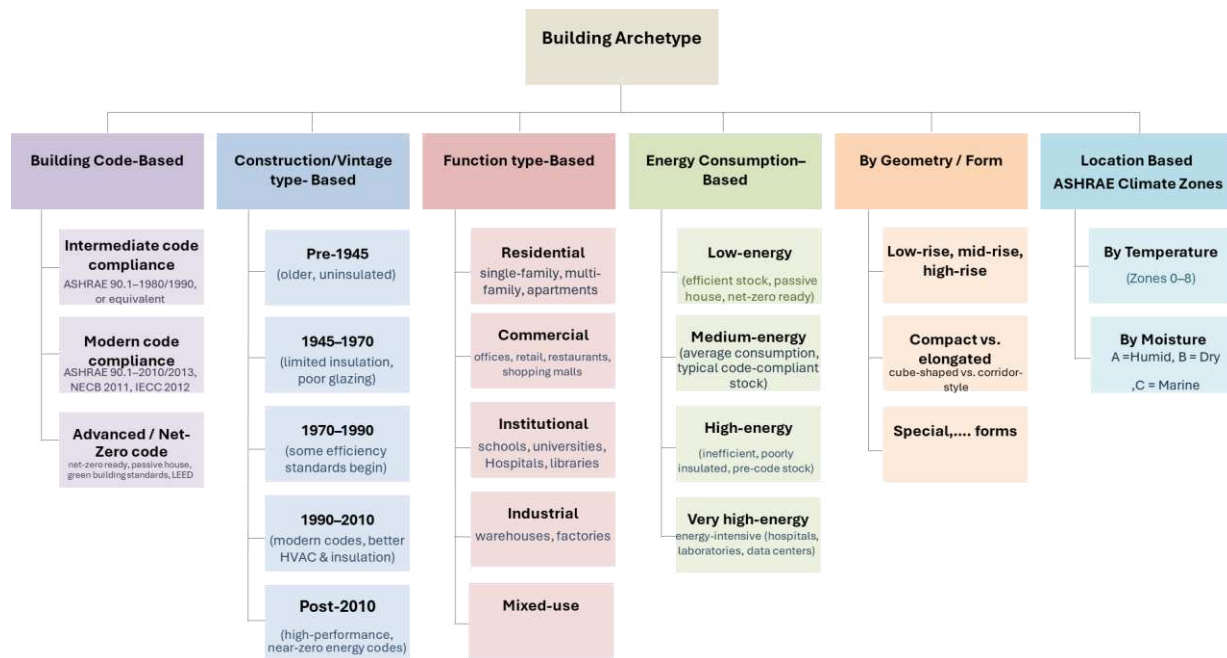


Figure 2.3 Building Archetype Categories

Figure 2.3 shows that some studies group buildings by the standards that were used when the building was constructed. Others sort them by the year they were built, because older buildings usually have different insulation, windows, and heating systems than newer ones. Another way is to organize buildings by their function, such as homes, offices, schools, or factories. Buildings can also be grouped by how much energy they normally use, separating low energy buildings from those that waste a lot of energy. Some studies focus on the building's shape, such as whether it is tall, short, compact, or spread out. Another common method is to classify buildings based on the climate they are located in, since weather strongly affects heating and cooling needs. Overall, these different options show that building archetypes can be created in many ways depending on data availability and the purpose of the model.

In BEM, archetypes show what a typical building looks like and how it works, including its materials, insulation, HVAC systems, and how people use it. With these models, we can run accurate simulations to test design or retrofit options.

2.4 Review of Previous Studies

In Kavgić et al. (2010), the authors wanted to solve the problem that there was no clear summary of how energy modeling is done for residential buildings. To reach this, they reviewed existing building stock modeling approaches. First, they divided modeling techniques into Top-down and Bottom-up methods. Then, they explained three types of Bottom-up models: statistical models, physics-based models, and hybrid models that combine both. Next, they compared well-known models from different countries. For each model, they looked at the type of data required, the level of detail, the inputs and outputs, accuracy, and the strengths and weaknesses. Their study found that physics-based Bottom-up models give the most accurate results, but they require a lot of detailed building data. When real data are missing, the results can be unclear or unreliable. They also said that uncertainty and user behavior strongly affect energy use and should be considered in future models. They suggested that upcoming models will move toward hybrid and combined approaches (Kavgić et al., 2010).

In the review study by Nayak et al. (2021), the authors examined how researchers use building archetypes to estimate energy consumption in residential buildings. To do this, they collected studies published between 2004 and 2021 from major databases. They kept only papers that used archetypes to predict residential building energy use. They extracted the modeling method (Top-down or Bottom-up) and the scale of analysis (national, city, or local level) used and how archetypes were classified (based on climate zone, construction age, building shape, function, or energy-use level). Advantages and limitations of each approach from each study. According to their findings, most archetype classifications rely on climate, year of construction, and building type. However, the review highlighted a major challenge: many studies do not include real occupant behavior, which can lead to inaccurate energy predictions (Nayak et al., 2010).

According to the study that done by Hong et al. (1016), with the title of “CityBES: A Web-Based Platform to Support City Scale Building Energy Efficiency,” used the CityBES platform to import basic city building data into a simulation environment. They used a web-based urban building energy platform called CityBES to import basic city building data. Then, they created detailed building simulations by combining CityGML 3D models with the EnergyPlus simulation engine through OpenStudio. They evaluated energy performance across an entire city’s building. They considered 4 archetype categories for their research:

1. Building Function (Use Type)

They classified buildings based on their function, such as offices, commercial stores, residences, hospitals, hotels, and other types.

2. Construction Vintage (Year of Construction / Energy Generation)

Buildings were grouped according to when they were built and which energy standards applied at that time, such as different versions of ASHRAE 90.1 or Title 24.

3. Climate Zone

They used EnergyPlus weather files (for example, the Manhattan climate file) to define the real heating and cooling needs of each building type.

4. Geometry and Physical Characteristics (from CityGML)

The shape and size of buildings were defined using 3D data, including floor area, height, number of stories, window-to-wall ratio, orientation, and overall building form.

They did several retrofit strategies, including improvements to building envelopes (additional insulation, high-performance glazing, and reduced air leakage), lighting and plug loads (LED retrofits, daylight controls, and smart plug systems), and upgrades to HVAC and water-heating systems (high-efficiency equipment, economizers, advanced control systems, and efficient gas water heaters). and for the last step they analyzed cost and payback. The result of their study shows that retrofit measures achieving approximately 30% energy savings are generally cost effective and offer short payback periods, whereas deeper retrofits had 50% savings and it require greater investment but long-term economic and environmental benefits for cities (Hong et al., 2016).

In the study done by Parekh (2005), a quick and easy method express to evaluate energy use and suggest retrofits for Canadian houses. With this method, inspectors do not need to measure every detail of a home. The authors collected real information from more than 3,800 low-rise houses, including insulation levels, window types, heating and water-heating efficiency, air leakage, and electricity and hot-water use. Some data came from direct measurements, and some from field surveys and official records. Next, homes were grouped into archetypes based on building type,

year built, and climate region. They choose 5 regions in Canada, and each region had its own values because houses and weather conditions were not the same everywhere. These typical models were turned into default libraries that contained standard values for: wall, roof, and floor insulation, window types, heating and water heating efficiency, air leakage, and electricity and hot water use. These values were entered into the HOT2 XP software. When an inspector visited a home, they only needed to enter basic information such as the house type, location, and dimensions. The software automatically filled in the rest using the appropriate archetype. If more accurate information was available, the inspector could update the default value. Finally, the software simulated the home's energy use and suggested the best retrofit options, such as adding more insulation, upgrading the heating or water heating system, and reducing air leakage. It also estimated how much energy each retrofit could save and ranked the options. This method reduced energy evaluations from several days to only 2–3 hours, while still providing accurate and reliable results (Parekh et al., 2005).

In the paper by Ali et al. (2021) called “Review of Urban Building Energy Modeling (UBEM) approaches, methods and tools,” the authors compare different ways of modeling building energy use at the city scale. They explain that choosing a UBEM method should depend on the data that is available, the scale of the project, and whether the goal is design or policy making, rather than only focusing on the highest technical accuracy. The article groups UBEM strategies into four main categories: Top-down models, Physics-based Bottom-up models, Data-driven or AI-based Bottom-up models and Reduced-order simplified models. The study shows that:

- Physics-based Bottom-up models are the most accurate but need lots of data and take a long time.
- Top-down models are fast and good for policy studies.
- Data/AI models work very well when there is a lot of data available.
- Reduced-order models give good results quickly and work well for city-scale studies.

Overall, the authors suggest that future UBEM will hybrid and combine different methods to get the best balance between speed and accuracy (Ali et al., 2021).

The paper with title of "Urban building energy modeling e A review of a nascent field" explains that the best way to model energy use at the city scale is through a Bottom-up approach based on building archetypes. Modeling every building with full detail is not possible for the whole city, so UBEM groups similar buildings into representative categories. In this method, available information such as construction years, building use, geometry, and climate is collected first. Buildings that share similar characteristics are placed into the same archetype. Then, a standardized thermal model is created for each archetype, including envelope properties, heating systems, and typical operation schedules. These models are simulated to estimate energy use. In the final step, the results are checked by comparing the simulations with real energy use data on the city scale. The study finds that the biggest challenge in UBEM is defining accurate archetypes,

because most cities do not have complete and reliable building data. Many values must be filled with assumptions. The authors conclude that UBEM models can only become more precise if cities provide better access to actual energy use records (Reinhart et al.,2016).

The paper Ding & Zhou (2020), “Profiling Urban Building Energy Use with Archetype Modeling and Statistical Prediction,” focuses on how to estimate city wide building energy use when detailed data are not available. The authors created three basic building types for Wuhan—residential buildings, small office buildings, and large office buildings. They used the CRECS database to collect important information such as building age, construction materials, heating and cooling systems, and how people use energy inside the buildings. These building types were then simulated in EnergyPlus, and the results were matched with real urban energy data to improve accuracy. The researchers then ran randomized simulations, creating hundreds of scenarios that varied building age, insulation levels, ventilation systems, and user behavior. The final step converted the complex simulation results into a fast statistical regression model, allowing energy use to be predicted for thousands of buildings without running EnergyPlus again. The study shows that even with limited data, cities can build a reliable urban energy database (Ding et al.,2020).

In the study with a title of “U.S. Department of Energy Commercial Reference Building Models of the National Building Stock” done by Deru et al. (2011), the main goal was to create reliable reference energy models for commercial buildings in the United States. These models would allow researchers, engineers, and policymakers to analyze building energy use and test retrofit strategies without having to build new models from beginning. To develop these references, the authors first used real building data from the national CBECS database to identify the most common commercial building types in the U.S. Next, for each building type, they created EnergyPlus models that included three construction vintages (pre-1980, post-1980, and new buildings compliant with ASHRAE standards). The models also put real building shapes and sizes, construction materials, HVAC system types, internal loads, and occupancy schedules. After completing the process, they produced 768 EnergyPlus models, representing 16 commercial building types across 16 climate zones. Results showed that these reference models show more than 60% of all commercial buildings in the United States. This means they can now be used as a common baseline for retrofit analysis, energy policy development, building standards, and evaluating new energy efficient technologies without needing to create new simulations each time (Deru et al., 2011).

Pongelli et al. (2022) worked on a method to include real Swiss building characteristics in energy simulations without doing on-site measurements. The research team made use of a large national dataset of building energy certificates (CECB) to build authentic residential archetypes that could be used in simulation programs. Rather than working with estimates or general assumptions, they pulled physical and energy information directly from real certificates. They began by filtering and organizing over 50,000 records, then grouped the buildings by two residential categories single-family and multi-family and by nine construction periods from 1919 to the present. This process

resulted in 18 real world archetypes, each containing actual values for building component U-values, geometric form, floor area, number of stories, energy source, and heating system type. Their findings showed that using real building data produces archetypes that actual energy performance more accurately than using standards or hypothetical values. As a result, these data driven archetypes are more reliable for retrofit planning and urban energy policy development (Pongelli et al., 2022).

Bernier et al. (2024) studied how single-family homes in Québec use energy without running simulations for millions of houses. To do this, they used only a small number of representative homes called archetypes. The research team used a large database (QSFBSSEM) that contains 200,000 houses already simulated with TRNSYS. They first cleaned the data and removed unusual cases. Then, instead of taking a simple average, they analyzed real energy behavior using a CDF statistical method to understand how homes actually use energy. After that, they chose specific houses whose yearly energy use and peak electricity demand were typical examples of their group. These houses were modeled again in TRNSYS and tested with different heating system scenarios. The final results showed that these selected archetypes can very accurately represent homes across the whole province, with an error of only 0.27% for annual energy use and 0.41% for peak electricity. This means that a few chosen models can replace millions of full simulations (Bernier et al., 2024).

In the study with the title of "A GIS-Based Approach to Estimate Energy Savings and Indoor Thermal Comfort for Urban Housing Stock Retrofitting" by Mastrucci et al. (2014), the authors looked for a way to estimate the energy use and indoor comfort of all residential buildings in Rotterdam without having to simulate each building individually. Instead of creating a separate model for every house, they built a bottom-up archetype model. First, they used GIS information from the city, such as building type, construction period, shape and size, number of units, and population data. Based on the patterns found in this dataset, the researchers created 16 representative building archetypes, grouped by housing type, year built, and geometry. Next, these archetypes were simulated in EnergyPlus under two scenarios: existing buildings, and after energy upgrades. The retrofit options tested included: adding wall and roof insulation, installing better windows such as Low-E glazing, reducing air leakage, and using more efficient heating systems. Finally, the results from these simulations were expanded to the entire city and displayed on GIS maps. The study showed that improving building envelopes and heating systems could save around 1.23 TWh of energy per year. However, the authors said that these upgrades might increase indoor temperatures during summer, meaning energy retrofits must be paired with strategies like shading or night ventilation to avoid overheating (Alessio Mastrucci, et al., 2014).

In the paper with the title of "Three methods for characterizing building archetypes in urban energy simulation: A case study" by Cerezo et al. (2016), the authors studied different ways of creating archetypes affecting the accuracy of urban energy modeling. They monitored electricity use from 140 single-family houses in Kuwait and recorded their real consumption. Next, they built three

different archetype models: (1) A basic model using information from codes and previous studies; (2) A more detailed model that used local data and building age; and (3) An advanced probabilistic model that added occupant behavior using statistical distributions and Monte Carlo simulation. All three archetypes were simulated in EnergyPlus and compared with the real electricity data. The results showed that the probabilistic model was the most accurate, while the building age model was cheaper and still reliable for city scale decisions. The study also found that simpler methods can work well for estimating retrofit savings across a city, but understanding actual user behavior requires a more advanced probabilistic approach (Cerezo et al.,2017).

In the thesis “Modelling Neighborhood-Scale Energy Scenarios” by Louis Leroy (2020), for four real buildings in Montreal (three residential and one commercial), several different archetypes were constructed, including age, form, and function, with different levels of detail in different software (UMI, EnergyPlus, TRNSYS, and SIMEB), and their results were compared with real measured data. (Leroy, 2020). Also, according to Ferrando et al. (2020), the types of archetypes used in UBEM tools and models are: Code-Based, Form-Based, Energy System-Based, Vintage-Location Based, Function-Based (Ferrando et al., 2020).

Also, there are others studied to see which archetype methods are used most often, thirteen studies published between 2017 and 2025 were reviewed. The table below shows which criteria each study used to create building archetypes.

Table 2.1 Classification of Reviewed Studies Based on Building Archetype Parameters

	Papers	Code-Based	Vintage	Function-Based	Energy-Based	Geometry Form	Location
1	Hong et al., 2016	✓	✓	✓			✓
2	Parekh et al., 2005		✓	✓			✓
3	Reinhart et al., 2016		✓	✓		✓	✓
4	Ding et al., 2020		✓	✓	✓		✓
5	Deru et al., 2011	✓	✓	✓		✓	✓
6	Pongelli et al., 2022		✓			✓	
7	Mastrucci et al., 2014		✓	✓		✓	✓

8	Nayak et al., 2021		✓	✓	✓	✓	✓
9	Cerezo et al., 2017	✓	✓	✓		✓	✓
10	Leroy, 2020		✓	✓		✓	✓
11	Bernier et al., 2024				✓		
12	Ferrando et al., 2020	✓	✓	✓	✓	✓	✓

By examining the selected papers, it appears that building age (vintage), building function, and location/climate are the most commonly used archetype criteria; almost all studies include these three because they strongly affect how buildings use energy. They directly affect envelope insulation, occupancy schedules, and heating/cooling demands. Geometry/form is also used in many cases (8 out of 11 studies), especially when detailed 3D or GIS data are available. In contrast, code-based archetypes are applied in only a small group of papers (4 studies), and energy performance-based archetypes are rare (2 studies), as they require more detailed data that is not always available for every city (Figure 2.4).

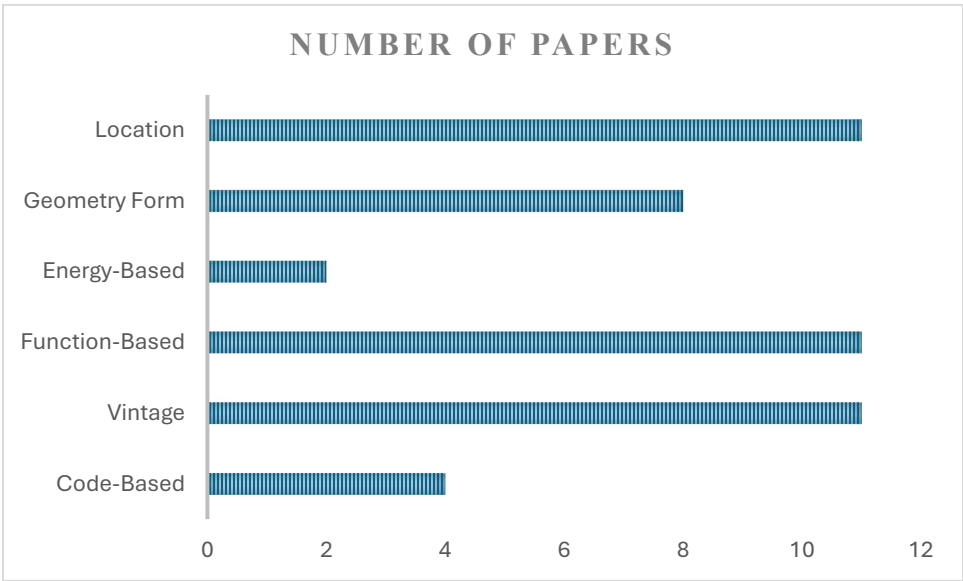


Figure 2.4 Comparison of archetype classification criteria used in selected studies

There are also others studying regarding retrofit strategy. In the thesis by Jahed (2018), the researcher explored how office buildings can improve their energy performance with a focus on façade retrofits. The study began by reviewing common difficulties in upgrading office buildings

and then using a step-by-step performance approach to evaluate facades in terms of heat performance, daylight, noise, and the interior layout of workspaces. Based on this evaluation, three retrofit strategies were introduced:

- Stabilization – small or incremental improvements like sealing air leaks or adding shading devices.
- Substitution – replacing parts of the façade, such as installing new windows or materials.
- Double-skin façade – adding a second glass layer to increase insulation and thermal control.

The findings show that choosing the right facade retrofit should not be based only on energy savings. It must also consider how the office interior is used and how the solution affects thermal comfort, daylight quality, and acoustic performance. Some upgrades may reduce energy use but negatively affect the comfort of building occupants, so a balanced decision is necessary (Jahed, 2018).

In Engblom’s paper (2006) with a title of “Scenario Analysis of Retrofit Strategies”, the aim was to examine and compare the energy performance of buildings with different retrofit scenarios. They identified the energy consuming components of the building (HVAC, shell, windows, control system, lighting, etc.). Then, for each component, two types of retrofit options were defined:

- Standard Retrofit according to building regulations,
- Low-Energy Retrofit based on the best available low energy models on the market.

In the next step, for each scenario, the actual values of the equipment (such as heat pump type, heat recovery efficiency, window glass type, insulation level and system control type) were entered into the modeling. The scenarios were simulated. The results showed that what retrofit option saves the most energy (Engblom, 2006).

According to Pacific Northwest National Laboratory and PECO (2011), the goal was to find practical and cost-effective ways to improve energy performance in office buildings. The guide introduces a three-step approach to retrofits:

- Existing Building Commissioning (EBCx): fixing operational problems without replacing major equipment. This includes improving controls and reducing unnecessary ventilation.
- Standard Equipment Upgrades: replacing common building components such as HVAC units, lighting systems, and windows with higher efficiency options that meet current standards.
- Deep Integrated Retrofit: upgrading the building envelope, mechanical systems, and lighting together.

According to the guide, this step-by-step method can start with low-cost savings of up to 25%, and if buildings move toward deep, integrated retrofits, they can achieve 45% energy reduction (Pacific Northwest National Laboratory & PEI, 2011).

Chapter 3 Research Methodology

3.1 Research Framework

This research uses a Bottom-Up Building Energy Modeling (BEM) approach because it uses detailed physics-based simulation of individual buildings. In a bottom-up framework, each building is modeled using its physical characteristics such as envelope properties, HVAC systems, occupancy patterns, and geometry allowing retrofit strategies to be evaluated with high accuracy. According to the literature review in Chapter 2, the most common and influential archetype parameters used for energy simulation are construction vintage, building function, and climate/location, since these strongly affect insulation quality, glazing type, internal loads, and heating/cooling demand. Based on these criteria, two representative office buildings (as a function archetype) in Montréal (as a location archetype) were selected; to show the energy behavior of typical office buildings from two different construction periods (as vintage archetype) to model typical office energy performance in Quebec’s cold humid climate zone (as a climate archetype).

The table presents a classification framework for office buildings in Montréal based on the most influential criteria used in Building Energy Modeling (BEM). Two representative archetypes (A–B) are defined to reflect the diversity of construction practices, usage, and energy performance in the city. These categories were selected because literature shows that construction code, age, function, and climate strongly influence building energy demand, HVAC type, insulation levels, and glazing performance.

Table 3.1 Office Building Archetype Classification Based on Energy Code Compliance

Archetype	Energy Code	Baseline Energy Performance
Type A	Post-Code	Modern high-rise office building designed under contemporary Canadian energy efficiency requirements (e.g., NECB-based), characterized by improved envelope insulation, high-performance glazing, and efficient HVAC systems.
Type B	Pre-Code	Older high-rise office buildings were constructed prior to the widespread adoption of modern energy efficiency standards, characterized by weaker envelope performance, less efficient glazing, and outdated mechanical systems.

The archetypes are primarily classified based on energy code compliance, Archetype classification based on construction vintage, reflecting differences in energy code influence and baseline building performance. Building function (office), climate (Montréal, ASHRAE Zone 6A), and geometry (high-rise) are held constant.

Each archetype represents a typical group of office buildings primarily classified based on energy code compliance, with construction period and baseline energy performance used as supporting characteristics. In this study, two representative high-rise office building archetypes were defined. Type A represents post-code office buildings designed under modern energy regulations, while Type B represents pre-code office buildings constructed before the widespread enforcement of energy codes and characterized by lower baseline energy performance.

By grouping buildings into these two types, complex building stocks can be simulated without modeling each building individually. This approach reduces time and data requirements while still representing real variations in building performance across Montréal's climate zone (ASHRAE Zone 6A). These archetypes are later used to test retrofit strategies and compare the energy and economic impact of improvements on different building categories.

One older office building and one newer building are selected for the study. The older office building was built before modern energy codes, and the other represents newer offices constructed under updated regulations. This comparison helps identify how retrofit strategies perform differently depending on the building's age and original design.

The first building, Model (1), is a high-rise office tower built in 2017. Because it represents a modern building type, its energy model was developed according to the requirements of the National Energy Code of Canada for Buildings (NECB 2017) for Climate Zone 6 in the National Energy Code of Canada for Buildings (National Research Council of Canada & Canadian Commission on Building and Fire Codes, 2017) which applies to Montreal's cold and humid conditions. Key envelopes and HVAC assumptions were based on the minimum energy standards for new construction, including efficient glazing systems, higher insulation levels, and modern mechanical systems.

The second building, Model (2), represents a typical office building, constructed in 1976 before mandatory energy codes were widely enforced. These buildings commonly include poor insulation, high-conductive windows, inefficient HVAC systems, and uncontrolled air leakage.

Based on NRC Major Energy Retrofit Guidelines in 2022 it directly written "Major energy efficiency retrofits, involving several energies retrofit measures across more than one building system, typically lead to energy savings of 15 to 40 %" (NRC, 2022).

Because complete architectural data was not available, the building was modeled in DesignBuilder using site observations, measured dimensions taken on-site, and envelope estimates from literature and historic construction for that period.

Once both baseline (existing condition) models were developed, different upgrade measures were tested. These scenarios included envelope improvements, glazing upgrades, shading, HVAC improvements, lighting, plug load reduction, operational control strategies such as night setbacks and schedule. A sensitivity analysis was done to evaluate the impact of building retrofits on energy

consumption. The main reason for this analysis was the uncertainty surrounding the actual energy savings that could be achieved through various upgrade measures (e.g., window glazing, wall insulation, roof envelope, HVAC systems). To achieve this, three categories of retrofit scenarios were defined:

- Low-level retrofit, which focuses on simple, low-cost actions such as improving controls, reducing infiltration, and upgrading lighting efficiency.
- Medium-level retrofit, in which building elements such as windows and portions of the envelope are replaced with more efficient options that meet current standards.
- High-level retrofit, which applies advanced measures like high-performance glazing, substantial insulation upgrades, and high-efficiency HVAC systems designed for deep energy savings.

These scenarios were compared with the baseline to identify the most effective and cost-efficient solution for each building type.

Each scenario was simulated and compared to the original baseline model in order to evaluate:

- energy savings (kWh/m²/year)
- annual cost savings (CAD/year)
- capital investment required (CAD)
- payback period (years)

By comparing an older pre-code building and a newer code-compliant building, the study shows how the same retrofit measure can produce different benefits, technical savings and financial payback periods depending on the building's vintage and baseline performance. It has benefits in the industry by cutting time and cost for energy audits. Improving how office buildings use energy helps reduce pollution and supports goals for cleaner, low-carbon cities.

Figure 3.1 shows the overall research framework used in this study. The framework is organized into four main steps: literature review, methodology development, retrofit strategy evaluation, and decision-making. **In Step 1**, a literature review was conducted to understand existing building energy modeling approaches and retrofit strategies. This step identifies important building energy modeling methods and key parameters used to describe building archetypes, including construction vintage, building function, location, climate, and energy code influence. **Step 2** describes the main methodology of the study. First, data were collected through site visits, observations, academic literature, previous case studies, and professional standards. This information was then used to develop detailed energy models in Design Builder. Important model inputs included climate data, construction materials, glazing properties, HVAC and lighting systems, internal loads, schedules, and cost inputs. The models produced outputs related to energy performance, such as annual energy use and energy savings, as well as economic results, including energy cost savings, retrofit investment cost, and payback period. **In Step 3**, different retrofit

strategies were developed and tested. Retrofit scenarios were grouped into low, medium, and high levels, representing basic improvements, moderate upgrades, and deep retrofit measures. Energy simulation results and cost calculations were combined to evaluate the performance of each retrofit option. Finally, **Step 4** focuses on decision-making. In this step, all retrofit scenarios were compared based on their energy savings and economic performance. The results were used to identify the best retrofit package that provides the highest energy benefits with reasonable costs and payback periods for office buildings in Montréal’s cold climate.

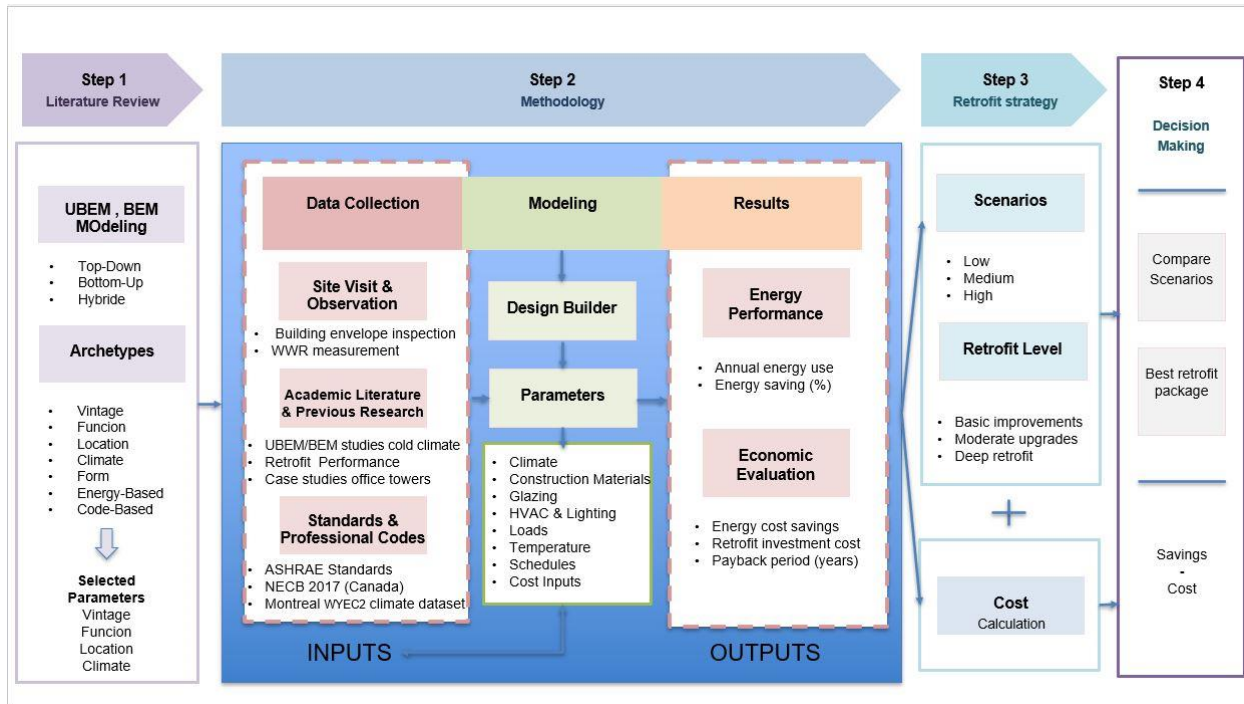


Figure 3.1 Research Framework

In this study, information about the two office buildings was collected through site visits, basic documents, and trusted technical sources. During the building visits, simple measurements were taken, such as window size, Window to wall ratio, floor height, wall dimensions, and the amount of shading. The type of windows, the building orientation, and how people used each floor were also observed. These observations helped estimate lighting, plug loads, and occupancy schedules.

Because full architectural and mechanical plans were not available, some missing information such as insulation levels and air leakage was taken from reliable standards and research. For the newer building, envelope properties were based on the National Energy Code of Canada for Buildings (NECB, 2017). For the older building, typical values found in studies on Canadian pre-code construction were used. HVAC system efficiencies were selected according to ASHRAE guidelines for each construction period.

The weather in Montréal has a big effect on heating demand because the city has a cold and humid climate (zone 6A). The official EnergyPlus weather file for Montréal was used in the simulation.

For cost analysis, Hydro-Québec electricity rates were used to calculate operating costs. Retrofit costs were entered by DesignBuilder's built-in cost database automatically selected realistic prices for materials and equipment based on the building's location, climate zone, and typical Canadian construction. This allowed retrofit costs to match the local market without extra calculations.

Overall, the study combined three types of information: direct building observations, trusted standards, and local cost and weather data. This approach made it possible to build accurate energy models even without full access to building drawings.

3.2 Data Collection

Data were collected through site visits, direct observations, academic literature, previous case studies, and professional standards.

Climate data were obtained from standard Canadian weather files for the study location.

For both Building Type A and Building Type B baseline models, key parameters such as building dimensions (used to calculate floor area), construction material, glazing properties, window-to-wall ratio (WWR), lighting systems, and office occupancy schedules were defined based on site observations.

The Heating, Ventilation, and Air Conditioning (HVAC) system type and roof characteristics were estimated according to typical design practices for buildings of similar age, size, and function in the same area. The thermal properties (U-values) of construction materials for Building Type A were defined based on National Energy Code of Canada for Buildings (NECB,2017) requirements, reflecting modern code-compliant construction. For Building Type B, U-values were selected based on typical characteristics of old office buildings, informed by the National Energy Code of Canada for Buildings and relevant literature.

Material and retrofit costs were estimated using the DesignBuilder cost database, ensuring consistency across all retrofit scenarios. and electricity and gas cost are taken from Hydro Quebec website. These costs were used to evaluate the economic performance of each retrofit option, including annual savings and payback periods.

3.3 Definition of Parameters

To build energy models, several physical and operational parameters and system-related parameters needed to be defined. These parameters describe how the buildings consume energy and how different retrofit measures influence heating, cooling, and electricity demand. Since complete drawings were not available, the parameters were chosen using a combination of on-site

observations, energy standards, and research on Canadian construction practices. All values were then entered into Design Builder simulations.

The defined parameters can be grouped into the following categories:

- **Building Envelope Parameters:**

These parameters characterize the thermal performance of the building envelope and include wall, roof, and floor insulation levels, window-to-wall ratio, glazing type, and air infiltration rates. Envelope properties for the newer, code-compliant building were defined using NECB 2017 requirements, whereas representative values from studies of Canadian pre-code construction were used for the older building.

- **HVAC and Mechanical System Parameters**

Mechanical parameters include heating and cooling system efficiency, ventilation rates, heat recovery efficiency, and system control strategies. HVAC system characteristics were selected according to each construction period.

- **Internal Loads and Occupancy Parameters**

Internal gains from occupants, lighting, and plug loads were defined based on building observations and standard office occupancy schedules.

- **Climate and Weather Inputs**

All simulations were performed using the official EnergyPlus weather file for Montréal, representing ASHRAE Climate Zone 6A.

- **Parameters Affecting Retrofits**

Several parameters were designed to change according to each retrofit scenario:

- U-values of walls, roofs, and windows
- Glazing type (double or triple)
- Infiltration rate
- HVAC system efficiency
- Lighting power density
- Mechanical control improvements

By adjusting these values across low, medium, and high retrofit levels, the model could measure both how much energy can be saved and how practical each option is in real buildings.

3.4 Typical Building Envelope Systems in Office Buildings

Typical building envelope systems in office buildings include the main exterior elements that separate the indoor environment from outdoor conditions, such as exterior walls, windows, and roofs. These systems play a critical role in controlling heat transfer, air leakage, moisture movement, and solar radiation, and therefore have a strong influence on overall building energy performance and occupant comfort. This section provides an overview of common envelope systems used in office buildings, serving as a reference framework for identifying and classifying the envelope characteristics of the case study buildings examined in this research.

Office building envelope systems have evolved significantly over time, mainly in response to increasing energy efficiency requirements and the introduction of building energy codes. In general, office buildings can be categorized into pre-code and post-code buildings, each characterized by distinct approaches to envelop design.

Figure 3.2 shows the conceptual comparison of building energy performance characteristics before and after the adoption of modern energy codes. Buildings constructed prior to comprehensive energy standards typically have thinner insulation, less effective air barriers, and low-performance glazing, resulting in higher heat losses and energy use. In contrast, post-code buildings incorporate higher insulation levels, continuous air barriers, and improved fenestration performance, which enhances thermal performance and reduces energy consumption



Figure 3.2 Changes in building energy code standards in Canada (1983–2021). Source: *Energy Codes Then and Now: 1983–2021*, Sustainable Energy Action. Last accessed January 16, 2026 from <https://sustainableenergyaction.org/resources/energy-codes-then-and-now-1983-2021>

3.4.1 Typical Exterior Wall Systems in Office Buildings

Pre-code wall assemblies often have poor thermal and moisture performance because they lack continuous insulation and clear control layers. As a result, they lose more heat, allow air leakage, and can develop durability problems over time.

The wall assembly shown in Figure 3.3 is considered thermally weak by current standards because thermal insulation is limited to the stud cavity and is not continuous across the wall section. As a result, significant thermal bridging occurs through the wood framing members, and the effective thermal resistance of the wall remains low. In addition, the absence of a dedicated and continuous air barrier leads to increased air leakage and heat loss. This type of wall assembly was commonly used in Canadian buildings constructed prior to the 1980s, when building practices focused primarily on structural performance and moisture control rather than energy efficiency. During this period, energy codes and requirements such as those later introduced by ASHRAE and the National Building Code of Canada were not yet widely enforced, resulting in buildings with limited insulation levels and comparatively poor thermal performance (Lstiburek, 2010).

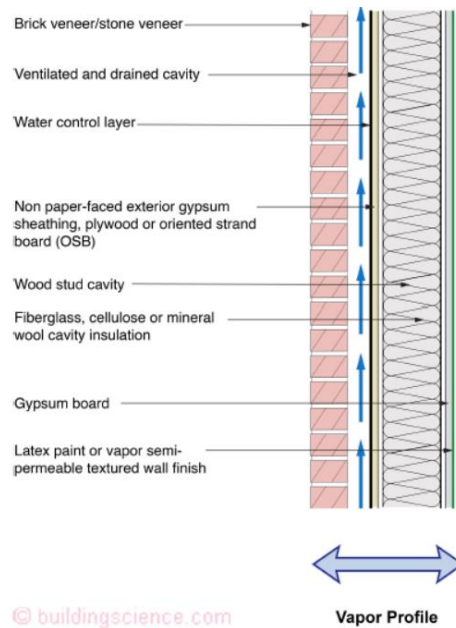


Figure 3.3 Representative wall assembly without continuous insulation in pre-code construction (Lstiburek, 2010)

In contrast, post-code wall systems were designed to fix these issues by adding continuous insulation and clear air, vapor, and water control layers.

The wall assembly shown in Figure 3.4 is considered thermally strong by current standards. In this wall, insulation is installed both inside the stud cavity and as a continuous rigid insulation layer on

the exterior side of the wall. Exterior insulation helps reduce heat loss by limiting thermal bridging through the framing elements. In addition, the air, vapor, and water control layers are clearly defined and continuous, which improves airtightness and moisture control. As a result, this wall has a higher effective thermal resistance and better overall energy performance. Wall assemblies of this type became common after Canada adoption of modern energy efficiency codes, such as ASHRAE and the National Building Code of Canada, and are typical of newer post-code buildings (Lstiburek, 2010).

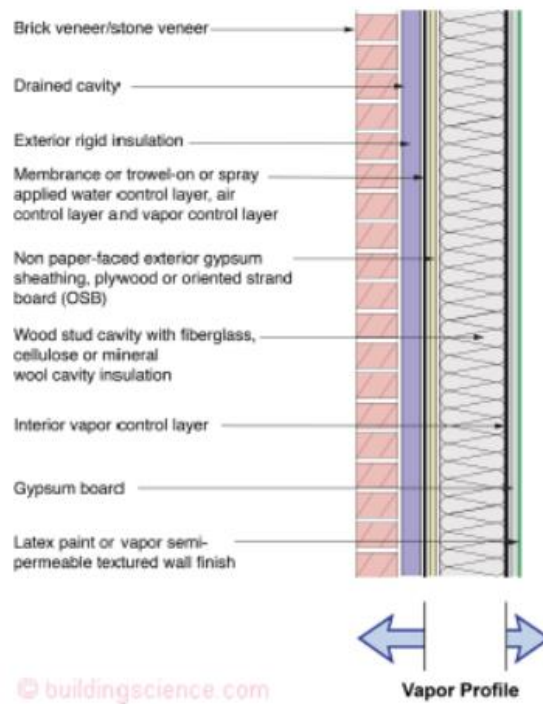


Figure 3.4 Representative wall assembly with continuous exterior insulation in post-code construction (Lstiburek, 2010)

Beyond thermal performance, moisture control strategies also improved over time, resulting in stronger and more durable wall systems.

Figure 3.5 presents different wall water-control strategies, illustrating how exterior wall systems have evolved from simple to more robust designs. The wall systems shown on the left use simple water-control approaches that depend on a single protective layer, with limited ability for the wall to dry. These systems are more vulnerable to moisture penetration and were commonly used in older, low-performance buildings. Moving toward the right, the wall assemblies incorporate drained and ventilated cavities that allow water to escape and promote drying. The most advanced systems also include continuous exterior insulation, which further improves moisture management and reduces thermal bridging. Overall, this figure demonstrates that modern post-code wall

assemblies provide better water control, improved durability, and enhanced thermal performance compared to earlier construction practices (Passive House Canada, 2021).

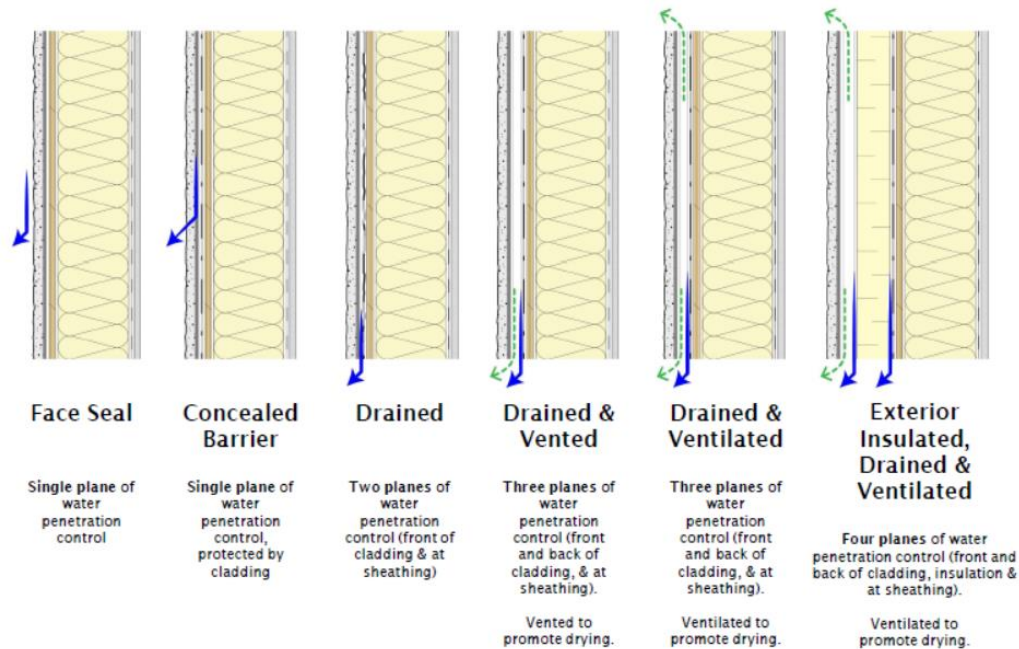


Figure 3.5 Progression of Wall Water Control and Drying Strategies in Older and Modern Buildings (Passive House Canada, 2021).

Another common pre-code wall type is concrete mass wall construction, which has different but equally important thermal weaknesses.

Figure 3.6 shows a typical concrete building enclosure system, where exposed concrete panels function as both the structural and exterior enclosure layer. The wall relies on face-sealed joints for water control, with thermal insulation and vapor control placed on the interior side. The absence of exterior insulation and drainage cavities results in significant thermal bridging, particularly at slab edges, which is characteristic of office buildings constructed prior to modern energy codes.

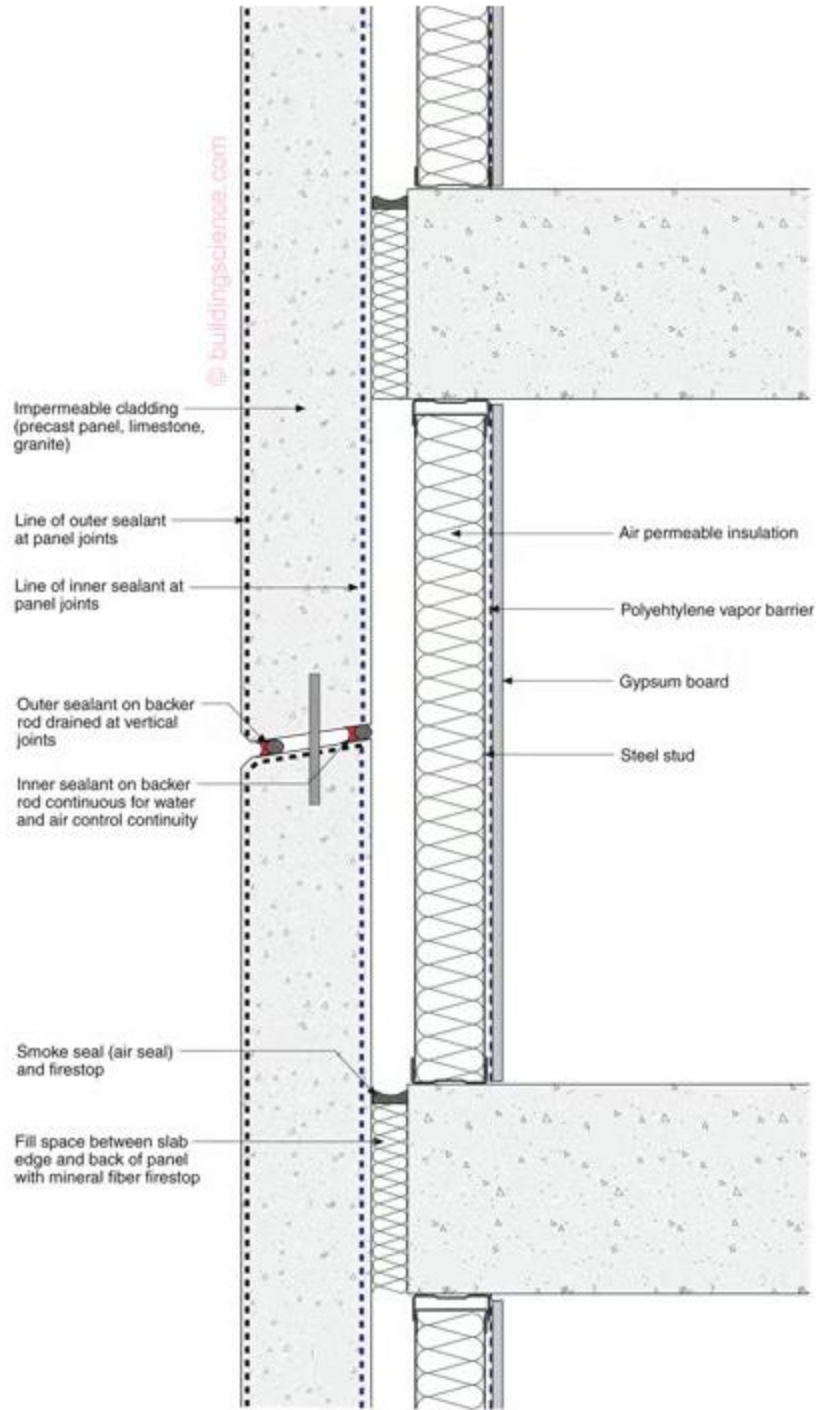


Figure 3.6 Typical legacy concrete building enclosure with face-sealed joints and interior insulation. Source: *BSI-054: Risky Business—High-Risk Walls*, Building Science Corporation. Retrieved January 16, 2026 from <https://buildingscience.com/documents/insights/bsi054-risky-business-high-risk-walls>

3.4.2 Typical Roofs Systems in Office Buildings

Roof assemblies in office buildings have also changed over time, mainly to reduce heat loss, limit thermal bridging, and improve moisture control in cold climates.

Figure 3.7 illustrates the evolution of roof assembly design by comparing conventional roof systems with protected-membrane roof assemblies. The roof assemblies shown on the left represent traditional construction practices, commonly found in older buildings, where thermal insulation is limited and not continuous across the roof section. In these assemblies, insulation is often placed within or directly above the structural elements, which leads to significant thermal bridging through framing or mass timber components and reduces the effective thermal resistance of the roof. Such roof configurations are characteristic of buildings constructed before the widespread enforcement of energy efficiency requirements, when roof design primarily focused on structural stability and basic moisture protection rather than thermal performance. As a result, these roofs are considered thermally weak by modern standards, as heat loss is relatively high and the risk of condensation increases in cold climates due to the unfavorable position of air and vapor control layers.

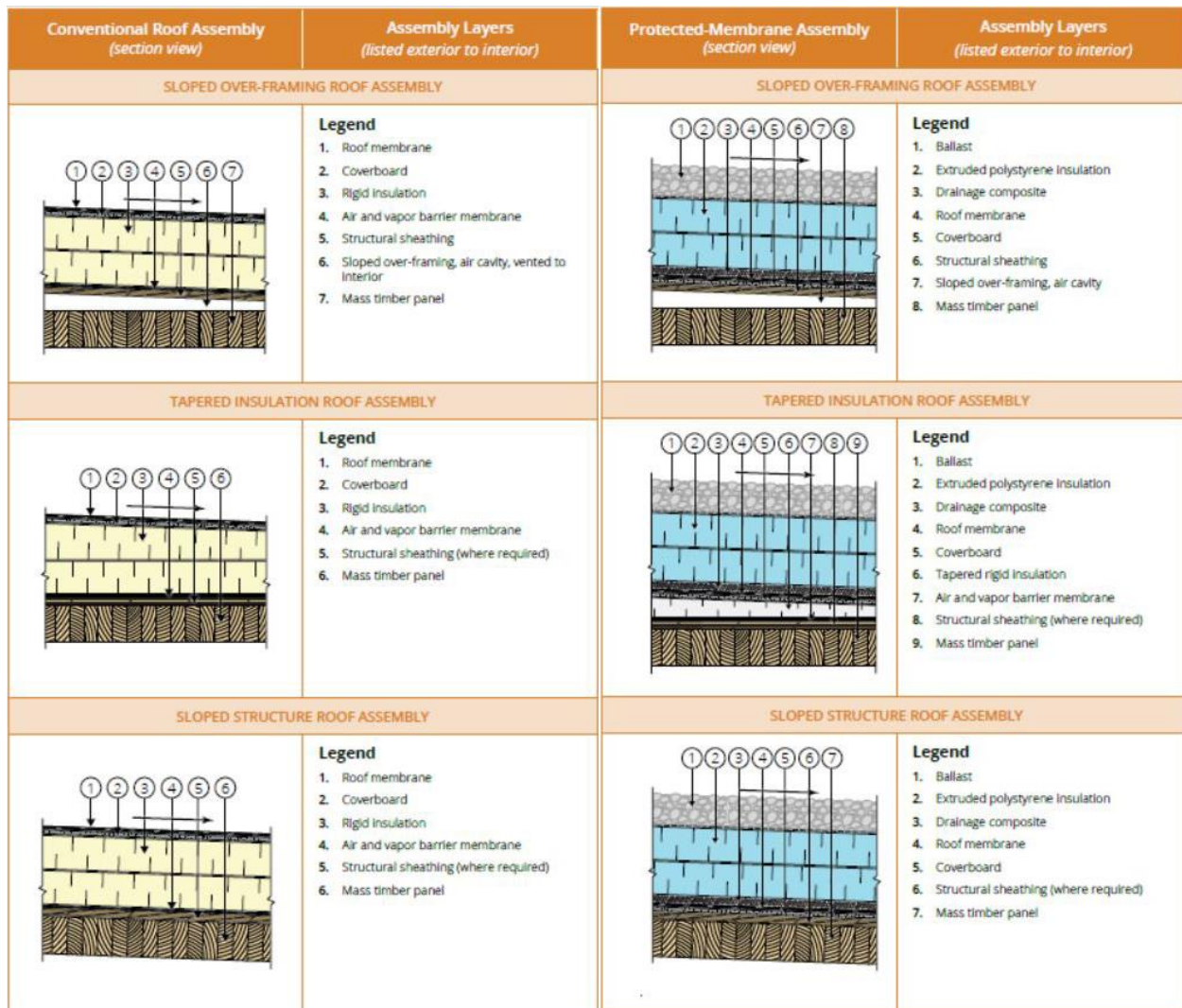


Figure 3.7 Progression of Roof Assembly Design from Low-Performance to High-Performance Roofs (RDH Building Science Inc., 2021)

Modern roof assemblies fix these issues by placing insulation on the outside and protecting the key control layers.

In contrast, the roof assemblies shown on the right show modern, post-code construction practices, where continuous exterior insulation is placed above the roof membrane in protected-membrane systems. This design significantly reduces thermal bridging, keeps the membrane and structural elements warmer, and improves both thermal and moisture performance. The progression illustrated in this figure shows the shift over time from thermally inefficient roof systems toward high-performance roof assemblies that align with current building codes and energy efficiency objectives (RDH Building Science Inc., 2021).

3.4.3 Typical Windows Systems in Office Buildings

Windows are one of the most important parts of a building's envelope because they have a big impact on heat loss, solar gains, and occupant comfort.

Figure 3.8 shows the progression of window glazing systems from traditional single-glazed units to advanced multi-layer glazing technologies. Single-glazed windows, which were commonly used in older buildings, consist of only one glass layer and provide very limited thermal resistance, resulting in high heat loss. Double-glazed systems introduce an insulated air or gas-filled cavity between two glass panes, significantly reducing heat transfer. Triple-glazed windows further improve thermal performance by adding an additional glass layer and cavity. Advanced systems such as vacuum glazing minimize heat transfer even further by reducing convection and conduction within the glazing unit. This progression reflects the evolution of window design over time, driven by increased energy efficiency requirements and the introduction of modern building codes (Aguilar-Santana et al., 2020).

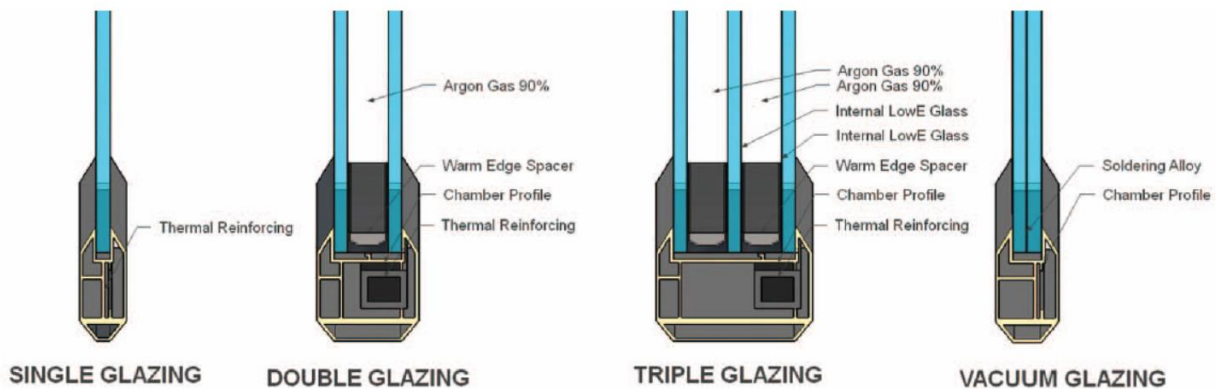


Figure 3.8 Progression of Window Glazing Technologies from Traditional Single Glazing to High-Performance Systems (Aguilar-Santana et al., 2020).

3.5 Case Study Description and Building Characteristics

To show typical office buildings in Montréal, two real buildings were selected as case studies. The goal was to compare the difference in energy performance between an older office building and a newer one designed under current energy standards. Selecting two buildings with different construction periods makes it possible to evaluate how the same retrofit measure behaves under different baseline conditions.

The first building, Model (1), is a modern office tower. It follows the requirements of the National Energy Code of Canada for Buildings (NECB 2017). Modern buildings like this usually have higher insulation, better windows, and more efficient mechanical systems. This building was

chosen to represent newer office buildings in Montréal that are already relatively energy-efficient but may still benefit from targeted upgrades.

The second building, Model (2), was old building, during a period when energy codes were less strict. Older office buildings often have weak thermal envelopes, higher air leakage, and less efficient heating and cooling systems. For this reason, this building was selected to represent older office stock commonly found throughout the city. Studying this type of building helps identify retrofit strategies that deliver large energy savings with the greatest financial impact.

Both buildings are located in the same city and climate zone (6A – cold and humid). Using two buildings with different ages but similar function and climate provide a fair comparison, making it possible to evaluate retrofit solutions for both existing and newer office infrastructures in Montréal.

3.5.1 Office Building Type A (Post-Code or New Building)

This section describes the Type A case study building with the main envelope components (facade, windows, and roof) used to define the baseline model.

1. Introduction

The post-code or new building in this study is located in the dense fabric of downtown Montreal (Boulevard de Maisonneuve). The building has 27 floors, classified as a high-rise building. It was built in 2017. Its approximate area is about 45574 m².

It has a significant floor area per floor and a very large total area. The floor plan is largely regular and repetitive. In terms of architectural form, the building has a more modern shell including extensive glass surfaces and facade systems with a high proportion of windows to walls (Figure 3.9).



Figure 3.9 Case Study Type (A) Post-Code (New) Building

2. Facade and Wall System

The building primarily uses a fully glazed curtain wall system over most of its exterior facade. In some areas, such as the lobby and building cores, solid concrete walls or precast concrete panels are also present.

Modern Characteristics (Post-2017) features are:

- A continuous curtain wall system, likely unitized or semi-unitized
- Double-glazed, energy-efficient glass designed to reduce heat loss and solar gains
- Aluminum frames with effective thermal breaks
- Improved air-tightness and water-tightness, achieved through well-detailed and uniform joints
- Strong emphasis on transparency, daylight access, and visual connection to the urban environment

This type of building envelope is fully consistent with contemporary office architecture and indicates that the building was designed according to the concept of high-transparency office buildings.

It also aligns with the performance requirements of recent energy codes, such as ASHRAE 90.1 and the National Energy Code of Canada for Buildings (NECB).

3. Window System

Window Type is Insulated Glass Units (IGUs) integrated into the curtain wall system. The windows consist mainly of double glazing, using warm-edge spacers and factory-applied sealing (Figure 3.10, Figure3.11).

Modern Features:

- Reduced heat transfer and improved solar control
- Better air-tightness compared to older aluminum window systems without effective thermal breaks
- Improved overall thermal and energy performance

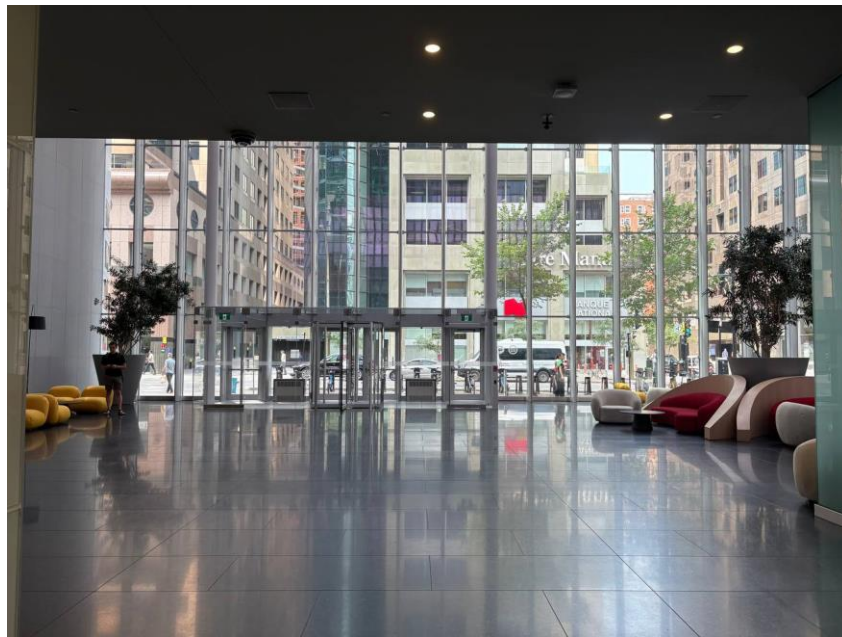


Figure 3.10 Case study (A) windows



Figure 3.11 Case study (A) Doors

4. Roof

The type of roof is Flat roof. Likely System is a continuous thermal insulation layer combined with a modern waterproof membrane, such as TPO, PVC, or a similar system.

Modern Features:

- High thermal insulation (high R-value)
- Proper detailing at the connection between the roof and the curtain wall, designed to control heat loss, air leakage, and moisture.

3.5.2 Office Building Type B (Pre-Code or Old building)

This section describes the Type B case study building with the main envelope components (facade, windows, and roof) used to define the baseline model.

1. Introduction

The old building in this study is a medium-scale urban office building located in the dense fabric of downtown Montreal (Boulevard de Maisonneuve). The building has 25 floors, classified as a high-rise building. It was built in 1976. Its approximate area is about 29685 m².

The building has a relatively large ground floor area, which, with local setbacks, creates semi-open spaces such as entrances and canopies/overhangs. This feature increases the contact area of the building shell with the exterior environment and plays an important role in the thermal behavior of the shell. The building plan is rectangular and elongated, which has been common for office

buildings of the past decades. The vertical organization of the building is simple and lacks complex volumetric breaks (Figure 3.12).



Figure 3.12 Case Study Type (B) Old Building

2. Facade and Wall System

The exterior walls are exposed cast-in-place concrete with exposed aggregate finish. This type of façade was very common in older office buildings and typically functions as a single-wythe structural wall or a structural concrete wall with little or no continuous exterior insulation.

Characteristics observed from the site:

- No visible exterior insulation layer
- No rainscreen or ventilated cavity
- Heavy thermal mass but low thermal resistance
- High likelihood of thermal bridging at floor slabs and columns

This wall system corresponds to an old and weak envelope category in terms of thermal performance. While the concrete provides durability and structural strength, it performs poorly in cold climates like Montréal when not combined with continuous insulation (Figure 3.13).



Figure 3.13 Case Study (B) Walls

3. Window System

The window from site observation has

- large rectangular glazing units,
- Aluminum frames with no visible thermal break,
- Flush-mounted glazing directly connected to the concrete facade
- No external shading devices

These characteristics are typical of older curtain wall or punched-window systems installed before energy-efficient glazing became standard.

Characteristics:

- Double glazing or early-generation insulated glass units
- High thermal conductivity through aluminum frames
- Significant heat loss in winter and heat gain in summer
- Limited airtightness at window-to-wall interfaces

This window system aligns with old-generation glazing systems, significantly weaker than modern low-E, thermally broken, or triple-glazed systems.

The existing windows in the case study building represent the double-glazing stage in the historical development of window systems. Although double-glazed windows were a clear improvement over single-glazed windows at the time of construction, the aluminum frames used in older buildings often lack effective thermal breaks. As a result, these windows still experience higher heat losses compared to modern high-performance glazing systems (Figures 3.14 and 3.15).



Figure 3.14 Case study (B) windows



Figure 3.15 Case study (B) Exterior Door

4. Roof and Ceiling System

No visible evidence of high-performance roof insulation or airtight detailing. While the roof assembly itself is not directly visible, buildings from this era typically used:

- Conventional flat roofs
- Limited insulation thickness compared to modern standards
- Minimal attention to air and vapor continuity

The roof assembly is most consistent with an older conventional roof system, offering basic weather protection but limited thermal and airtight performance by current standards (Figure 3.16).

This building has a typical pre-code office building envelope, where:

- Thermal mass is high
- Insulation and airtightness are low
- Envelope heat losses are dominated by walls and windows



Figure 3.16 Case study (B) Roof

3.6 Model Development

The energy models for the two selected office buildings were created using DesignBuilder, which uses the EnergyPlus simulation engine. The modeling process involved building geometry, adding construction features, and defining the system and operational settings.

First, the building shapes were drawn based on measured site dimensions such as floor area, height, glazing ratio, and window orientation.

Next, the building envelope inputs were assigned. Since complete drawings were not available, insulation values, glazing performance, and air leakage were taken from reliable sources. For the newer building, data followed the NECB 2017 standard, while the older building used typical values reported in Canadian construction literature.

After the envelope, system characteristics were added. Each building was assigned HVAC components that match their age category. The modern office tower included high-efficiency equipment, while the old building model used systems commonly found in Canadian pre-code commercial buildings. Standard efficiency data from ASHRAE was used to define typical performance levels.

To represent real operation, internal loads such as lighting, plug equipment, people density, and working schedules were defined using observations from the building visit and common office guidelines. Montréal's climate file from EnergyPlus was applied to reflect local weather, especially winter heating demand.

Once all inputs were set, baseline models were simulated and later used to test different retrofit options. These baseline results were later used as the starting benchmark for calculating savings and comparing upgrade scenarios.

Figure 3.2 below shows the overall methodological framework used in this study to evaluate energy retrofit strategies for office buildings. The process begins with baseline energy modeling of the existing buildings in Design Builder, where key parameters such as climate data, building geometry, envelope characteristics, glazing, lighting, internal loads, HVAC systems, occupancy, and operating schedules are defined. Two representative office building archetypes are modeled to reflect different construction and performance characteristics. The baseline models are then simulated to evaluate building energy performance and establish a reference for comparison. Based on these baseline results, multiple retrofit scenarios are developed, including single measures and combined retrofit packages at low, medium, and high intervention levels. Each scenario is assessed not only for energy performance but also for economic feasibility through the calculation of retrofit investment costs, annual energy cost savings, and payback periods. Finally, the energy and economic results are compared to support decision-making and identify the most cost-effective and energy-efficient retrofit solution for office buildings in Montréal's cold climate.

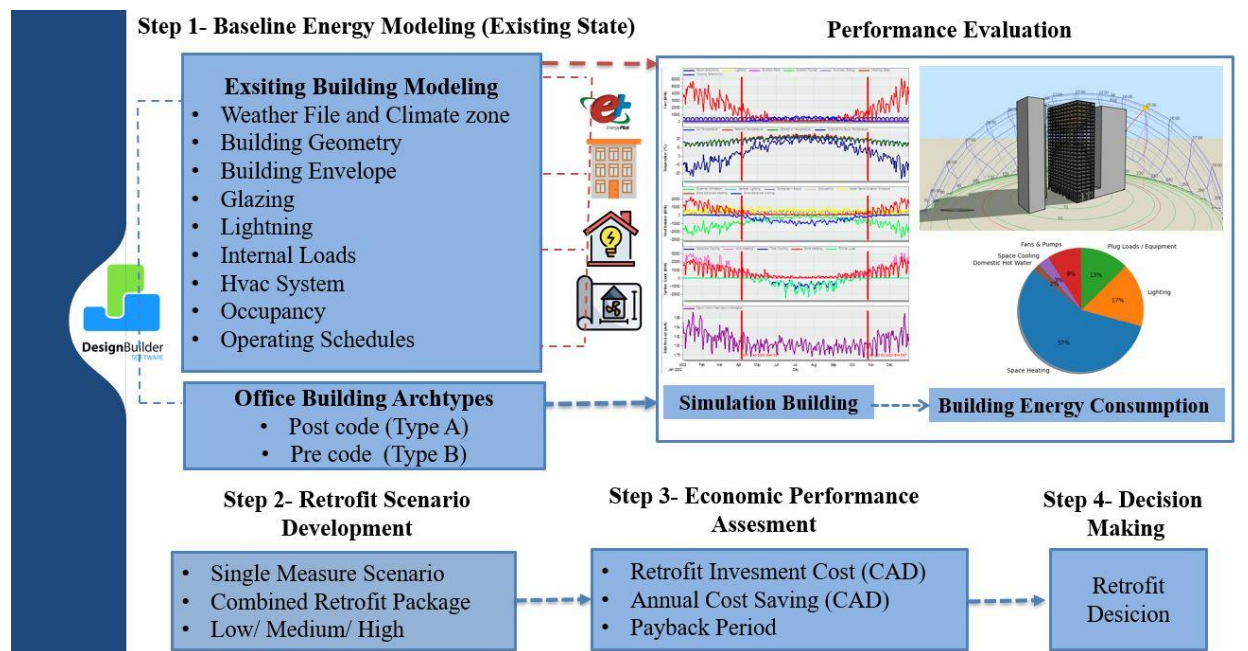


Figure 3.17 Model Development Steps

3.7 Scenario Design

To evaluate energy improvement options, three retrofit levels were created for both buildings. Each level represents a different amount of upgrade effort and investment. The scenarios focus on changes to the building envelope, windows, schedule and thermal insulation, Lighting, because these elements strongly affect heating demand in Montréal’s cold climate.

The retrofit scenarios in this study were developed step by step, using a gradual approach to reflect the realistic decisions that building owners and engineers usually make.

The scenario development process began with the evaluation of individual retrofit measures. Single upgrades such as window replacement, roof insulation improvement, lighting efficiency enhancement, schedule optimization, and setpoint adjustment were first simulated independently to understand their isolated impact on energy consumption and cost. This initial step helped identify the relative contribution of each retrofit measure.

Based on the performance of individual measures, retrofit combinations were then developed incrementally. Measures that demonstrated limited impact or poor economic performance when applied alone were either excluded or only considered as supporting elements in combined scenarios. In contrast, measures with strong energy-saving potential or favorable payback performance were prioritized for further combination.

Retrofit scenarios were grouped into three levels: low, medium, and high, based on the depth of retrofit, expected energy savings, and associated investment cost. This classification reflects

common retrofit decision pathways observed in practice, where budget constraints and risk considerations influence the level of intervention.

The table below summarizes the three retrofit levels applied to the two case study buildings. Each level shows a different level of retrofits.

Table 3.2 Retrofit Scenario Level applied to the two office building archetypes

Scenario Level	Main Strategy
Low Retrofit	Minor, low-cost improvements
Medium Retrofit	Balanced cost-performance upgrade
High Retrofit	Advanced, high-performance upgrade

This comparison shows which retrofit level gives useful energy savings without spending too much money.

Low-level retrofit scenarios focus on low-cost and minimally invasive measures. These scenarios typically include operational and control-based improvements such as schedule optimization, lighting control upgrades, minor envelope enhancements, and infiltration reduction. The primary objective of this level is to achieve modest energy savings with minimal capital investment and short payback periods.

Medium-level retrofit scenarios represent a balanced approach between cost and performance. At this level, selected envelope components such as roof insulation or window glazing are upgraded to higher-performance standards, often in combination with basic operational improvements. These scenarios aim to deliver noticeable energy savings while maintaining acceptable investment levels.

High-level retrofit scenarios involve deeper and more integrated interventions. These scenarios combine advanced operational controls (e.g., optimized schedules, setpoint adjustments, lighting sensors), mechanical system improvements (such as ventilation optimization and heat recovery), and targeted envelope upgrades. The objective of this level is to maximize energy savings while maintaining reasonable economic feasibility through synergistic effects between measures.

Multiple retrofit combinations were initially tested within each intervention level. However, not all tested scenarios were retained for final analysis. Scenarios that resulted in very low energy savings, excessively long payback periods, or impractical cost-performance relationships were excluded. The final set of scenarios presented in this thesis therefore represents the best options for each retrofit level.

3.8 Cost Calculation and Formulas

The economic performance of each retrofit scenario was evaluated using both the Simple Payback Period (SPP) and the Discounted Payback Period (DPP).

The Simple Payback Period represents the time required for cumulative energy savings to recover the initial investment cost, ignoring the time value of money:

$$SPP = \frac{\Delta C_{inv}}{S}$$

Equation 3.1

where:

- ΔC_{inv} = incremental investment cost (CAD),
- S = annual energy cost savings (CAD/year).

Discounted Payback Period (DPP)

To incorporate the time value of money, the Discounted Payback Period was computed following the closed-form equation proposed by De la Torre, Martinez & Lemmon (2016):

$$N = \frac{\ln(CF) - \ln(CF - k \times I_0)}{\ln(1+k)}$$

Equation 3.2

where:

- N = discounted payback period (years),
- I_0 = initial investment (CAD),
- CF = annual cash flow (energy cost savings, CAD/year),
- k = discount rate (decimal form).

This formula determines the number of years required for the discounted value of energy savings to equal the initial retrofit cost, assuming constant annual cash flows and a fixed discount rate.

In this study, the discount rate was taken as $k = 0.0225$ (2.25%), corresponding to the Bank of Canada's rate as of October 29, 2025. This rate reflects prevailing long-term financing and investment conditions for municipal and institutional projects in Quebec.

The DPP therefore provides a more realistic indicator of the project's financial performance compared with the SPP, which neglects the time value of money.

Chapter 4 Analysis and Results

4.1 Overview of Retrofit Scenario Evaluation

This chapter shows the result of the energy simulations and retrofit evaluations for the two selected office buildings. The findings include the baseline performance for each building, the effects of applying single retrofit measures on their own as well as groups of upgrades applied together, and comparisons. The goal is to understand how different retrofit strategies affect both energy consumption and economic performance in Montréal's climate.

To assess the energy and economic performance of the selected office building, multiple retrofit scenarios were simulated in DesignBuilder/EnergyPlus. The scenarios included changes in envelope insulation, glazing systems, shading controls, and operational schedules. Each scenario was evaluated based on Three key indicators:

- Annual Energy Saving (%)
- Simple Payback Period (years)
- Discounted Payback Period (years)

These indicators enabled categorization of scenarios into three performance groups: Low, Medium, High.

4.2 Assumptions

The assumptions used for the cost and payback calculations are summarized below:

- **Discount Rate:** 2.25 rate of bank Canada in 2025
- **Electricity Price:** 0.078458 CAD/kWh (Hydro-Québec,2025)
- **Gas Price:** 0.054921 CAD/kWh (Énergir,2024).

4.3 Baseline Model Before Upgrading

This section describes the baseline energy model for each case study building before applying any retrofit measures includes the main building characteristics and existing envelope and system conditions used as the reference for all comparisons.

4.3.1 Case Study 1, Modern Office Building (Type A)

This building represents a newer commercial office tower located in Montréal and constructed after the year 2017. Its baseline model includes:

- Insulated wall and roof systems compliant with post-2000 Canadian codes,
- Standard double Low-E glazing,
- Typical weekday office occupancy schedules,
- Standard HVAC operations for mixed-air systems.

The baseline envelope and system assumptions were selected according to the National Energy Code of Canada for Buildings (NECB 2017).

The figure below shows the exterior view of the modern office building used in Case Study 1.

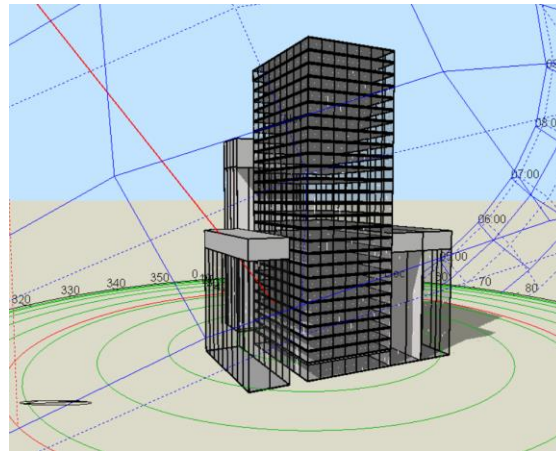


Figure 4.1 The exterior view of the modern office building (Type A) used in Case Study 1.

4.3.2 Case Study 2, Older Office Building (Type B)

The second building represents a typical older office building constructed in year 1976. Such buildings typically include:

- weaker insulation,
- older, clear double glazing,
- higher infiltration,
- less efficient HVAC operation.

These characteristics make older buildings more energy intensive.

As shown in the figure below, these characteristics allow heat to be continuously lost through the roof, exterior walls, windows, and floors, while uncontrolled air infiltration increases heat loss by allowing warm indoor air to escape and cold outdoor air to enter the building. To maintain indoor comfort, the HVAC system must compensate for these continuous losses by operating more frequently and at higher capacity. This combination of envelope-related heat losses and inefficient mechanical operation directly results in higher heating demand and greater overall energy consumption in cold climates (Figure 4.2).

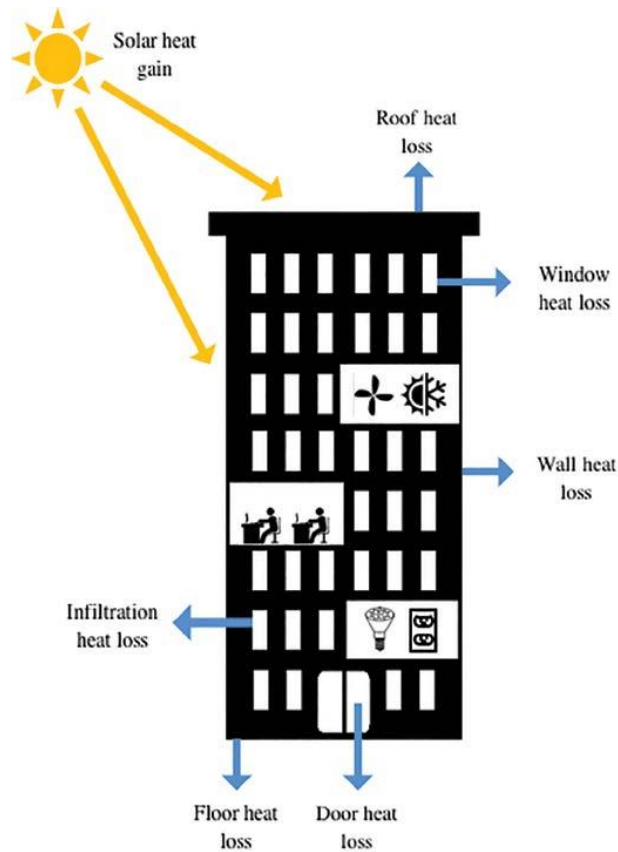


Figure 4.2 heat transfer processes in an older office building, including weak envelope transmission, air infiltration, and HVAC-related losses (Natural Resources Canada, 2011)

The figure below shows Exterior view of the older pre-code office building (Type B) used as Case Study 2.

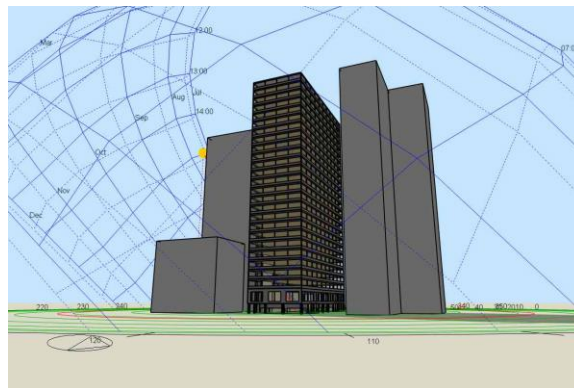


Figure 4.3 Exterior view of the older pre-code office building (Type B) used as Case Study 2.

According to Canadian research on existing commercial buildings, inadequate envelope insulation and glazing performance are the primary drivers of excessive winter heating loads in Montréal's cold climate (study reported in ESIM Conference 2024 and Urban Building Energy Modeling

review 2023). The studies confirm that older buildings in Québec exhibit higher heating demand due to poor envelope performance (Al Jadaa,2024; Gavaldà,2025).

The simulated energy cost of the baseline is used as the reference against which all scenarios are compared. All savings and economic calculations in later sections are expressed relative to this baseline condition.

4.4 Proposed Model After Upgrading

The scenarios were divided into three levels low, medium and high.

4.4.1 Retrofit Performance Model (1) Building type A

This analyzes the performance of building type A (built according to NECB2017) against 50 energy improvement scenarios, of which 12 were selected. The results show that even in a modern building, energy savings of 6% to 38% can be achieved, depending on the combination of measures. And it is exactly written National Research Council for major energy retrofits guidelines upgrading multiple building systems at the same time can reduce energy use up to 40% (NRC,2016) depending on how deep the retrofit is and what measures are included the exact amount of savings varies. This table shows the summary of results for building model (1):

Table 4.1 Comparison of Energy Efficiency Retrofit Scenarios Based on Economic and Energy Performance levels

Scenario	Extra Cost (CAD)	Difference Annual cost Saving (CAD)	Energy Saving Percentage (%)	Energy saving level
Double Low-E Arg	770,024	88,021	14.13872	Low
RoofR45-Triple glazing+ lightning sensor	2,011,762	177,620	28.5309	High
Double Low-E Arg + shading	1,757,083	38,709	6.217784	Low
Roof R 60+ Triple glazing	770,024	138,312	22.2169	Medium
Roof R60+ Double Low-E Arg	770,024	138,010	22.16839	Medium
shading+ Triple glazing+ RoofR45	2,566,740	79,978	12.84678	Low
RoofR45Shading+ Double glazing Arg	217,039	89,374	14.35605	Low
schedule shading+ Double glazed Arg	2,310,067	181,023	29.07752	High
schedule triple+ Roof R45+ lightning sensor	473,713	197,519	31.72726	High
schedule Double Low-E Arg+ Roof R45+ lightning sensor	770,024	163,811	26.31278	High
schedule Double Low-E Arg + Roof R45+ lightning sensor + ventilation+ heat recovery	770,024	166,721	27	High

schedule Double Low-E Arg + Roof R45+ lightning sensor + ventilation+ heat recovery+ setpoint	770,024	234,385	38	High
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4.4.1.1 Classification of Retrofit Scenarios by Energy Saving levels (Based on Model A)

To analyze the performance of the energy upgrade scenarios in the new building (Model A), the results were classified into three groups based on the level of savings: low, medium, and high savings. This classification helps to evaluate options based on energy and cost impact.

Low Savings Group (5–15%)

This group includes scenarios that only reduce energy use by a small amount with low investment cost, include:

- Double Low-E Arg
- Double Low-E Arg + shading
- Shading+ Triple glazing+ RoofR45
- RoofR45+Shading+ Double glazing Arg

Shading is very sensitive in cold climate and can reduce the effect of the envelope upgrade in winter.

Medium Savings Group (15–28%)

These scenarios balanced both technological upgrade and cost:

- RoofR60+Triple glazing
- RoofR60+ Double glazing Arg

Increasing roof insulation and using high-performance triple glazing reduced heating losses and produced steady energy savings throughout the year. These envelope upgrades performed well but remained moderate because the building already has a strong envelope baseline. As a result, they had a good reduction but were still less effective than operational control strategies.

High Savings Group (28–35%)

This group had the strongest impact with payback periods within acceptable industry standards:

- Schedule + shading+ Double glazing Arg
- Triple glazing+ Roof R45+ lightning sensor
- Schedule + Triple glazing+ Roof R45+ lightning sensor
- schedule + Double Low-E Arg+ Roof R45+ lightning sensor
- schedule + Double Low-E Arg+ Roof R45+ lightning sensor+ ventilation+ heat recovery
- schedule + Double Low-E Arg + Roof R45+ lightning sensor+ ventilation+ heat recovery+ setpoint

Figure 4.4 shows the classification of retrofit scenarios by energy saving level (Type A).

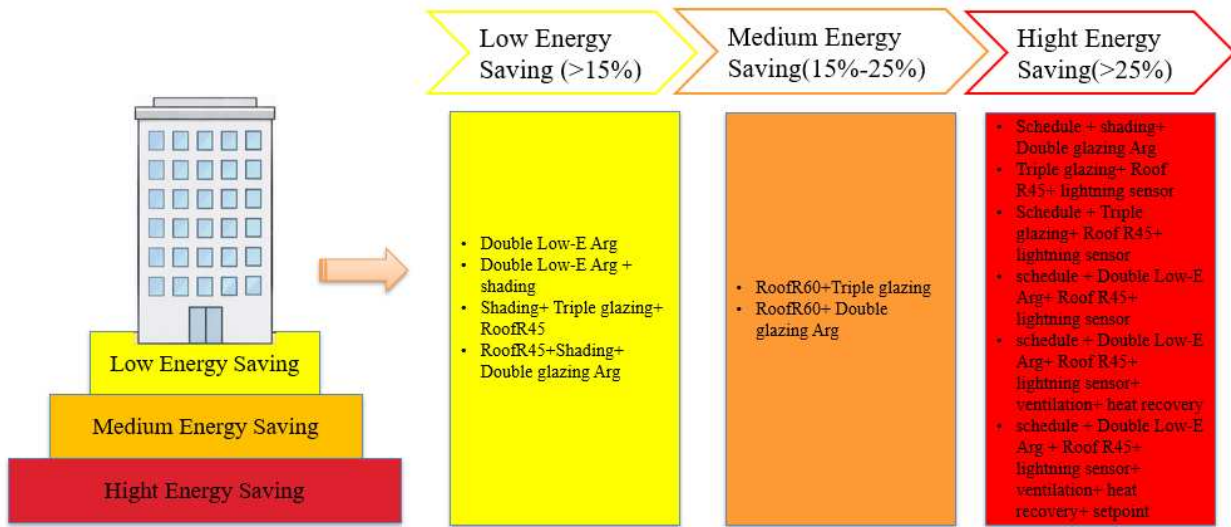


Figure 4.4 Classification of Retrofit Scenarios by Energy Saving Level (Type A)

4.4.1.2 Energy-Saving Mechanisms of Retrofit Scenarios (Type A)

High-level retrofits work the best because they mix many strong upgrades together. In this group, the upgrades are not only about improving the building envelope, but also about smart operational controls, ventilation optimization, heat recovery, and setpoint adjustments. When these measures work together, the building performs much better. The results show that:

- Schedule control is the main driver of savings of high scenario with 31% savings

When HVAC and lighting work only when needed, energy drops quickly.

In high-level scenarios, schedule control alone had around 22% of the improvement.

- Set point adjustments add another strong layer of savings

Lowering temperatures during unoccupied hours helped reduce heating loads.

This measure contributed around 10% of total savings.

- Envelope upgrades still help, but they are not the main factor

Improvements like Roof R-45/R-60 and double/triple glazing had ~12% in the high-level group. They support the savings but are not the main factor.

- Lighting sensors had ~3%, ventilation optimization had ~2%, and heat recovery had ~3% of energy saving. Individual small, together they reinforce overall efficiency.

4.4.1.3 Cost and Economic Results (Type A)

In building type A, scenarios are categorized based on three key indicators (Figure 4.5):

- Energy Saving Rate (%)
- Investment Cost (Extra Cost)

- Return on Investment (SPP / DPP)

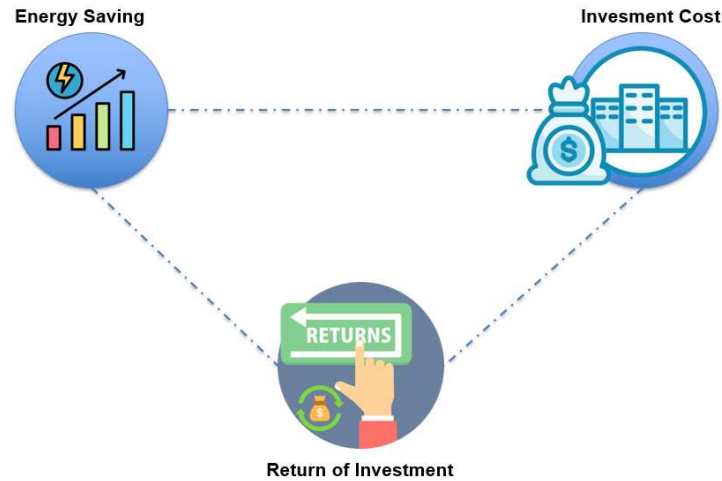


Figure 4.5 Cost and Economic Result

The following table summarizes cost performance of all retrofit scenarios for building type A:

Table 4.2 Cost and economic performance of all retrofit scenarios for Building Type A Model 1

Scenario	Building Total Cost	Annual Energy Cost	Extra Cost (CAD)	Difference Annual cost Saving (CAD)	Simple Payback Period (yrs)	Discounted Payback Period (yrs)
Double low-E Arg	54,730,508	534,532	770,024	88,021	8.74	9.71
RoofR45-Triple glazing, lightning sensor	55,972,246	444,933	2,011,762	177,620	11.32	12.98
Double low -E Arg, shading	55,717,567	583,844	1,757,083	38,709	45.3	-
Roof R60, Triple	54,730,508	484,241	770,024	138,312	5.56	6.03
Roof R60, Double Low -E Arg	54,730,508	484,543	770,024	138,010	5.57	6.04
Shading, Triple, RoofR45	56,527,224	542,575	2,566,740	79,978	32.09	
RoofR45, Shading, Double glazing Arg	54,177,523	533,179	217,039	89,374	2.42	2.52
Schedule, Shading, Double Glazed Arg	56,270,551	441,530	2,310,067	181,023	12.76	14.88
Schedule, Triple, Roof R45, lightning sensor	54,434,197	425,034	473,713	197,519	2.39	2.48
Schedule, Double Low -E Arg, Roof R45, lightning sensor	54,730,508	458742	770,024	163,811	4.70	5.02

Schedule, Double Low -E Arg, roof r45, lightning sensor , ventilation, heat recovery	54,730,508	455,832	770,024	166,721	4.61	4.93
Schedule, Double Low -E Arg, Roof R45, lightning sensor , ventilation, Heat Recovery, Setpoint	54,730,508	388,168	770,024	234,385	3.28	3.45

In the Low-level group, the energy savings are small. Some options are low cost and some high cost, but shading is not recommended because it blocks winter solar heat and creates very long payback. In the Medium level, the envelope upgrades give about 22% energy savings with a reasonable payback, even though the investment is not very high. In the high level, advanced retrofit performance is used from combining schedule control, setpoints, lighting sensors, ventilation and heat recovery with moderate envelope upgrades. These combined strategies give the highest energy savings and also the shortest payback, making them the most cost-effective options overall.

4.4.1.4 Best Performing Retrofit Scenarios (Type A)

This table shows best performance retrofit scenarios:

Table 4.3 Best Performing Retrofit Scenarios (Building type A)

Category	Best Scenario	Explanation
Best Low-Cost Option	RoofR45+Shading+ Double glazing Arg	Lowest investment cost fastest payback
Best Medium-Cost Option	Roof R60 + Triple Glazing	Excellent balance between cost and performance
Best High-Impact Cost Option	Schedule + Low-E + Roof R45 + Lighting + Heat Recovery + Setpoint Control	Highest total savings; strong synergy of control + envelope; most cost-effective high-impact solution

The best retrofit options depend on budget. The cheap upgrades like better glazing or more roof insulation save some energy, but not a lot. The medium upgrades, such as triple glazing with a better roof, save more because they reduce heat loss. But the strongest results come from the high-level options like fixing the schedules, adjusting temperature setpoints, adding lighting sensors, and improving ventilation and heat recovery. When these controls are mixed with a bit of improvement of the envelope, the savings become the highest. The best overall scenario is the one that combines all these controls together with Roof R45 and Low-E glazing, giving the biggest energy reduction and a fast payback.

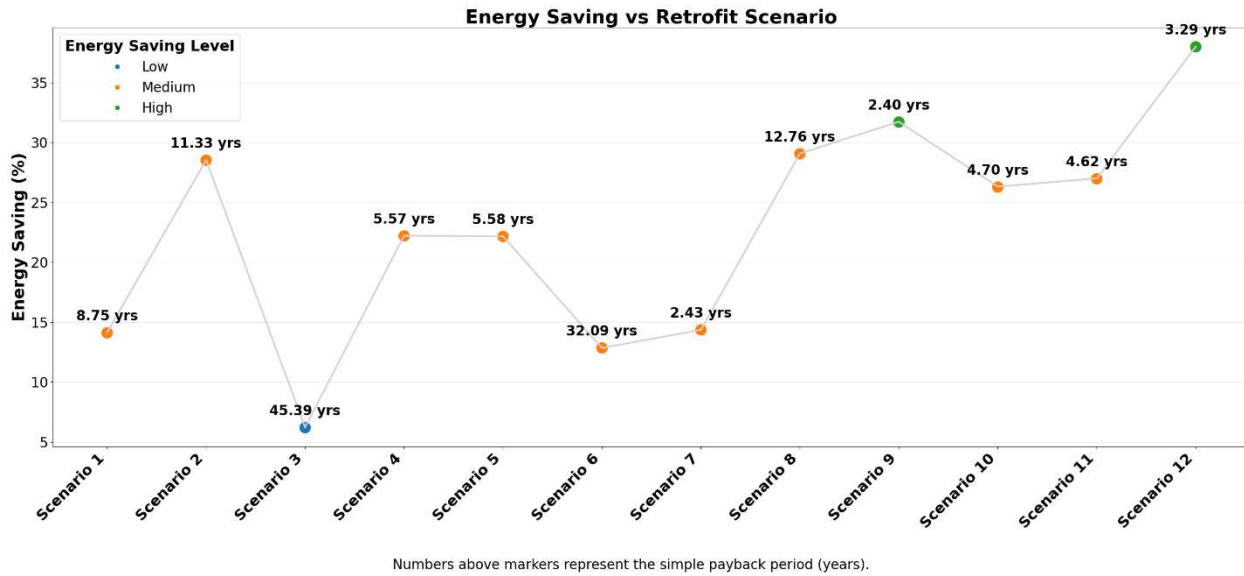


Figure 4.6 Energy Saving and payback period vs. Retrofit Scenario (Type A)

Scenario descriptions:

- Scenario 1: Double Low-E Arg
- Scenario 2: Roof R45 + Triple glazing + Lighting sensor
- Scenario 3: Double Low-E Arg + Shading
- Scenario 4: Roof R60 + Triple glazing
- Scenario 5: Roof R60 + Double Low-E Arg
- Scenario 6: Shading + Triple glazing + Roof R45
- Scenario 7: Roof R45 + Shading + Double glazing Arg
- Scenario 8: Schedule + Shading + Double glazing Arg
- Scenario 9: Schedule + Triple + Roof R45 + Lighting sensor
- Scenario 10: Schedule + Double Low-E Arg + Roof R45 + Lighting sensor
- Scenario 11: Schedule + Low-E + Roof R45 + Lighting + Ventilation + Heat recovery
- Scenario 12: Schedule + Low-E + Roof R45 + Lighting + Ventilation + Heat recovery + Setpoint

The figure compares multiple retrofit scenarios by showing both their energy saving performance and payback period. Each point shows a retrofit option, with its height indicating the percentage of energy savings and the label above showing the number of years required to recover the investment cost.

The best scenario in the whole study is the “Schedule + Low-E + Roof R45 + Lighting Sensor + Ventilation + Heat Recovery + Setpoint” package. It gives the highest energy saving (38%) while still keeping the payback very short (≈ 3.3 years). This scenario works so well because it combines smart operational control (schedule, setpoint, sensors) with moderate envelope improvements

(Low-E glazing + Roof R45). The controls reduce wasted energy during unoccupied hours, and the ventilation/heat-recovery upgrades improve system efficiency. Together, they have the strongest performance with the best balance between cost and saving, making this scenario the most cost-effective and technically efficient option for the building.

For modern office buildings in Montréal, low-cost operational strategies such as schedule optimization and temperature setback provide the highest cost-effectiveness, while high-level energy savings are achieved only when these controls are combined with targeted envelope upgrades and ventilation heat recovery.

4.4.2 Retrofit Performance Model (2) Building Type B

This analyzes the performance of building type B (built according to Gavaldà, 2025& Al Jadaa, 2024) against 38 energy improvement scenarios, of which 7 were selected. The results show that even in an old building, energy savings of 5.7% to 57% can be achieved, depending on the combination of measures. This table shows the summary of results for Model (2) building:

Table 4.4 Comparison of Energy Efficiency Retrofit Scenarios Based on Economic and Energy Performance levels

Scenario	Extra Cost (CAD)	Differences Annual Saving (CAD/yr)	Energy Saving Percentage (%)	Energy Saving Level
All double Low-E glazing	345,798	41,473	6.58%	Low
Low-E + Shading control	1,037,396	36,398	5.77%	Low
1°C setpoint reduction + Wall upgrade+ Double Low-E Arg+ LED+ Sensor lightning	2,095,067	147,567	23.39678	Medium
Wall upgrade+ Low-E	245,627	46,557	7.38%	Low
Triple glazing + Wall Upgrade	360,887	40,350	6.40%	Low
2°C setpoint reduction+ Wall upgrade + Double Low-E Arg+ Natural ventilation (Summer)+ LED+ Sensor lightning	2,095,067	321,065	51.00%	Hight
1°C setpoint reduction + Wall upgrade+ Double Low-E Air+ Natural ventilation (Summer)+ LED+ Sensor lightning+ Infiltration	1,955,923	363,918	57.69928	Hight

4.4.2.1 Classification of Retrofit Scenarios by Energy Saving levels (Type B)

To analyze the performance of the energy upgrade scenarios in the old building, the results were classified into three groups based on the level of savings: low, medium, and high savings. This classification helps to evaluate options based on energy and cost impact.

Low Savings Group (5–15%)

This group includes scenarios that only reduce energy use by a small amount with low investment cost, include:

- Wall improvement + Window Double Low-E glazing
- Window Triple glazing + Wall improvement
- Window Double low-E glazing
- Window Double low-E glazing+ shading

The shading is not effective and is not recommended.

Medium Savings Group (15–28%)

These scenarios balanced both technological upgrade and cost:

- 1°C setpoint reduction+ Wall upgrade+ Double Low-E Arg+ LED+ Sensor lightning

High Savings Group (28% and more)

- 2°C setpoint reduction+ Wall upgrade + Double Low-E Arg+ Natural ventilation (Summer)+ LED+ Sensor lightning
- 1°C setpoint reduction + Wall upgrade+ Double Low-E Air+ Natural ventilation (Summer)+ LED+ Sensor lightning+ Infiltration

The second scenario achieves about 6% more energy savings than the first one because it includes infiltration reduction and uses a more effective combination of Low-E Air glazing together with improved control strategies and making it suitable for deep-retrofit or net-zero-ready.

The table below shows classification of retrofit scenarios by energy saving level (Type B):

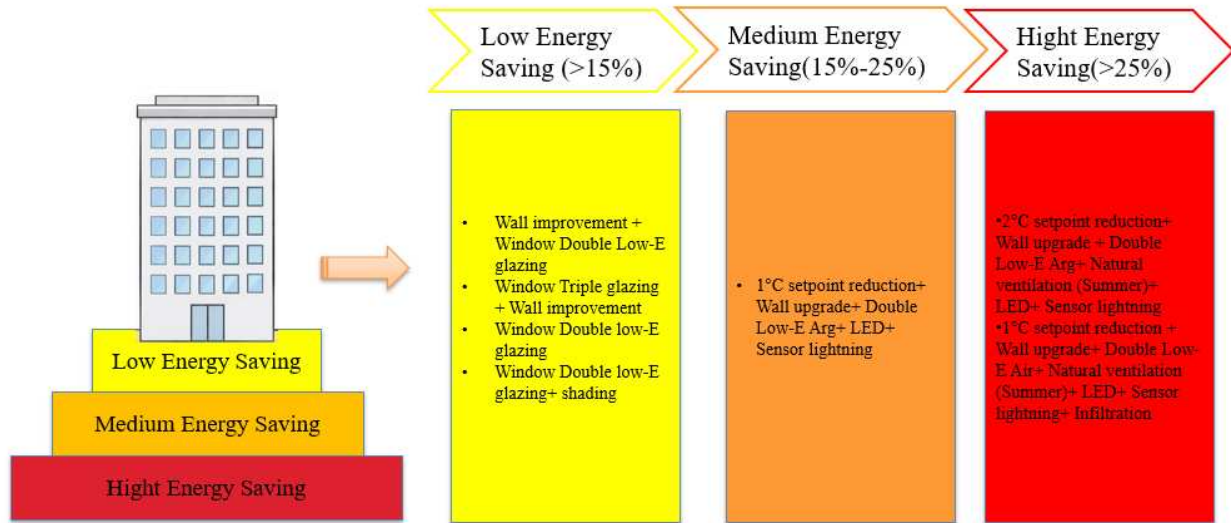


Figure 4.7 Classification of Retrofit Scenarios by Energy Saving Level (Type B)

4.4.2.2 Energy-Saving Mechanisms of Retrofit Scenarios (Type B)

The analysis shows that high level retrofit scenarios achieve the greatest improvement because they combine several strong upgrades at once. Instead of focusing on only one component (like glazing or walls), these scenarios integrate operational changes, envelope improvements, setpoint reductions, and passive ventilation strategies. When these measures work together, the building’s performance increases substantially.

In the best retrofit scenario of the old building (Type B), the total energy saving of $\approx 58\%$ comes from the combined effect of several upgrades. The envelope upgrades (better walls and Low-E windows) give only 6–7% savings, so their effect is small. LED lighting and daylight sensors add about 3–4%, which helps but is not a major factor. The setpoint reduction is much stronger and gives about 12–13% savings by lowering the heating demand. The biggest improvement comes from natural ventilation in summer, which adds 25–30% savings on its own. Finally, reducing infiltration (air leakage) adds another 5–7% because the building keeps heat and cool air better. When all these measures are combined, the Savings reach 58%, and most of it comes from controls, natural ventilation, and infiltration reduction, not the envelope alone.

4.4.2.3 Cost and Economic Results (Type B)

The table compares all retrofit scenarios and shows how each option affects energy use, cost, and payback.

Table 4.5 Cost and economic performance of all retrofit scenarios for Building Type B Model 2

Scenario	Building Total Cost	Annual Energy Saving Cost	Extra Cost (CAD)	Difference Annual cost Saving (CAD)	Simple Payback Period (yrs)	Discounted Payback Period (yrs)

All double Low-E glazing	46,727,377	589,242	345,798	41,473	8.34	9.34
Low-E + Shading control	47,418,975	594,317	1,037,396	36,398	28.49	46.08
1°C setpoint reduction+ Wall upgrade+ Double Low-E Arg+ LED+ Sensor lightning	48,476,646	483,148	2,095,067	147,567	14.19	17.3
Wall upgrade+ Low-E	46,627,206	584,158	245,627	46,557	5.28	5.68
Triple glazing + Wall Upgrade	46,742,466	590,364	360,887	40,350	8.94	10.1
1°C setpoint reduction + Wall upgrade+ Double Low-E Arg+ Natural ventilation (Summer)+ LED+ Sensor lightning	48,476,646	309,650	2,095,067	321,065	6.52	7.14
1°C setpoint reduction + Wall upgrade+ Double Low-E Air+ Natural ventilation (Summer)+ LED+ Sensor lightning+ Infiltration	48,337,502	266797	1,955,923	363,918	5.37	5.79
All double Low-E glazing	46,727,377	589,242	345,798	41,473	8.34	9.34
Low-E + Shading control	47,418,975	594,317	1,037,396	36,398	28.49	46.08
1°C setpoint reduction+ Wall upgrade+ Double Low-E Arg+ LED+ Sensor lightning	48,476,646	483,148	2,095,067	147,567	14.19	17.3
Wall upgrade+ Low-E	46,627,206	584,158	245,627	46,557	5.28	5.68
Triple glazing + Wall Upgrade	46,742,466	590,364	360,887	40,350	8.94	10.1

The results show that upgrading only the building envelope such as adding Low-E glazing, triple glazing, or improving walls gives only small benefits, about 6–7% savings. These changes help, but not enough for older buildings. Adding shading also does not work well and has a very long payback, so it is not a good retrofit choice.

Energy savings become much higher when operational controls are added. A scenario with a 1°C setpoint reduction, wall upgrades, Low-E Argon windows, and efficient lighting increases savings to about 23%, although the higher cost creates a longer payback time.

The strongest improvements come from combining several advanced strategies: setpoint optimization, natural ventilation in summer, better glazing, LED lighting with sensors, and reducing infiltration. These combined actions achieve very high savings of 51–58% and keep the payback short (about 5–7 years).

Overall, the analysis shows that envelopes upgrade alone are not enough. The best results come from mixing controls, ventilation strategies, and infiltration reduction to create a whole-building optimization approach.

4.4.2.4 Best Performing Retrofit Scenarios (Type B)

Table 4.6 Best Performing Retrofit Scenarios (Building type B)

Category	Best Scenario	Explanation
Best Low-Cost Option	Wall upgrade + Low-E glazing	low energy savings
Best Medium-Cost Option	1°C setpoint reduction + Wall upgrade + Double Low-E Argon + LED + Sensors	Good balance of cost and performance. Strong mid-level savings.
Best High-Impact Cost Option	1°C setpoint reduction + Wall upgrade + Double Low-E Air + Natural ventilation (summer) + LED + Sensors + Infiltration reduction	Highest energy savings; most cost-effective high impact retrofit.

The best retrofit option for Building Type B is the high-impact scenario, which combines 1°C setpoint reduction, wall upgrades, Double Low-E Air glazing, summer natural ventilation, LED lighting, daylight sensors, and infiltration reduction. This scenario shows the highest total energy savings while maintaining a short payback period. Compared with low- and medium-cost options, this scenario delivers the greatest improvement in overall energy efficiency and offers the most cost-effective high-impact solution for retrofitting pre-code office buildings.

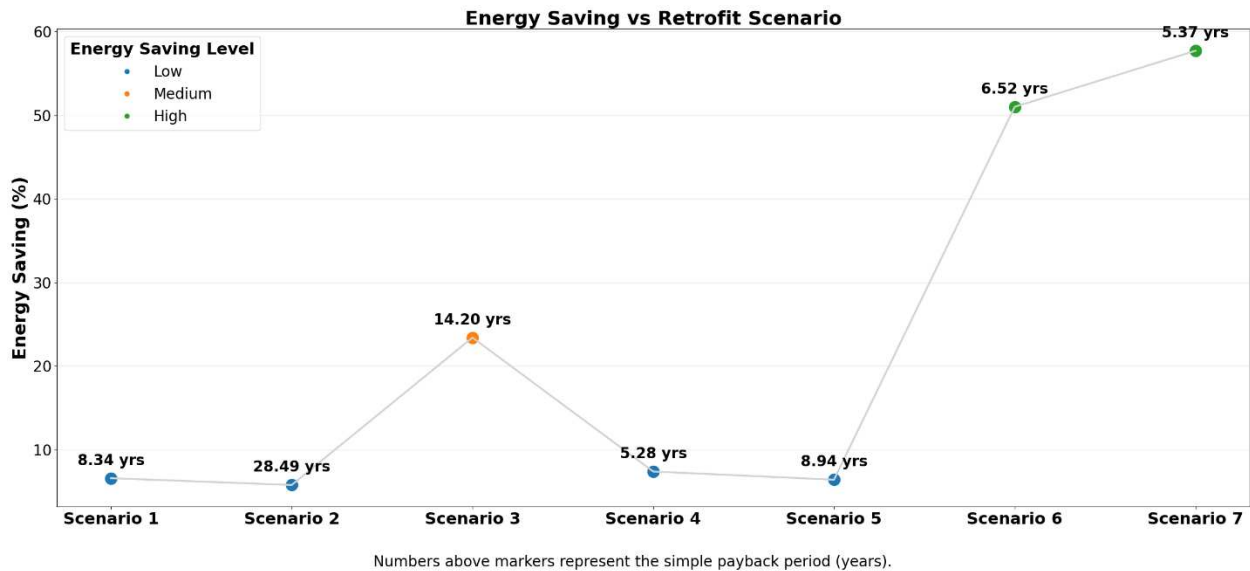


Figure 4.8 Energy Saving and payback period vs. Retrofit Scenario (Type B).

Scenario descriptions:

- Scenario 1: All double Low-E glazing
- Scenario 2: Low-E glazing + Shading control
- Scenario 3: 1°C setpoint + Wall upgrade + Double Low-E Arg + LED + Sensor lighting
- Scenario 4: Wall upgrade + Low-E

- Scenario 5: Triple glazing + Wall upgrade
- Scenario 6: 1°C setpoint + Wall upgrade + Double Low-E Arg + Natural ventilation + LED + Sensor lighting
- Scenario 7: 1°C setpoint + Wall upgrade + Double Low-E Air + Natural ventilation + LED + Sensor + Infiltration improvement

The figure 4.8 compares energy savings and simple payback periods for seven retrofit scenarios. Marker colors indicate saving levels (Low/Medium/High), while labels above each point show the payback time. Scenarios 6 and 7 yield the highest energy savings (over 50%) with the shortest payback periods, while Scenarios 1, 2, 4, and 5 provide limited savings with longer paybacks.

Table 4.7 shows for older office buildings, low-cost and simple retrofit measures such as wall insulation and Low-E glazing provide limited energy savings and are suitable only for minor improvements. In contrast, advanced and higher-cost strategies that combine setpoint optimization, natural ventilation, infiltration reduction, efficient lighting, and integrated control systems deliver substantially higher energy savings and are necessary to achieve deep retrofit performance.

Table 4.7 Comparison of Retrofit Strategies by Energy Saving Level and Implementation Complexity and Cost

Energy Saving Level	Type of Measures	Cost	Complexity	Energy Savings
Low (5–15%)	Envelope-only upgrades	Low	Simple	Limited
High (>28%)	Controls + Ventilation + Airtightness	High	Advanced	Very high

4.5 Retrofit Investment Levels and Cost Ranges Across Energy-Saving Scenarios

To support the economic comparison of retrofit strategies, the retrofit investment is grouped into three energy-saving levels: low (5–15%), medium (15–28%), and high (28–35%). Each level represents a different intensity of upgrades. Low-level retrofits typically include limited envelope improvements such as wall upgrades and double/triple glazing, sometimes combined with shading. These measures require relatively smaller investment and lead to modest savings. Medium-level retrofits combine envelope upgrades with cost-effective operational measures such as a small setpoint adjustment and improved lighting (e.g., LED and sensors), resulting in a stronger balance between cost and savings. High-level retrofits represent the most comprehensive packages, where envelope upgrades are combined with advanced controls and system-level measures such as ventilation strategies and infiltration-related improvements, leading to the highest energy and cost savings but also the highest investment. The cost values are reported as indicative, range-based estimates derived from the scenario “extra cost” results, and they are intended to show the order of magnitude of investment for each savings level.

The cost ranges presented in Table 4.8, 4.9 are used as reference values to classify retrofit scenarios in later chapters. Individual retrofit scenarios analyzed in the case studies are assumed to fall within these ranges, depending on the combination and intensity of measures applied.

Table 4.8 Retrofit Cost Ranges for Office Buildings Type A

Retrofit Level	Typical Measures	Cost Range (KCAD)
Low (5–15%)	Window upgrades, limited roof insulation	40–90
Medium (15–28%)	Roof insulation + improved glazing	90–140
High (28–35%)	Envelope + controls + ventilation upgrades	160–240

Table 4.9 Retrofit Cost Ranges for Office Buildings Type B

Retrofit Level	Typical Measures	Cost Range (KCAD)
Low (5–15%)	Envelope improvements (walls, double/triple glazing, shading)	30-50
Medium (15–28%)	Envelope + lighting + minor operational controls (1°C setpoint)	120-150
High (28–35%)	Envelope + controls + ventilation + infiltration measures	300-400

4.6 Findings

From a practical perspective, the results suggest that retrofit decisions should be guided by budget constraints, desired level of intervention, and acceptable return periods rather than energy savings alone.

For post-code office buildings (Type A), operational and control-based strategies emerged as the most cost-effective options. Because these buildings already benefit from relatively efficient envelopes, additional envelope upgrades provide diminishing returns unless combined with smart operational controls.

In contrast, pre-code office buildings (Type B) showed significantly higher sensitivity to envelope-related upgrades due to their weak baseline thermal performance. In these buildings, envelope improvements combined with operational measures resulted in both substantial energy savings and reasonable payback periods.

Overall, the results emphasize that optimal retrofit strategies differ depending on building age and baseline performance, they need differentiated retrofit priorities.

Figure 4.9 shows total findings in this study.

-
- Retrofit performance depends on building age and baseline condition
 - The same retrofit can perform very differently in old and new buildings.
 - Combined retrofit strategies work better than single measures.
 - Some measures are not cost-effective in cold climates.
 - Retrofit decisions must consider both energy savings and payback.
 - It can be useful for the building industry in Montréal and other cold regions
 - Helps building owners and engineers make better investment decisions.
 - Supports selection of effective retrofit packages under limited budgets.
 - Aligns with energy efficiency and decarbonization goals of NECB,..

Figure 4.9 Research Findings

Chapter 5 Conclusions and Recommendations

5.1 Conclusions

This research evaluated the energy and economic performance of retrofit strategies for office buildings in Montréal's cold climate (ASHRAE Climate Zone 6A) using a physics-based Bottom-Up Building Energy Modeling (BEM) approach. Two representative high-rise office building archetypes were analyzed:

- (1) a newer post-code, code-compliant office tower (Type A), and
- (2) an older pre-code office tower constructed before modern energy standards (Type B).

Multiple retrofit scenarios were simulated in Design Builder/ Energy Plus, and their economic viability was assessed using Simple Payback Period (SPP) and Discounted Payback Period (DPP).

The results clearly demonstrate that retrofit effectiveness is strongly dependent on building age and baseline condition. The older pre-code building (Type B) showed substantially higher energy-saving potential than the newer building, due to its inefficient envelope, higher infiltration rates, and less efficient HVAC systems. In contrast, the newer post-code building (Type A), which already meets modern energy standards, exhibited more limited savings from envelope-only upgrades.

Across both building types, the highest energy savings were achieved when envelope, mechanical, and operational measures were combined. Integrated retrofit packages consistently delivered superior performance compared to single-measure upgrades.

Economic analysis indicates that not all energy-efficient measures are economically attractive, particularly in cold climates. Retrofit options that focus mainly on adding shading showed produced limited energy savings and very long payback periods due to reduced winter solar gains. In contrast, control-based strategies provided the most favorable balance between energy savings and investment cost.

The economic results show that we must choose retrofit options carefully based on building archetype and baseline performance. The payback periods in the scenarios are very different from each other: Some combined retrofit packages have short payback periods. Other options, especially those with shading, have very long payback periods because they cost a lot and save little energy in winter. This means that energy savings alone are not enough to choose a retrofit. So, it is important to look at the cost and financial return.

The finding is directly useful for people working in the building industry in Montréal and other cold regions. Building owners, facility managers, and engineers often have limited money and many retrofit options to choose from. The results of this study show which retrofit measures give the best performance for:

- Older buildings (built before energy codes), and
- Newer buildings (built under modern codes).

This helps the industry:

- Make better investment decisions
- Choose retrofit packages that work
- Understand what level of energy savings and payback to expect
- Support energy efficiency goals from NECB, ASHRAE, and Montréal's decarbonization plans

These findings give clear, practical guidance for improving energy performance in office buildings.

5.1.1 Summary of Key Findings

This study evaluated the energy and economic performance of multiple retrofit strategies for two representative office building archetypes in Montréal's cold climate. The results demonstrate that retrofit effectiveness strongly depends on the building's construction era and baseline performance.

Overall, the results indicate that combined retrofit packages consistently outperform single-measure upgrades in both energy savings and economic performance.

5.1.2 Scientific Contributions of the Thesis

The main scientific contributions of this thesis are as follows:

- Development of a systematic framework for evaluating the energy and economic performance of retrofit strategies for office buildings in cold climates.
- Shows how retrofit priorities differ significantly between pre-code and post-code office buildings.
- Integration of energy simulation results in economic indicators including Simple Payback Period (SPP) and Discounted Payback Period (DPP) to support cost-effective retrofit decision-making.

This thesis provides a transferable methodology that can be applied to other office buildings and expanded to support future guideline development.

The main contribution of this thesis is not limited to the numerical estimates of energy savings reported for the two case studies. Rather, the research provides a structured and transferable decision-support framework for selecting energy retrofit strategies in office buildings.

By categorizing retrofit strategies into low, medium, and high intervention levels and evaluating them simultaneously based on energy savings, investment cost, and payback period, this study moves beyond traditional single-metric evaluations. The proposed framework allows building

owners and engineers to compare retrofit options in a systematic and practical manner, reflecting real-world budget constraints and decision-making processes.

Another key contribution of this research is the explicit differentiation of retrofit priorities between pre-code and post-code office buildings. The results demonstrate that modern, code-compliant buildings benefit most from operational and control-based strategies, whereas older buildings with weak envelopes achieve greater improvements through envelope-focused retrofits combined with operational measures.

Although the numerical results are specific to the modeled cases, the underlying decision logic and prioritization framework developed in this study are transferable to other office buildings with similar characteristics, construction periods, and climatic conditions.

5.2 Limitations and Future Works

This section includes the main limitations of the study and suggests directions for future work.

5.2.1 Limitations

Despite the use of detailed energy modeling and real building data, this study is subject to several limitations.

The analysis is based on two representative high-rise office building archetypes in Montréal, selected to reflect differences in construction practices and energy code influence. While this archetype-based approach enables a clear comparison of retrofit strategies across buildings with different baseline energy performance, the results may not be directly transferable to other building typologies such as low-rise, mid-rise, or mixed-use buildings, or to office buildings located in different climatic regions.

In addition, complete architectural and mechanical documentation was not available for the case-study buildings. Consequently, some building characteristics, including insulation levels, air leakage rates, and HVAC system efficiencies, were estimated using on-site observations, national standards, and values reported in Canadian building energy studies. Although these assumptions are consistent with common practices in building energy modeling, they may not fully capture the actual as-built and as-operated conditions of the buildings, which can affect absolute energy consumption results.

The economic evaluation conducted in this study focuses on retrofit investment costs, energy cost savings, and simple and discounted payback periods. Other economic aspects, such as maintenance costs, future energy price variations, incentive programs, and policy-driven financial mechanisms, were not included.

Finally, the simulations were performed using a standard EnergyPlus weather file representative of Montréal's cold and humid climate (ASHRAE Climate Zone 6A). Short-term extreme weather

events and long-term climate variability were not considered, which may influence future building energy performance and the long-term effectiveness of retrofit strategies.

5.2.2 Recommendations for Achieving Energy Efficiency

For the new office building (post-code) the main recommendation is to focus first on how the building is operated, rather than on expensive physical upgrades. The results show that the largest and most cost-effective energy savings come from optimizing operating schedules, applying temperature setbacks during non-working hours, and reducing lighting and equipment use when spaces are unoccupied. These measures are low-cost, easy to implement, and provide fast payback. Envelope upgrades such as improving roof insulation or upgrading glazing can further support energy savings, but they should be applied selectively and only after operational controls are optimized. Shading systems should be used carefully in Montréal's cold climate and only with seasonal or smart control, since uncontrolled shading can reduce useful solar heat in winter. Overall, high energy savings in modern office buildings are achieved through a combined strategy that prioritizes smart controls and targeted upgrades, offering a practical and transferable framework for similar post-code office buildings.

Based on the results of Building Type B (pre-code office buildings), the main recommendation for practitioners is to prioritize operational and control-based retrofit measures before investing in costly envelope upgrades. The simulations show that heating setpoint optimization, improved scheduling, and efficient lighting controls can deliver substantial energy savings at relatively low complexity, while envelope-only measures provide limited reductions. For higher energy-saving targets, setpoint reduction should be combined with summer natural ventilation and infiltration reduction, as these strategies significantly reduce heating and cooling demand and work especially well in older, leaky buildings. Envelope upgrades such as Low-E glazing and wall insulation should therefore be applied as supporting measures rather than primary drivers of savings. Overall, deep retrofits in older buildings should follow a whole-building optimization approach that integrates controls, ventilation strategies, and airtightness improvements to achieve high energy savings with reasonable payback periods.

5.2.3 Future Research

Future research can expand this framework by analyzing the framework to a larger number of office buildings with different geometries and operational patterns. The same approach can also be tested on other types, such as residential, institutional, and mixed-use buildings, and in different climate zones, to show that it can be used in many situations.

In addition, future studies can integrate carbon emissions analysis and life-cycle assessment so that retrofit decisions consider environmental impacts.

Future studies could include more financial factors in the economic analysis. Adding maintenance costs, changes in energy prices, and available incentives would give a more realistic picture of retrofit costs and benefits and help decision-makers make better long-term choices.

References

- Ali, U., Shamsi, M. H., Hoare, C., Mangina, E., & O'Donnell, J. (2021). Review of urban building energy modeling (UBEM) approaches, methods and tools using qualitative and quantitative analysis. *Energy and Buildings*, 246, 111073. <https://doi.org/10.1016/j.enbuild.2021.111073>
- Al Jadaa, D., & McArthur, J. J. (2024). *Development of granular archetypes for Canadian existing commercial office and multi-unit residential buildings in climate zone 5*. In *Proceedings of eSim 2024: 13th Conference of IBPSA-Canada*. Edmonton, Canada.
- Aguilar-Santana, J. L., Jarimi, H., Riffat, S., & Akeiber, H. (2020). A review on window-glazing technologies and future prospects. *International Journal of Low-Carbon Technologies*, 15(1), 112–131.
- ASHRAE. (2016). *ANSI/ASHRAE/IES Standard 90.1-2016: Energy standard for buildings except low-rise residential buildings*. American Society of Heating, Refrigerating and Air-Conditioning Engineers. <https://www.ashrae.org/technical-resources/bookstore/standard-90-1>
- Bernier, M., Neale, A., & Kummert, M. (2024). *Development of archetypes to represent residential building stock*. Polytechnique Montréal.
- Building Science Corporation. (n.d.). *BSI-054: Risky business—High-risk walls*. Retrieved January 16, 2026, from <https://buildingscience.com/documents/insights/bsi054-risky-business-high-risk-walls>
- Canada Green Building Council. (2022). *Decarbonizing Canada's large buildings: A technical and economic pathways report*. CaGBC. <https://www.cagbc.org/news-resources/research-and-reports/decarbonizing-canadas-large-buildings/>
- Cerezo Davila, C., Reinhart, C. F., & Bemis, J. L. (2016). Modeling Boston: A workflow for the efficient generation and maintenance of urban building energy models from existing geospatial datasets. *Energy*, 117(1), 237–250. <https://doi.org/10.1016/j.energy.2016.10.057>
- Cerezo Davila, C., Sokol, J., Reinhart, C. F., Al-Mumin, A., & Hajiah, A. (2017). Three methods for characterizing building archetypes in urban energy simulation: A case study in Kuwait City. *Energy and Buildings*, 154, 321–334.

- Ding, C., & Zhou, N. (2020). Using residential and office building archetypes for energy efficiency building solutions in an urban scale: A China case study. *Energies*, 13(12), 3210. <https://doi.org/10.3390/en13123210>
- Énergir. (2024). *Natural gas rates for commercial and institutional customers*. Énergir, Québec, Canada.
- Engblom, L. A. (2006). *Scenario analysis of retrofit strategies for reducing energy consumption in Norwegian office buildings* (Master's thesis). Massachusetts Institute of Technology.
- Ferrando, M., Causone, F., Hong, T., & Chen, Y. (2021). Urban building energy modeling (UBEM) tools: A state-of-the-art review of bottom-up physics-based approaches. *arXiv Preprint*. <https://arxiv.org/abs/2103.01761>
- Finch, G. (2021). Building enclosure control layers: Water, vapour, and air control for large passive house projects. Passive House Canada.
- Gavaldà Torrellas, O., Monsalvete, P., Ranjbar, S., & Eicker, U. (2025). The Urban Building Energy Retrofitting Tool: An open-source framework to help foster building retrofitting using a life cycle costing perspective. First results for Montréal. *Preprints*. <https://doi.org/10.20944/preprints202410.1766.v3>
- Gavaldà-Torrellas, O., Monsalvete, P., & Eicker, U. (2024). The urban building energy retrofitting tool: An open-source framework—First results for Montréal. *Preprints*, 2024101766. <https://doi.org/10.20944/preprints202410.1766.v1>
- Hong, T., Chen, Y., Lee, S. H., & Piette, M. A. (2016, August). *CityBES: A web-based platform to support city-scale building energy efficiency*. In *Proceedings of the 5th International Urban Computing Workshop (UrbComp)*. San Francisco, CA.
- Hydro-Québec. (2025). *Electricity rates for business customers*. Hydro-Québec, Montréal, Canada.
- International Energy Agency. (2021). *Net zero by 2050: A roadmap for the global energy sector*. IEA.
- International Energy Agency. (2023). *Buildings – Energy system*. <https://www.iea.org/energy-system/buildings>
- Jahed, N. (2018). *Performance-based facades: Retrofit strategies for energy efficiency and comfort in existing office buildings* (Master's thesis). Middle East Technical University.
- Kavgic, M., Mavrogianni, A., Mumovic, D., Summerfield, A., Stevanovic, Z., & Djurovic-Petrovic, M. (2010). A review of bottom-up building stock models for energy consumption in the residential sector. *Building and Environment*, 45(7), 1683–1697. <https://doi.org/10.1016/j.buildenv.2010.01.021>

- Leroy, L. (2020). *Modelling neighborhood-scale energy scenarios* (Master's thesis). Polytechnique Montréal.
- Li, W., Zhou, Y., Cetin, K. S., Eom, J., Wang, Y., Chen, G., & Zhang, X. (2017). Modeling urban building energy use: A review of modeling approaches and procedures. *Energy*, *141*, 2445–2457. <https://doi.org/10.1016/j.energy.2017.11.071>
- Lstiburek, J. (2010). Understanding walls (Building Science Insight BSI-012). Building Science Corporation.
- Maleki Afarin, A. (2009). *Life-cycle cost evaluation of building envelope energy retrofits* (Master's thesis). Ryerson University. <https://utoronto.scholaris.ca/items/74e0d8ad-d005-4955-a7f7-5d5598b7990c>
- Mastrucci, A., Baume, O., Stazi, F., Salvucci, S., & Leopold, U. (2014). *A GIS-based approach to estimate energy savings and indoor thermal comfort for urban housing stock retrofitting*. RWTH Aachen University.
- National Research Council Canada. (2026). *Energy use in Commercial/Institutional Sector*. Website: <https://oee.nrcan.gc.ca/publications/statistics/trends/2018/commercial.cfm> (last accessed, January 2026).
- National Research Council Canada. (2020). *Archetypal building energy models for Canada*. NRC Publications.
- National Research Council Canada. (2017). *National Energy Code of Canada for Buildings (NECB 2017)*. Codes Canada.
- Natural Resources Canada. (2016). *Major energy retrofit guidelines for commercial and institutional buildings: Principles* (Cat. No. M144-268/2016E-PDF). <https://publications.gc.ca/site/eng/9.811806/publication.html>
- Natural Resources Canada. (2022). *Comprehensive Energy Use Database: Commercial/Institutional Sector – Canada*. Government of Canada.
- Natural Resources Canada. (2011). *Major energy retrofit guidelines for commercial and institutional buildings: Office buildings*. Government of Canada. <https://natural-resources.canada.ca>
- Pacific Northwest National Laboratory, & PECL. (2011). *Advanced energy retrofit guides: Office buildings*. U.S. Department of Energy.
- Parekh, A. (2005). *Development of archetypes of building characteristics libraries for simplified energy use evaluation of houses*. In *Proceedings of the 9th IBPSA Conference* (pp. 921–928). Montréal, Canada.

- Piro, M., Ballarini, I., & Corrado, V. (2023). From building energy models (BEM) to urban building energy models (UBEM): Input data and modelling approaches. *Building Simulation* 2023, 1882–1889.
- Pongelli, A., Priore, Y. D., Bacher, J.-P., & Jusselme, T. (2022). Definition of building archetypes based on the Swiss energy performance certificates database. *Buildings*, 13(1), 40. <https://doi.org/10.3390/buildings13010040>
- Reinhart, C. F., & Cerezo Davila, C. (2016). Urban building energy modeling – A review of a nascent field. *Building and Environment*, 97, 196–202. <https://doi.org/10.1016/j.buildenv.2015.12.001>
- RDH Building Science Inc. (2021). Mass timber building enclosure best practice design guide (Version 2.2). Vancouver, BC: RDH Building Science Inc.
- Sokol, J., Cerezo Davila, C., & Reinhart, C. F. (2017). Validation of a Bayesian-based method for city-scale building energy modelling. *Energy and Buildings*, 134, 11–24. <https://doi.org/10.1016/j.enbuild.2016.10.050>
- Swan, L. G., & Ugursal, V. I. (2009).
- Sustainable Energy Action. (n.d.). *Energy codes then and now: 1983–2021*. Retrieved January 16, 2026, from <https://sustainableenergyaction.org/resources/energy-codes-then-and-now-1983-2021>
- Modeling of end-use energy consumption in the residential sector: A review. *Renewable and Sustainable Energy Reviews*, 13(8), 1819–1835. <https://doi.org/10.1016/j.rser.2008.09.033>
- United Nations Environment Programme. (2022). *Global status report for buildings and construction 2022*. UNEP. <https://www.unep.org/resources/report/global-status-report-buildings-and-construction>
- U.S. Department of Energy. (2020). *Commercial prototype building models*. Office of Energy Efficiency and Renewable Energy.
- World Business Council for Sustainable Development. (n.d.). *Transforming the built environment*. <https://www.wbcsd.org/actions/transforming-the-built-environment>
- Zhang, H. (2020). *Life cycle costing analysis of deep energy retrofits of a mid-rise building*. University of British Columbia. <https://arxiv.org/abs/2304.00456>