

**Optimization of the thermal performance of the Montpetit Hall
envelope: A case study**

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Abstract

Climate change is the most severe global sustainability issue our planet faces today, and the construction industry plays a significant role in the increasing demand for global energy. Consequently, prioritizing enhanced energy efficiency in existing buildings is a critical strategy for addressing these challenges. One way of achieving this involves simulating older buildings and evaluating their energy use for thermal optimization, which are essential tasks. Deep retrofitting is necessary to manage climate and energy consumption. The challenge lies in selecting the most effective energy retrofitting strategy for a specific building, given the numerous possible combinations of retrofit measures and conflicting goals. The unique weather conditions in Canada further complicate building energy retrofit challenges. In this study, the focus was on optimizing the thermal performance of the Montpetit Building on the University of Ottawa campus. This thesis aims to create a model that reduces energy usage and increases economic returns using a multi-objective optimization technique based on simulation. The simulation was first run using SketchUp software with the OpenStudio plugin to build a simulation-based multi-objective optimization framework. The results were then exported to EnergyPlus software. This framework combines the NSGA-II algorithm in MATLAB® as an optimization engine with EnergyPlus as a dynamic energy simulator, aiming to achieve optimal reductions in energy consumption and associated costs. The algorithm explores various solutions for the building envelope, including insulation and windows. The final solutions were chosen based on their respective Pareto fronts, considering cost-optimality and energy efficiency. Notably, the results show 50 fixed ideal answers by the outcome.

By optimizing the building's envelope, a reduction of approximately 10% in total primary energy consumption is expected for one of the solutions with the least energy consumption. Furthermore, adjusting the cooling setpoint from 22°C to 25°C and modifying the heating setback by 2°C presents a potential reduction ranging from 10% to 30%. Specifically, during January, February, October, November, and December, optimization efforts may yield a reduction of up to 24% before adjusting the setpoint and setback and up to 48% following these adjustments. Additionally, implementing the aforementioned setpoint and setback changes on extreme winter days could result in a 20% decrease in total energy consumption; even on extreme summer days, a reduction of 27% is achievable. The second solution which is examined has the least cost. There is a notable reduction, especially in January, October, November, and December, with savings of up to 12% after optimization. With the changes in setpoints and setbacks to the mentioned values, the optimization increased to 42% savings in October. Also, the total energy efficiency increases by 90% after retrofitting and adjusting new setpoints and setbacks during extreme winter days and extreme summer days. Additionally, The sum weight method was used to select the third option. In this case, after optimization, we have a significant reductions of energy consumption, especially in January, October, November, and December which is up to 22%. By adjusting new setpoints and setbacks to the mentioned values, energy efficiency increased to 47% in October, 31% in September, and 43% in May, and after retrofitting and adjusting new setpoints and setbacks, total energy efficiency increased by 90% and 92% during extreme winter and summer days respectively. Moreover, the two-dimensional Pareto front demonstrates the inverse link between NPV and total energy usage.

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List of Symbols and Abbreviations

| Acronym | Description |
|-----------------------|--|
| A/C | Air Conditioning |
| AHU | Air Handling Unit |
| ANSI | American National Standards Institute |
| ASHRAE | American Society of Heating, Refrigerating and Air-Conditioning Engineers |
| AutoCAD | Automatic Computer-Aided Design |
| AWD | Actual Weather Data |
| BAU | Business As Usual |
| BLAST | Basic Local Alignment Search Tool |
| CO₂ | Carbon Dioxide |
| CT | Certainteed (brand) |
| CV(RMSE) | Coefficient of Variation of Root Mean Square Error |
| DHI | Diffuse Horizontal Radiation |
| DNI | Direct Normal Radiation |
| ECMs | Energy Conservation Measures |
| EE | Energy-Efficient |
| EEM | Energy-Efficient-Measurement |
| GA | Genetic Algorithms |
| GHGs | Greenhouse Gases |
| GHI | Global Horizontal Radiation |

| | |
|-----------------|--|
| HSPT | Heating Set Point Temperature |
| HVAC | Heating, Ventilation, and Air Conditioning |
| HW | Hot Water |
| IEA | International Energy Agency |
| IES | Illuminating Engineering Society |
| JK | John Manville (brand) |
| MS Excel | Microsoft Excel |
| NECB | National Energy Code for Buildings |
| NMBE | Normalized Mean Bias Error |
| NSGA-II | Non-dominated Sorting Genetic Algorithms |
| NSRDB | National Solar Radiation Database\ |
| NPV | Net-Present-Value (Price) |
| PDF | Portable Document Format |
| PV | Photovoltaic |
| RH | Relative Humidity |
| RW | Rockwool (brand) |
| SHGC | Solar Heat Gain Coefficient |
| TWD | Typical Weather Data |
| uOttawa | The University of Ottawa |
| VLT | Visible Light Transmittance |
| .epw | EnergyPlus Weather File |
| .csv | Excel File |

1. Introduction

1.1. Problem statement

Over the past twenty years, the significant increase in worldwide energy use has raised concerns about various adverse environmental impacts, including global warming, ozone layer depletion, air pollution, loss of biodiversity, and deforestation, which the leading cause is the continuously increasing release of greenhouse gases (GHGs), mainly from burning fossil fuels (Moradi and Kavgic 2022). Furthermore, energy is harnessed in multiple ways across different sectors of human activities in the industry, such as buildings, which account for approximately 40% of the total global energy consumption (U.S. Energy Information Administration (EIA) 2016; “Energy Outlook 2018 | News and Insights | Home” 2021).

Older buildings are replaced with new ones at a relatively low rate due to their extended lifespan, which can last up to 50 or 100 years. The National Research Council on Household Energy Use's 2011 Survey indicates that 49% of today's households were constructed before 1980¹. Since 75% of Canada's buildings will still be used by 2030, current construction must be more energy-efficient². Implementing retrofit solutions in existing structures is a practical and effective approach to achieving this goal (Rossi, Howard, and Wright 2020). Also, Enhancing energy efficiency in the building industry is fundamental for a more sustainable approach to energy and can benefit both the economy and the environment (Rouleau, Gosselin, and Blanchet 2018; Zhu et al. 2018).

¹ <https://nrc.canada.ca/en/certifications-evaluations-standards/codes-canada/codes-canada-publications/final-report-alterations-existing-buildings>

² <https://www.canada.ca/en/services/environment/weather/climatechange/climate-action/federal-actions-clean-growth-economy/homes-buildings.html>

Therefore, reducing energy usage in existing buildings is essential to promoting sustainability and lowering global energy consumption (Seghier et al. 2022; Jafari and Valentin 2017).

Energy retrofit is the most practical and affordable way to lower the energy usage intensity (EUI) levels in building stock. It involves operational or physical modifications that improve building energy performance, including equipment, tenant behaviour, and the building envelope (Wang, Xia, and Zhang 2014).

Building energy modelling makes it possible for engineers and designers to evaluate the efficacy of these methods for increasing a building's energy efficiency from the beginning of its design (Gao, Koch, and Wu 2019).

One of the various energy simulation tools available to engineers for testing and energy consumption measurement is EnergyPlus. It allows them to model building energy consumption, including the energy used for electricity, lights, heating, cooling, ventilation, and process loads. For buildings, the following tasks can be accomplished with thermal simulation tools such as EnergyPlus: determining the proper HVAC system size, detecting and evaluating energy use, figuring out the cost of energy used, and lowering energy expenses (Gao, Koch, and Wu 2019).

The primary obstacle in building energy retrofitting is determining which mix of energy-saving techniques, from the many available, would yield the best results. The project team should provide stakeholders with a thorough economic assessment of the project to suggest the best course of action. Thus, developing a framework that makes energy

efficiency calculations easier and gives investors a clear understanding of the financial advantages of energy retrofit projects may be beneficial (Malatji, Zhang, and Xia 2013).

It is also almost impossible to thoroughly search and simulate an entire building due to the vast array of combinations of energy efficiency measures. More specifically, a detailed analysis of every potential solution is not computationally feasible given the time needed to simulate the energy performance of a given combination of measures in a building. Therefore, optimization techniques that quickly find optimal solutions, like genetic algorithms, can be used to address this difficulty (A. Safari 2022).

Lastly, it is emphasized that energy retrofitting projects trade-off between the financial gain from increasing the energy efficiency of the structure and the original investment (Ma et al. 2012) to gain social, economic, and environmental benefits (Jafari and Valentin 2017). Reversing the above aims can be achieved by implementing an energy efficiency measure. Thus, applying a multi-objective optimization framework is necessary to get a suitable choice among competing objectives (Nguyen, Reiter, and Rigo 2014; Hamdy, Hasan, and Siren 2010).

This research aims to enhance building envelope performance to optimize the thermal performance of the current structure. Improved insulation blocks heat transfer by limiting air leakage inside and outside the building. In addition, when cutting the building's energy usage, the windows should not be disregarded. Because there is a gas layer between the two sides of the glass in double-glazed windows, energy losses are significantly reduced. Moreover, setpoint temperature also has a significant effect on building energy use. As a result, comparing the cost and energy-efficient measures is necessary to determine the ideal values. In the following the novel research contributions are given:

The present study differs from other research on building retrofitting in three significant ways. Firstly, previous research has primarily focused on optimization using continuous variables, which may not fully reflect real-world circumstances due to businesses' strict requirements and manufacturing of insulations (Mostafazadeh, Eirdmoussa, and Tavakolan 2023) while discrete variables better address practical industry constraints and options.

The next significant benefits set this study apart from earlier research that concentrated on the multifunctional building, featuring a variety of facilities such as offices, classrooms, a gym, and a swimming pool. The case study is the Montpetit Hall building, which is a complex structure. This analysis optimizes the building and retrofits a detailed model with multiple zones. In comparison, small buildings were the focus of earlier research. In addition, not much research has been done in regions with cold climates and hot, humid summers like Ottawa. Therefore, solutions developed elsewhere can be applied here. Also, more research is needed on such a climate and weather, particularly in Ottawa, which is the second benefit of this research.

Finally, this study uses passive methods (insulations and windows) and active methods (setpoints and setbacks) for optimization.

1.2. Objective and scope

The primary objective of this research was to investigate the potential for optimal deep energy envelope retrofit of the large and multifunctional Montpetit Hall at the University of Ottawa (uOttawa). In this respect, a thorough examination of retrofit scenarios designed to minimize Montpetit Hall's energy consumption and costs is conducted.

The main objectives of this research are outlined below:

- 1- To develop a realistic Montpetit Hall model employing several software tools, including SketchUp, OpenStudio, and EnergyPlus.
- 2- To create a 2012-2013 weather file for Ottawa in the “.epw” (EnergyPlus) format needed for model evaluation and assessment.
- 3- To compare the outputs of the simulation against the benchmark to assess the developed model's predicting accuracy.
- 4- To couple the whole building energy model of Montpetit Hall with Matlab to perform multi-objective optimization and find the optimal solution values of two conflicting goals, energy savings derived from deep retrofit and cost of investment.
- 5- To analyze a set of preferred solutions, the Pareto front, produced by the optimization algorithm NSGA-II, and to select the optimal deep energy retrofit option.
- 6- To discuss results and provide recommendations regarding the feasibility of deep envelope retrofit of the Montpetit Hall.

The sub-objectives of this research are outlined below:

- 1- To gather data for developing a detailed whole-building energy model of Montpetit Hall by undertaking on-site visits and frequent communications with the uOttawa facility and sustainability offices to obtain technical data about the building.
- 2- To extract data needed for whole-building energy modelling from the NECB standard and ASHRAE that is inaccessible.
- 3- To collect information about fenestrations and insulation costs for optimization analysis.

1.3. Thesis structure

Chapter 2

This section presents an in-depth overview of the thermal optimization process in buildings. The scope includes building energy modelling and explaining relevant tools and parameters. Furthermore, two types of energy retrofitting, shallow and deep, are discussed. The chapter consists of a description of energy efficiency in Canada and an outline of the optimization process.

Chapter 3

The methodology of this study is explained in the following sections, covering modelling from geometry and energy. Subsequently, options for optimization are introduced, accompanied by an explanation of decision variables. This chapter also presents objective functions for optimization. The optimization method is then discussed within the multi-objective optimization framework, and multi-criteria decision-making is employed to identify the optimal solution. Also, in this chapter, every step of the methodology is explained in detail for the case study of research. Modelling of the building by SketchUp, OpenStudio, and EnergyPlus is discussed. After introducing objective functions in this study, the variables are introduced. Then, to optimize building energy and find the best solution, NSGA-II, employed as an optimization algorithm written under MATLAB, is explained.

Chapter 4

The results section thoroughly examines selected options from the Pareto front. It introduces the window and insulation variables for exterior walls, roof, and floor, along with their associated cost and energy efficiency measurements.

Chapter 5

This chapter provides a comprehensive conclusion of the whole project process. It also provides recommendations for future research, considering the identified limitations.

2. Literature review

2.1. Introduction

Global attention has been directed towards energy-efficient retrofitting of aging properties due to benefits such as significant potential energy savings and improvement in indoor environmental quality. Focusing on the energy improvement of the existing buildings is justified, considering that buildings account for approximately one-third of the world's total energy consumption and contribute a similar proportion of global carbon dioxide emission (Balaras et al. 2005). Consequently, implementing energy efficiency retrofitting strategies holds considerable promise for reducing energy consumption and CO₂ emissions in older buildings (Sadineni, Madala, and Boehm 2011).

In Canada, the imperative for refurbishment of aging buildings is accentuated by forecasts indicating that a quarter of all homes and buildings in the country will still be in use by 2030 (Lockhart & Haley, 2020). Additionally, an assessment delineated in McKinsey's Global GHG Abatement Cost Curve (Enkvist et al., 2010) underscores the economic viability of retrofitting buildings, with an estimated cost of approximately -\$50 per ton of CO₂ mitigated. This stark juxtaposition is evident compared to alternative strategies, such as installing solar panels, which cost approximately +\$0.7 per ton of CO₂ mitigated.

2.2. Energy Efficiency in Canada

In Canada, in 2013, the commercial/institutional sector was the fourth largest energy user, using 10% of the total energy (see Figure 2.1) (Efficiency and Leading Canadians to Energy Efficiency at Home 2013).

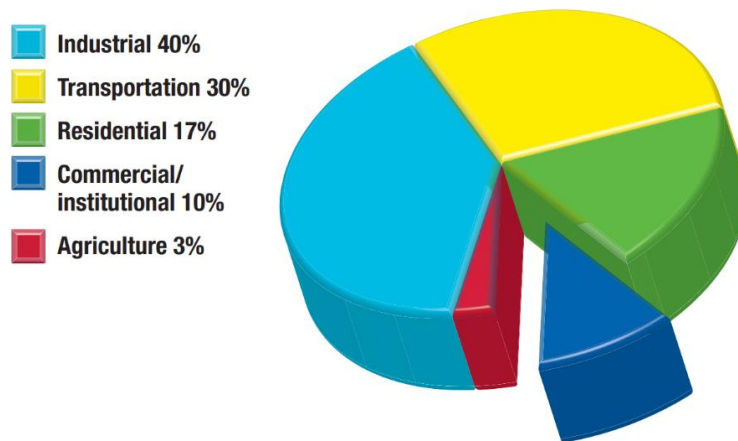


Figure 2.1 Commercial/institutional energy use by end use 2013.

Energy is utilized in the commercial/institutional sector for various tasks, including lighting, heating, cooling, and space heating. It also runs auxiliary motors, computers, and other medical equipment. The highest portion of energy use, roughly 55%, is attributed to space heating, with additional equipment coming in second at 14% (Figure 2.2). Although not connected to floor space activities, street lighting is included in total energy but not in the factorization analysis. Trade, finance, real estate, public administration, education, and commercial services are all included in the commercial/institutional sector. Ten subsectors have been assigned to these activities (Efficiency and Leading Canadians to Energy Efficiency at Home 2013).

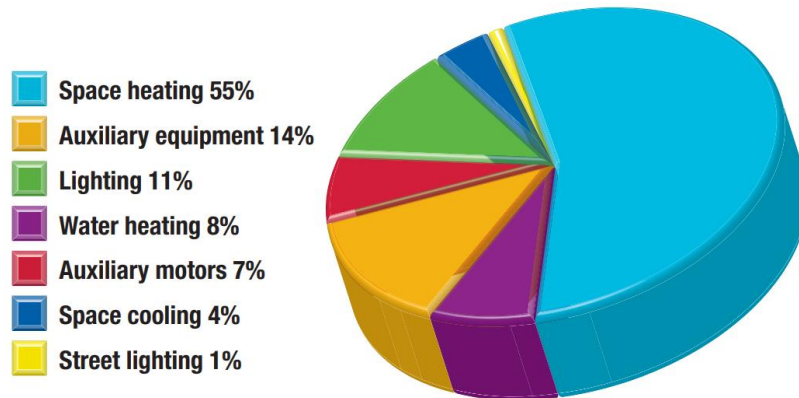


Figure 2.2 Energy use by sector in Canada

Since 1990, Canada's commercial and institutional sector has saved \$5.4 billion in energy because of improvements in energy efficiency. The increases in energy efficiency in the commercial and institutional sectors were strikingly similar to those in the residential sector. These include modifications to the building's thermal envelope (insulation, windows) and higher energy-efficient appliances, lighting, and auxiliary equipment in commercial and institutional buildings. The energy efficiency of this industry increased by 33% between 1990 and 2013, saving 241.8 PJ, or \$5.4 billion, in energy (Figure 2.4) (Efficiency and Leading Canadians to Energy Efficiency at Home 2013).

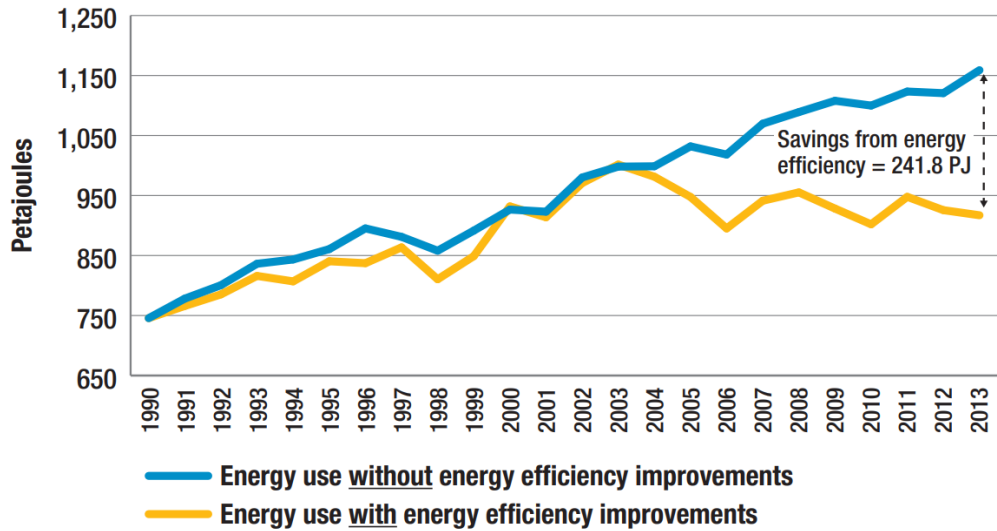


Figure 2.4 Commercial/institutional energy use

Figure 2.5 depicts the influence of various factors on the change in commercial/institutional sector energy use between 1990 and 2013. The following are the effects: Activity, structure, weather, service quality, and energy efficiency are all present (Efficiency and Leading Canadians to Energy Efficiency at Home 2013).

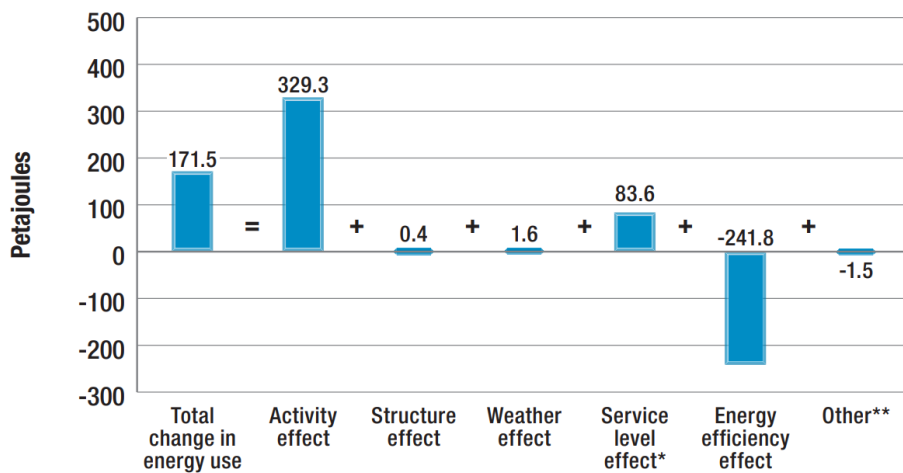


Figure 2.5 Impact of activity, structure, weather, service level, and energy efficiency on commercial/institutional energy use change, 1990–2013.

Kaitlin Carlson's team in Canada studied four large office buildings in Toronto to comprehend the impact of improving energy efficiency on their value and contribute to the understanding of energy efficiency in Canadian buildings. Through data analysis before and after energy upgrades, they discovered that, despite having limited information, enhancing energy efficiency can reduce costs, increase occupancy, and boost rental revenue. This positively influences the overall value of the buildings (Kaitlin Carlson, n.d.).

Kaitlin Carlson used U.S. studies for comparison since there were few like them in Canada. The U.S. and Canadian commercial building sectors are similar from some perspectives, and their economies are connected. So, what they learn from U.S. studies can be applied to Canadian commercial buildings. To explore the link between how efficiently buildings use energy and their value, four commercial office buildings in downtown Toronto, Canada, were chosen for analysis. All these buildings are high-grade commercial spaces that recently went through improvements. It's important to note that the buildings managed by the same entity underwent upgrades, with some undergoing extensive improvements. Notably, the building with the more limited retrofit exhibited lower energy savings and significantly higher energy use intensity (EUI) than before and after the upgrades (Kaitlin Carlson, n.d.).

Making buildings more sustainable involves investigating how upgrading existing office buildings in Canada (Toronto) affects their overall value. In Canada, a considerable number of buildings, with more than half not renovated by 2009, present an opportunity for cost-effective investments in energy efficiency and the planet's well-being (Kaitlin Carlson, n.d.).

Even though Canada currently lacks a law requiring buildings to share their energy information, it's expected soon. If there's mandatory disclosure of energy use, it might make many existing office buildings less appealing to tenants. Additionally, some buildings might become outdated if there are minimum energy performance requirements. In anticipation of these changes, the aim is to convince those in the industry that investing in energy improvements for commercial office buildings is environmentally responsible and a smart financial move. Adding building value to economic assessments will give owners and investors a better understanding of the business benefits of sustainable building practices (Kaitlin Carlson, n.d.).

2.3. Energy performance of buildings

Measuring how much-saved energy is used in different ways to make a building more energy-efficient can be complicated. Usually, an energy simulation is needed to look at the energy use of the whole building in detail (Ye et al. 2021).

The energy simulations aim to examine the original model and get a trustworthy assessment of the advantages linked to different retrofitting choices (Stevanović 2013; Wilde 2018). Building energy performance simulation can be conducted using two main approaches: mathematical methods and dynamic methods involving simulation software (Javadikasgari, Soltesz, and Gillinov 2018; Murray et al. 2014). Analyzing various factors influencing building performance and their interactions falls under dynamic modelling. However, it is essential to recognize that dynamic energy simulations demand more time than static modelling (A. Safari 2022).

Mauro and the team (Mauro et al. 2015) showcased a simulation-based cost optimization model. They employed EnergyPlus as the simulation engine to study the most cost-effective ways to improve energy efficiency in a sample of representative buildings (Mauro et al. 2015).

Ferrara and colleagues (A. Safari 2022) employed TRNSYS to simulate energy while they utilized GenOpt and MATLAB for optimization. Fesanghary and team (Fesanghary, Asadi, and Geem 2012) introduced a model to reduce building life cycle costs and carbon dioxide emissions. They utilized EnergyPlus for simulation and the Harmony Search algorithm (HS) for optimization.

2.4. Energy retrofiting

Energy retrofit of current building structures provides a significant opportunity in the shift towards a low-carbon future. Furthermore, investing in highly efficient building materials and systems can replace extended energy imports, contribute to cost savings, and generate numerous new jobs. However, despite the ready availability of technologies to enhance energy efficiency, substantial technological advancements have yet to be achieved, and widely recognized optimal methods for incorporating building technologies and sustainable energy sources remain confined to smaller "niche" applications (Lohse, Rüdiger, Zhivov 2019).

The International Energy Agency (IEA) highlights the significance of prioritizing deep energy transformation (DET) and improved building standards to tackle this issue. For practical guidance in the construction sector, it is pivotal that national policies integrate three crucial elements:

- 1- Embrace a comprehensive strategy for entire building systems with sophisticated components.
 - 2- Enforce building standards, particularly in emerging construction markets, and apply these standards when updating components in developed nations.
- 2.4.1. Formulate business models to ensure the cost-effectiveness of deep energy transformation (DET) (M. Zhao, Mehra, and Künzel 2022; Lohse, Rüdiger, Zhivov 2019).

2.4.2. Deep energy retrofitting vs. Shallow energy retrofitting

Current research suggests that the standard way to upgrade existing buildings involves:

- A "shallow renovation" approach.
- Focusing on individual actions like lighting updates.
- HVAC replacements.
- Quick-return measures.

However, these projects often overlook necessary improvements like insulating facades, changing windows, fixing thermal issues, or enhancing a building's airtightness. In countries with strict energy goals for renovations, building owners often prefer renewable energy and heating solutions over measures that boost energy efficiency (Lohse, Rüdiger, Zhivov 2019).

For public building owners, choosing shallow renovations, especially HVAC replacements, comes with a risk of missing opportunities if crucial improvements like upgrading facades, roofs, or windows are ignored. A combined approach could lead to a more minor HVAC system, reduced heating and cooling needs, elimination of perimeter zone conditioning, and improved comfort (Lohse, Rüdiger, Zhivov 2019).

When making decisions about buildings, it's crucial to find budget-friendly routes for deep energy renovations (DER) instead of just focusing on essential criteria in "shallow refurbishment" strategies (Lohse, Rüdiger, Zhivov 2019).

2.4.3. Deep energy retrofitting and measurements

Energy efficiency improvements can be achieved through different energy retrofit measures (M. Zhao, Mehra, and Künzel 2022). Using energy efficiency measures (EEMs), coupled with essential technologies and high-efficiency appliances, can lead to further reductions in energy consumption (Lohse, Rüdiger, Zhivov 2019). These measures may include tasks to the building envelope, which will be explained in this section, such as adding insulation to walls or roofs, upgrading windows, sealing air leaks, replacing lighting fixtures and ballasts, and adjusting operational schedules. Some of these are considered aspects of deep retrofit energy measures (M. Zhao, Mehra, and Künzel 2022).

Building envelope: Thermal insulation and fenestration are two main components of the building envelope for deep retrofitting (M. Zhao, Mehra, and Künzel 2022).

- **Thermal insulation:** Saving energy from the base case by implementing passive energy-efficient strategies, including adding insulation to the building envelope (Sadineni, Madala, and Boehm 2011). Thermal insulation's purpose is to slow the movement of heat by conduction, convection, and radiation by applying one or more materials accordingly. Too much heat transfer between a building's interior and exterior is stopped by its high thermal resistance. Reducing energy usage and, therefore, reducing cost are two benefits of using thermal insulation in buildings.

Thermal insulation, thermal bridges, and leakage of envelope assemblies can all be improved to increase a building's energy efficiency (Papadopoulos 2005).

The ability of insulation materials to impede heat transfer, as measured by the thermal conductivity value (λ in W/m K) or, for composite materials, the thermal transmittance coefficient (U in W/m² K), has been broadly stable over the past ten years and can be considered highly satisfactory, which should not mean that modern materials are equivalent to those from 1990 (Al-homoud 2005). Additionally, Al-homoud in Figure 2.6 shows that a higher thickness of insulation does not necessarily mean more efficiency. So, life cycle cost (LCC) analysis is the best way to determine its true value. This figure shows that this analysis considers the building's type, size, and construction, the specific insulated component, local climate, insulation type, costs, air-conditioning efficiency, energy savings, and maintenance. Also, some materials might need to be thicker to prevent settling over time and maintain thermal resistance (Al-homoud 2005).

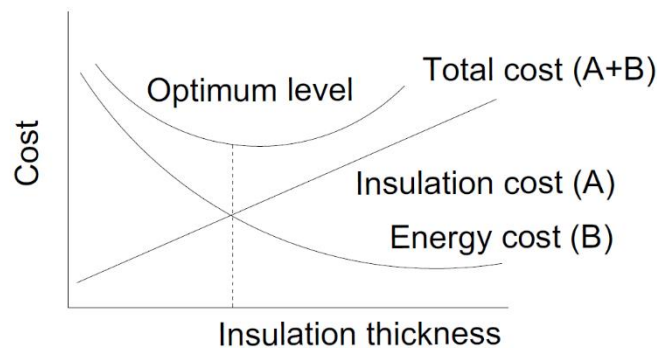


Figure 2.6 The effectiveness and economic value of thermal insulations.

Moreover, the type of building, the kind of insulation used, and where it is installed within the structure affect how insulation is installed. For walls, the insulation can be applied to the inside, outside, or in between (sandwich wall). All of the locations' benefits and drawbacks have already been covered. For roofs, the insulation might be positioned above a suspended ceiling, below a slab, or underneath a slab. Figures 2.6 and 2.7 show a schematic of installing insulation on roofs and walls (Al-homoud 2005). Finally, Building insulation is far more important in areas with cooling degree hours than in areas with heating degree hours (Bolattu 2008).

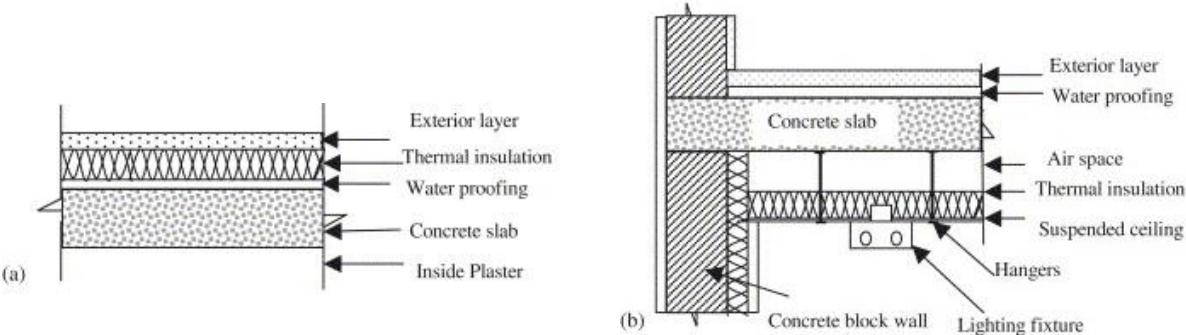


Figure 2.7 Strategies for installing insulation on roofs. a) Roof insulation in concrete structure, b) Roof insulation in suspended ceiling.

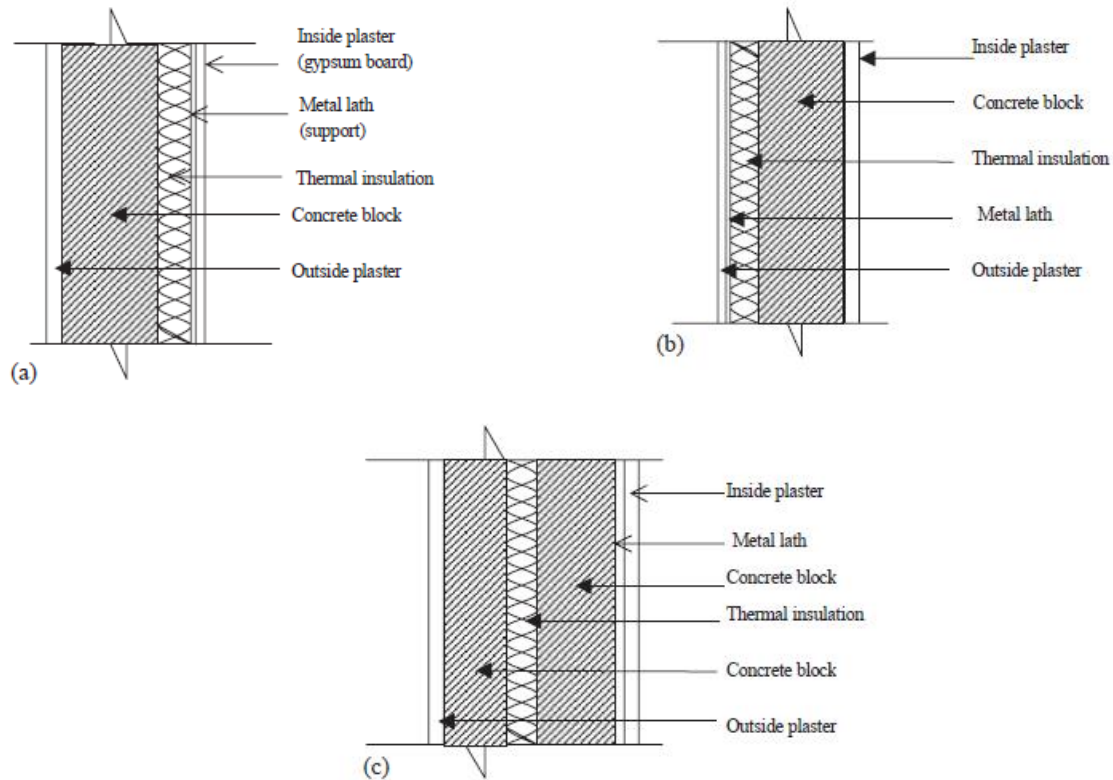


Figure 2.8 Options for installing wall insulation. a) inside, b) outside, c) middle.

- Fenestration:** The main elements of fenestration are windows and doors. The essential element preserving the bond between a building's exterior and interior is its windows. Buildings need a heating burden in a cold climate. Glazed units are a crucial component of the building envelope, letting natural light and solar heat into a building's internal space and enabling views from the inside to the outside. Glazed windows have worse thermal performance than other building envelope materials. About half of all the energy used in buildings comes from heat gain or loss through the windows, a factor that has dramatically expanded in recent decades (Ghosh 2022).

While "Deep Energy Retrofit" is commonly used, there isn't a globally accepted definition. Since the energy crisis in the 1970s, global energy standards for new construction and building renovations have greatly improved. Since the 1980s, the United States has seen a more than 50% enhancement in building energy requirements (excluding plug loads). Additionally, buildings and their systems naturally deteriorate over time, developing issues like cracks in the building structure, unclean and leaky ducts, and decreased efficiency when HVAC systems aren't regularly commissioned. These factors can lower energy performance by at least 10%. Technologically, it's possible to recover these inefficiencies and further reduce building energy usage by over 50% using readily available market technologies. This can be achieved by simply adapting current requirements for new buildings to the refurbishment of existing building stock (Lohse, Rüdiger, Zhivov 2019). Also, improving the thermal efficiency of a building's envelope through deep retrofitting is essential for ensuring comfortable indoor temperatures, reducing cooling demands, and lowering overall energy usage. The deep retrofit process involves selecting high-performing materials and components based on design variables and predefined objectives (Seghier et al. 2022). Deep energy retrofitting involves fully leveraging improvement projects' economic energy efficiency capacity, primarily focusing on optimizing the building envelope of existing structures. This produces remarkably high-energy performance (Semprini, Gulli, and Ferrante 2017). To deep energy retrofit, the suggested strategies encompassed:

- Thermal insulation
- Enhance daylight utilization and implement filtering mechanisms to prevent glare.
- Adjustment of the heated volume within rooms on a seasonal basis.

- Utilization of the buffer zone entrance as a wintertime strategy.
- Reestablishing ventilation and shading to optimize cooling efficiency.
- Using seasonal greenery on the pergola and cool pavement for shading and cooling (Eliopoulou and Mantziou 2017).

One another method of deep retrofitting involves enhancing the U-values of the building envelope to meet established standards, which can effectively reduce the energy required for heating and cooling, leading to a decrease in the overall energy demand for these purposes. Also, for older buildings, success in energy retrofits can be ensured by updating standards, creating renovation guidelines, training local artisans, and integrating historic buildings into district energy plans (M. Zhao, Mehra, and Künzel 2022). Upgrading the current building stock through a deep energy retrofit (DER) is a valuable approach to lessen fossil fuel use and reduce CO₂ emissions. However, the funding needed to carry out DER is substantial (Lohse, Rüdiger, Zhivov 2019).

Moreover, in regions with cold climates and hot summers, excessive solar heat during the summer can lead to overheating in buildings, requiring mechanical cooling. Integrating passive cooling methods into building designs has effectively addressed this challenge, reducing the demand for cooling and mitigating summertime overheating (Arnault, Mathieu-Potvin, and Gosselin 2010).

2.5. Building energy modelling

The literature on building energy modelling encompasses various topics, with software constituting a significant aspect. Discussions within this domain include infiltration, weather files, building envelope, schedules, occupancy, activities, clothing levels,

equipment, and lighting. Subsequent sections look into existing studies conducted in these areas.

2.5.1. Energy modelling software (EnergyPlus)

Energy simulation tools for entire buildings are essential in forecasting energy efficiency and providing vital data on energy usage, carbon emissions, indoor air quality, and expenses (Al-janabi et al. 2019). These tools also enable users to assess buildings in various situations (Science and Company 2020). In the last 60 years, progress in building energy modelling has resulted in the availability of many dependable software programs (Al-janabi et al. 2019).

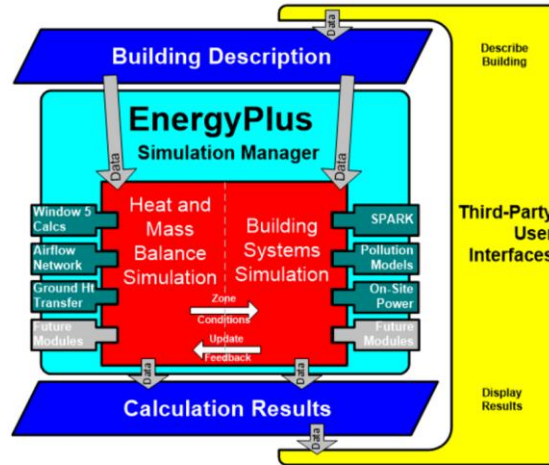
Additionally, there are simulation-driven decision-making approaches developed to support financially feasible planning and cost-effective design alternatives, incorporating energy-centric design tools and financial considerations into the initial design phase of almost zero energy buildings (nZEBs) (Semprini, Gulli, and Ferrante 2017; Dunster, Simmons, and Gilbert 2008; Shady Attiaa, Elisabeth Gratiaa, André De Herdea 2012; M. Kapsalaki a, V. Leal a 2012; G. Evolaa, G. Margani b 2013). One effective method to improve building energy efficiency is using Building Energy Modelling (BEM) technology. BEM helps assess designs, select optimal systems, manage energy budgets, ensure compliance with standards, and optimize economic outcomes during the building design phase (Gao, Koch, and Wu 2019).

Furthermore, aligning with the aims, the construction and operation of a facility can be simulated using computer software, leading to an advanced digital representation. This

data-rich model is intelligent, object-oriented, and parametric, addressing the varying needs of users (Gao, Koch, and Wu 2019).

Over 400 applications for analyzing building energy performance are found within major Building Energy Modeling (BEM) tools. These tools can be classified into two categories: those using the US Department of Energy's calculation engine (e.g., eQUEST, DesignBuilder, EnergyPlus, Autodesk Green Building Studio) and those with their calculation engines (Gao, Koch, and Wu 2019).

Within the scope of this investigation, EnergyPlus functions as the simulation powerhouse for multi-objective optimization. At the same time, Sketch-Up, complemented by the Open-Studio Plugin, serves as the visual interface to construct a foundational model for the building under study. EnergyPlus is one of the most common tools used for building energy simulation to analyze energy and design HVAC systems retrofit options by the geometry drawn in various programs by different tools such as Design Builder and SketchUp. EnergyPlus program can analyse energy building by using data related to the envelope of the building, internal gains, heating, cooling, ventilation, schedules of using spaces, and occupants. Also, the Fortran90 coding language is its primary language (Crawley et al. 2001). Unlike other software, this tool also permits users to customize heating and cooling equipment components, providing a more adaptable simulation that accurately mirrors real-world conditions. This feature enhances the software's utility for detailed and precise energy performance assessments in academic and professional contexts (Gao, Koch, and Wu 2019).



(b) Structure of EnergyPlus

Figure 2.9 The overall program structure

This software application relies on a pair of principal input datasets (see Figure 2.8) (IDF and EPW); the outputs can be accessed via EP-Launch interference (Moradi et al. 2023).

EnergyPlus, with its integrated solution technique, allows users to assess complex processes better than BLAST and DOE-2. This includes realistic system controls, moisture behaviour in building materials, radiant heating and cooling, and Interzone airflow. Also, it enables researchers and designers to forecast factors that assist them in determining the most effective approach for cost savings and energy efficiency (Moradi et al. 2023).

Finally, MATLAB is employed alongside EnergyPlus as a dynamic energy simulation engine for optimizing building energy and determining the best solution among variables (A. Safari 2022).

2.5.2. Building energy modelling parameters

Energy modelling combines various factors and parameters, including organizational energy management rules and technologies (scheduling and setpoints), electrical

devices, human actions (Tao Zhang, Peer-Olaf Siebers 2011), and other environmental factors.

2.5.2.1. Weather file

Despite these improvements, the ongoing issue of the energy performance gap continues to be a significant concern within the design field, characterizing notable disparities between expected and actual energy performance (H. X. Zhao and Magoulès 2012).

Numerous research studies indicate that simulation weather files introduce uncertainties that affect model predictions. The choice of weather data is critical for accuracy. Typical Weather Years (TWY) provide 8760 hourly meteorological values for a year but lack long-term variability. An alternative is the Typical Meteorological Year, created by selecting 12 months from a multi-year database. Actual Weather Years (AWYs) allow multi-year simulations and offer more accurate results than TWY, addressing climate change and worst-case scenarios. Designers should carefully choose weather data for better building performance simulation (Moradi and Kavgic 2022).

2.5.2.2. Occupant behaviour and schedule modelling

Prioritizing occupants' well-being, satisfaction, and efficiency is crucial in designing and functioning environmentally friendly buildings. Nevertheless, occupant actions also have a "passive" influence on the indoor environment by producing heat, CO₂, and other "disturbances" (Jie Zhao, Bertrand Lasternas, Khee Poh Lam, Ray Yun 2014). Jie Zhao and the team found a steady group schedule for people in the office, covering different individual habits with office devices. Compared to the schedule used in the Department of Energy's example medium office buildings, the learned program indicates

a 36.67–50.53% lower rate of people being there on different weekdays. To see how this affects heating, ventilation, and air conditioning (HVAC) energy, they investigated it by simulating EnergyPlus models in 17 diverse climate zones. The simulation shows that the influence of when people are in the building on HVAC energy use changes a lot depending on the climate (Jie Zhao, Bertrand Lasternas, Khee Poh Lam, Ray Yun 2014).

The people using the building are actively involved in controlling it individually. Additionally, their more passive role also affects how well the construction works. Specifically, in terms of the building's temperature and indoor air quality, occupants are seen as sources of heat and CO₂ that move around, and this can significantly impact how much energy the HVAC system uses. That's why occupants are often viewed as things that can cause disturbances in the HVAC control system. It's essential to study how individuals act and when in groups to understand this passive impact (Jie Zhao, Bertrand Lasternas, Khee Poh Lam, Ray Yun 2014).

Also, working beyond regular hours is widespread globally. This extra time causes increased heat within the building due to people, lighting, and plugged-in devices. It also results in the HVAC system working more during overtime periods. The prolonged working hours and extended use of building services beyond the usual working hours due to overtime directly impact the overall energy consumption of the building (Kaiyu Sun, Da Yan, Tianzhen Hong 2014).

2.5.2.3. Electrical equipment

The relationship between electrical equipment and energy consumption is vital for understanding and managing overall energy usage. Energy modelling becomes essential

to analyze and optimize how various electrical devices impact energy consumption. Tracking the behaviour of electrical equipment and its influence on energy usage helps develop effective energy management strategies. This involves considering user behaviour, scheduling, and equipment efficiency to gain insights into energy consumption patterns. Such modelling allows informed decision-making to enhance energy efficiency and reduce overall energy consumption in diverse settings (Tao Zhang, Peer-Olaf Siebers 2011).

2.5.2.4. Mechanical equipment

Designing the HVAC system in a building is crucial for how it uses energy. About 75% of a building's energy goes to heating, cooling, and hot water, all controlled by HVAC. When the HVAC system is well-designed, it helps the building use energy efficiently and be more eco-friendly. This matters because much of the energy comes from non-renewable sources like fossil-fuel-fired boilers, with only a tiny part from renewables.

The European Union has set goals in the "2030 Climate and Energy Framework" to reduce pollution, increase renewable energy use, and improve overall energy efficiency. A good HVAC system design is critical to meeting these goals, making buildings more energy-efficient and eco-friendly. A smart HVAC system design isn't just about comfort; it's vital for using energy wisely and protecting the environment (Marika Pilou 2023). Marika Pilou and her team suggest that their model can forecast how well a building's energy system works in simple terms and with numbers. It usually matches the actual results significantly when things change a lot. The tool they made is easy to adjust to work for different energy setups and ways of operating. This means it can help decide on new energy systems and improve existing ones (Marika Pilou 2023).

2.6. Optimization

Building energy optimization is an emerging method to attain energy-efficient building designs (Pérez-Fargallo and Pulido-Arcas 2018) to reduce primary energy consumption, minimize cost, and optimize overall value. There are two approaches to optimizing energy efficiency: passive and adaptive strategies. Passive strategies involve optimizing the building envelope and installing sun shading components, while adaptive systems entail adjusting the cooling/heating setpoint temperature while keeping other input parameters constant. The sample building's annual cooling/heating energy load is then simulated using these adaptive strategies (Ge, Jian ; Wu, Jiajing ; Chen, Shuqin ; Wu 2018). To investigate strategies for optimizing energy efficiency, Jian Ge et al. employed a sample building model and simulated its cooling/heating energy consumption (Ge, Jian; Wu, Jiajing; Chen, Shuqin; Wu, 2018) then Wanga incorporated a genetic algorithm (GA) into a simplified tool for assessing building thermal performance, aiming to minimize energy consumption for optimization (Weimin. Wang and ; Hugues. Rivardb; Radu. Zmeureanu 2005).The optimization algorithm explores solutions, including building features and envelopes, HVAC systems, and renewable energy sources (A. Safari 2022). The effectiveness of optimization algorithms plays a pivotal role in ensuring the success of building energy optimization techniques (Binghui Si a et al. 2018); these processes will show strategies for minimizing both energy consumption and CO₂ emissions, illustrating practical approaches to reduce overall energy usage within buildings(Pérez-Fargallo and Pulido-Arcas 2018).

Rychnbrg presented the concept of evolutionary account for the first time in 1940 with his research on the evolution strategy. Over time, his theory was examined by many

researchers, and finally, Holland, a computer science expert at the University of Michigan, introduced the genetic algorithm in 1975 (Xin-SheYang 2010). The genetic algorithm is one of the computational models inspired by nature and the evolution process of living organisms, and its basis is based on Darwin's theory of the principle of survival and sustainability of the fittest, which states that weaker organisms die and more robust microorganisms remain. In the genetic algorithm, a population of people will survive in the environment according to their desirability, and people with superior abilities will have more chances of marriage and reproduction (Bajpai et al. 2007).

Genetic algorithms (GAs) were developed with the original version of the NSGA, and its second version, NSGA-II, was published in 2002. One advantage of this technique is its unlimited ability to select continuous and discrete variables. Numerous technical disciplines have employed this algorithm. Optimizing and utilizing this approach requires coding it into multiple software components. Selecting the optimal goal function is challenging for scientists since most optimization problems contain many objective functions. These objective functions also fight each other and improve as the issue gets smaller (Baghoolizadeh and Rostamzadeh-renani 2023).

The NSGAI method provides the user with a collection of optimal points called the Pareto front, from which they can choose the optimal point that best meets their requirements. Combining this tool with Energy Plus software makes optimization chores easy to accomplish (Baghoolizadeh and Rostamzadeh-renani 2023).

3. Methodology

3.1. Introduction

In this dissertation, an in-depth exploration is conducted on the deep energy retrofitting of a commercial building in Ottawa, Canada, distinguished for its frigid climatic conditions. This investigation relies on respected software tools such as SketchUp with the OpenStudio plugin, EnergyPlus, and MATLAB. The methodology of my research consists of six stages. The two initial stages are related to modelling. The first phase involves generating the building's geometry, achieved through SketchUp utilizing the OpenStudio plugin. The second stage is building energy modelling using EnergyPlus software to simulate the overall energy performance of a building by integrating the data gathered. The four following stages are for optimization. The following step involves identifying variables that influence decisions and constructing a model that can be adjusted based on these variables. The fourth stage is finding and creating the objective functions. Subsequently, a multi-objective optimization is done using the Non-Dominated Sorting Genetic Algorithm (NSGA-II) within the MATLAB programming software. It keeps improving the EnergyPlus building model until it finds optimal concepts or solutions. Finally, the sixth step will consider the best way to optimize. The framework for this methodology is depicted in Figure 5.1.

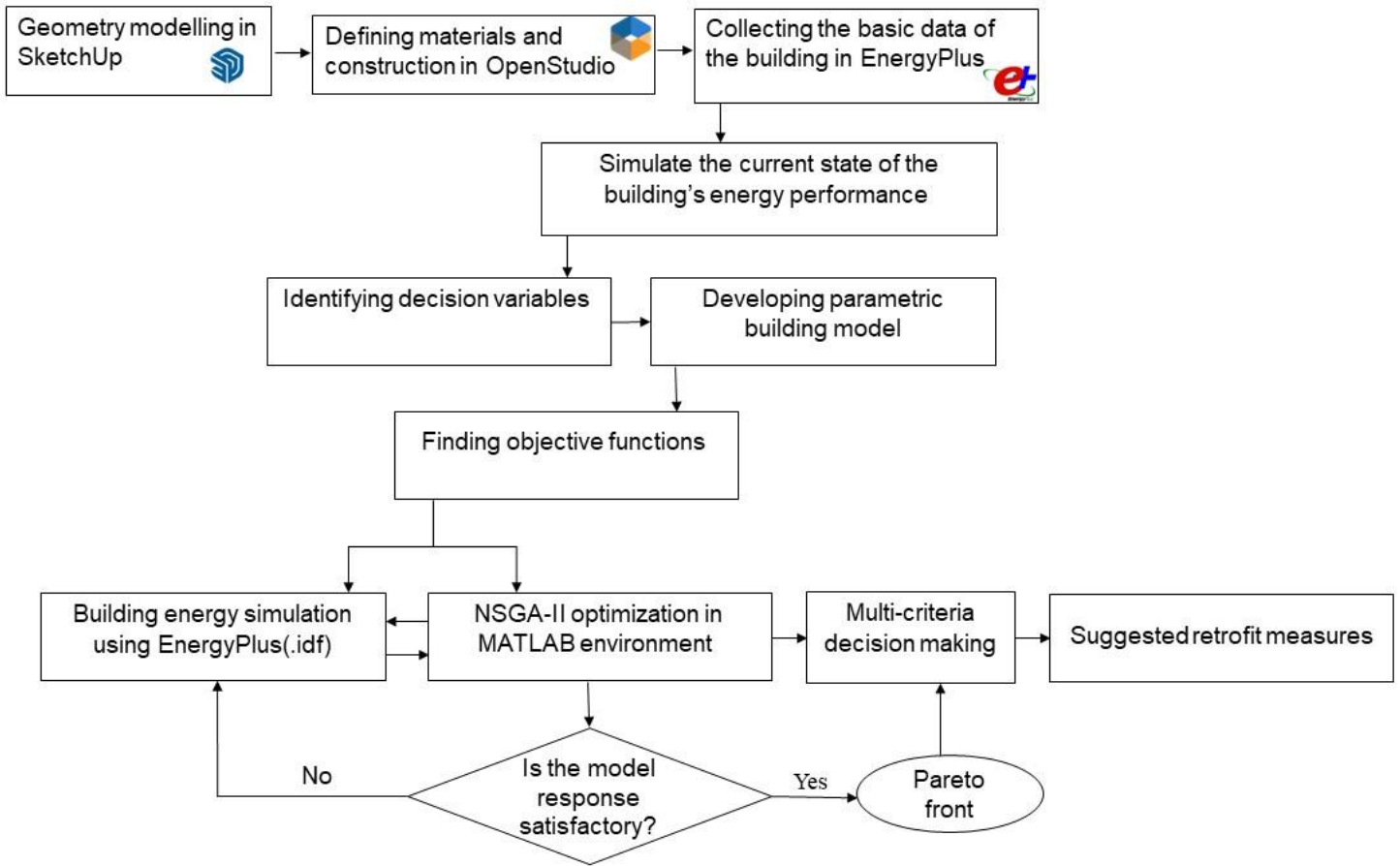


Figure 3.1 Methodology framework.

3.2. Case study

The mixed-use building, Montpetit Hall, is a place for the Gee Gees' varsity athletic teams and the Faculty of Health Sciences. The area is 3,583 square meters and was built in 1972 with an orientation of approximately 29 degrees westward (see Figure 3.2) with 17,096 square meters of floor area.

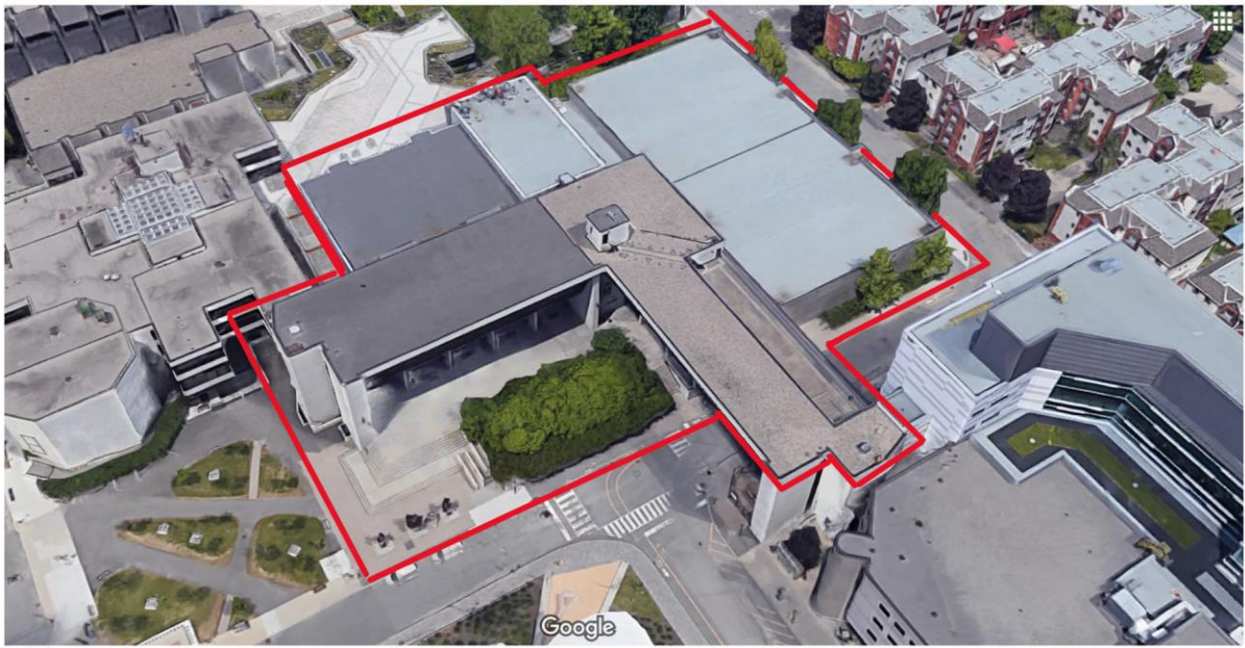


Figure 3.2 Montpetit building and site outline (Chiasson 2020)

The building is attributed to activities such as operating an Olympic-sized pool, saunas, communal showers, fitness rooms, offices, and research laboratories with significant fresh air requirements. The facility accommodates approximately 4,100 people while adhering to safety regulations, providing space for about 1,500 students in classrooms and auditoriums. In addition to its academic functions, it serves as a sports center, featuring amenities like an Olympic-sized pool, three basketball courts, three squash courts transformed into a high-performance training area, a public gym, a dance studio,

and a martial arts room, capable of hosting up to 2,000 people during games. The building, reaching a maximum height of 23.75m, consists of four usable levels above ground and two below. Its primary structure forms an L-shape (see Figures 3.3 and 3.4), with two interconnected sections housing the gymnasium and pool. The building connects to the University Centre from the north, accessible from the second level, and links to Lamoureux Hall through a second-level overpass. The exterior predominantly features poured concrete, with solar-reflective paint applied to the south and west walls to mitigate heat absorption. Partial roof replacements have resulted in a 2-ply asphalt membrane covering half of the remaining roof. Internally, the facility includes two spacious changing rooms with showers and a steam-heated sauna. Montpetit Hall accommodates sports activities and serves the Health Sciences faculty's needs, encompassing nutrition and human kinetics departments. The third and fourth floors feature offices and labs, with two large auditoriums added in the 1990s, each seating 244 students. There is an identified need for an energy assessment and optimization of thermal performance to enhance the building's sustainability (Chiasson 2020).

In the following, the reasons to select this

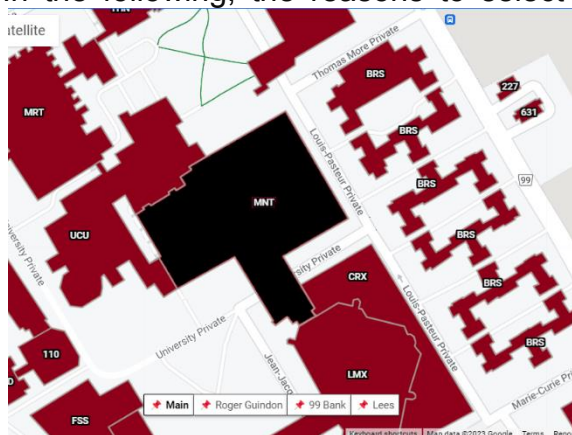


Figure 3.3 Site plan of Montpetit Hall



Figure 3.4 Main view of Montpetit Hall

building are outlined:

- It is a multifunctional complex building with various spaces, and the energy consumption of this building is high. One of the university's multifunctional buildings is compared with the case study. This is the Roger Guindon building. Figure 3.5 shows the building on the site. The area of the Roger Guindon building is 50,900 m², including academic, laboratory, library, office space, common areas, and miscellaneous. Also, it was built in 1981.



Figure 3.5 Picture of the Roger Guindon building.

Figure 3.6 shows information about the Roger Guindon building of the University of Ottawa Campus and compares its energy use intensity (EUI) with that of Montpetit Hall.

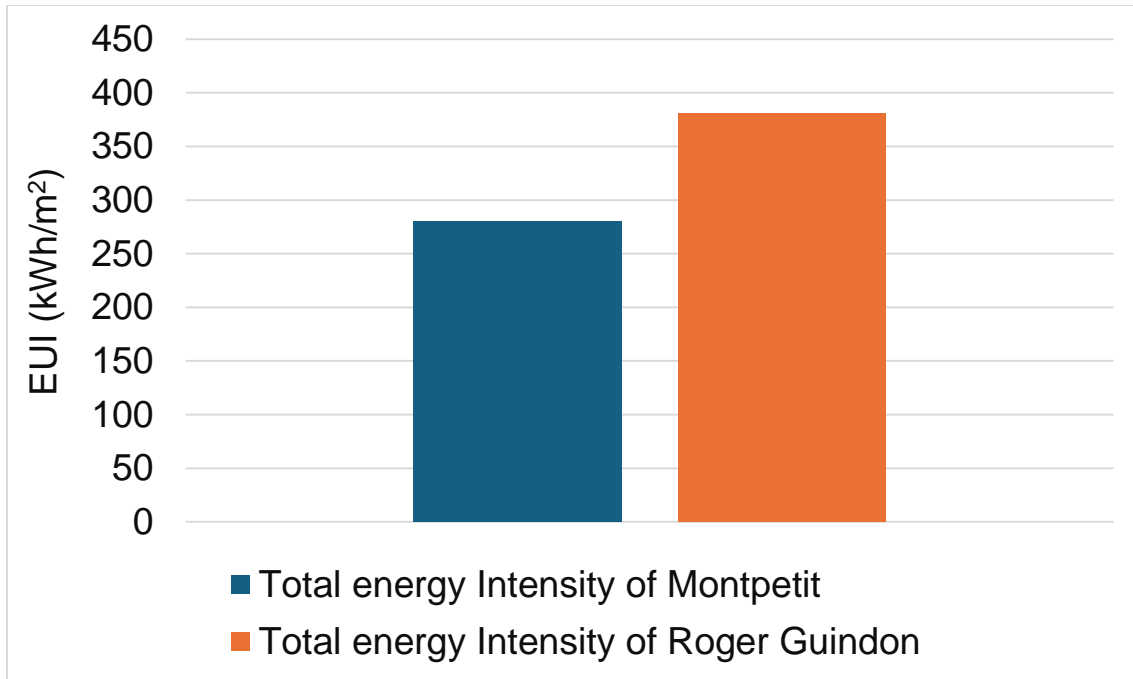


Figure 3.6 Comparison between the Energy intensity of Montpetit Hall and Roger Guindon

- Montpetit Hall was a typical prefabricated concrete structure of that period. It is typical for this period not just for the University of Ottawa but across Canada and Ottawa in general. There are many such constructions, even in Europe, for brutalist architecture. Also, it is essential because by developing this building, the solutions and recommendations may apply to similar buildings that suffer from similar problems.
- The University of Ottawa plans to become zero-carbon by 2040. To achieve this goal, these buildings will not be demolished but should be retrofitted. Therefore, this decision and goal regarding retrofitting these buildings will help the university align with its sustainability objectives.

3.3. Geometry modelling

Each building's optimization relies on various factors, which are derived from specific conditions unique to each building. One such factor is the geometry. With a geometry model of a building, the subsequent stages can be conducted to evaluate energy efficiency and optimize the building.

The geometry is made with SketchUp utilizing the OpenStudio plugin. Additionally, materials for various building components and the envelope were defined within SketchUp using plugin software for construction. The construction was then assigned to the building. By exporting the simplified AutoCAD file (see Figure 3.7 to 3.11) into SketchUp and through the OpenStudio plugin in SketchUp, a 3D model of the building is generated, rendering it prepared for the subsequent simulation stages.

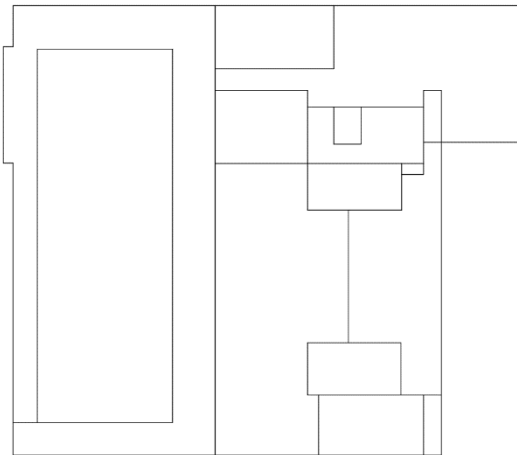


Figure 3.7 Second basement plan.

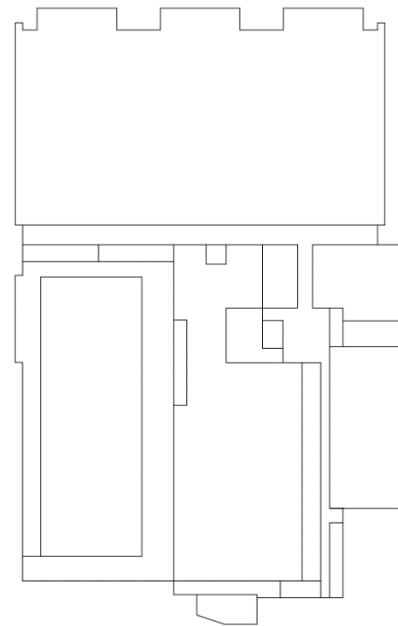


Figure 3.8 First basement plan.

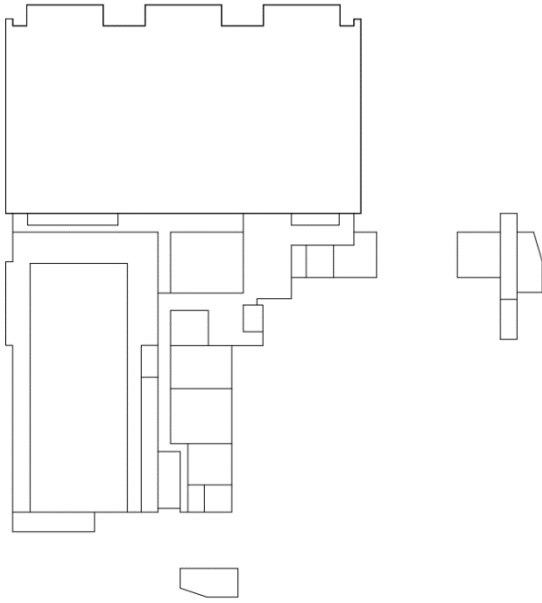


Figure 3.10 First floor plan.

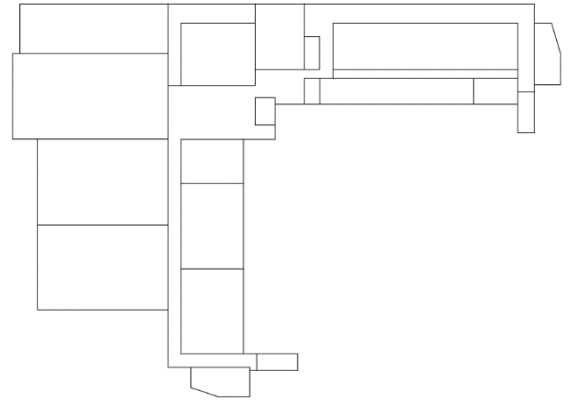


Figure 3.9 Second floor plan.

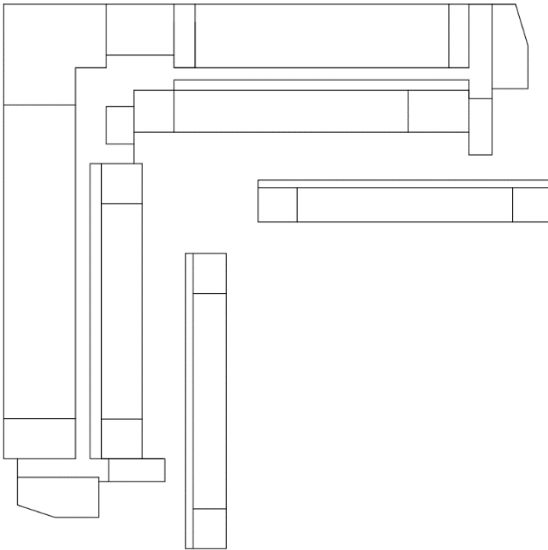


Figure 3.11 Third floor plan (2 half floors).

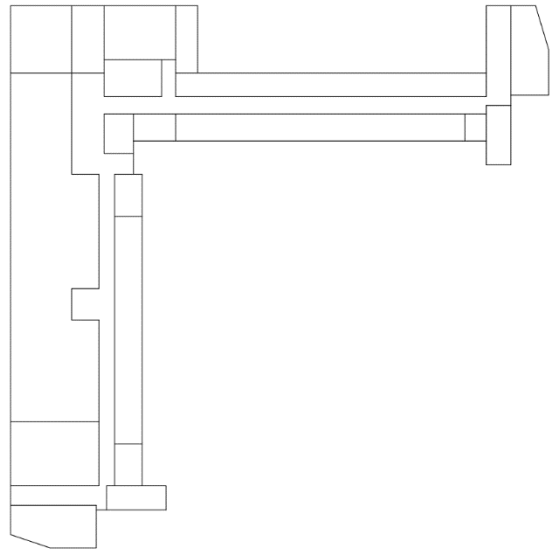


Figure 3.12 Forth floor plan.

These simulations are conducted within the software, utilizing OpenStudio and EnergyPlus for comprehensive energy simulations. Figures 3.13 and 3.14 visually represent the geometry from the south and north angles prepared for this study.

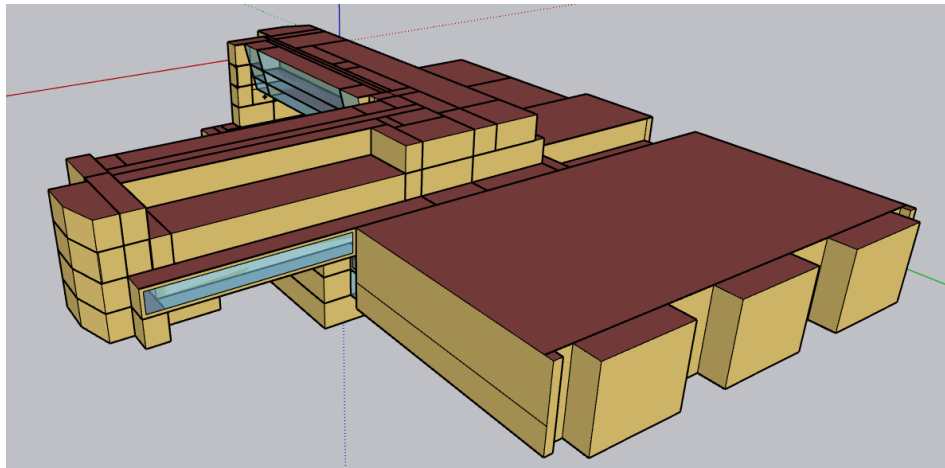


Figure 3.13 Geometry model of Montpetit Hall (south view)



Figure 3.14 Geometry model of Montpetit Hall

The subsequent stage involves defining thermal zones for spaces. Firstly, the AutoCAD file is simplified to establish the most coherent thermal zones. This simplification involves merging holes with identical schedules, directions, and uses as much as possible. The

objective is to minimize the number of thermal zones, facilitating a more straightforward simulation and enhancing the accuracy of energy consumption evaluation.

3.3.1. Thermal zone

Spaces' thermal zones need to be defined to determine energy loading and consumption in the following stages, as different thermal zones have other specifications, such as orientation, use, and schedule. The thermal zones of different spaces and rooms are defined based on their orientation, function, and schedule.

In Figure 3.15, the geometry is represented by thermal zones, each depicted in a distinct colour. This building has 129 thermal zones. Different spaces with varying specifications, including orientation, purpose, and scheduling, are categorized on each floor. Notably, on the second basement floor plan, mechanical and maintenance rooms sharing similar conditions have been united into a singular thermal zone. The scheduling for these spaces aligns consistently with the National Energy Code for Buildings (NECB). Similarly, on the first basement floor plan, spaces such as the pool, gymnasium, exercise areas, and dancing classes, all exhibiting comparable conditions about the external environment and sharing the same schedule, are grouped in one zone.

The first and second floors are used for classrooms and offices, each with distinct orientations. Zones of spaces with similar conditions on the same floor are merged.

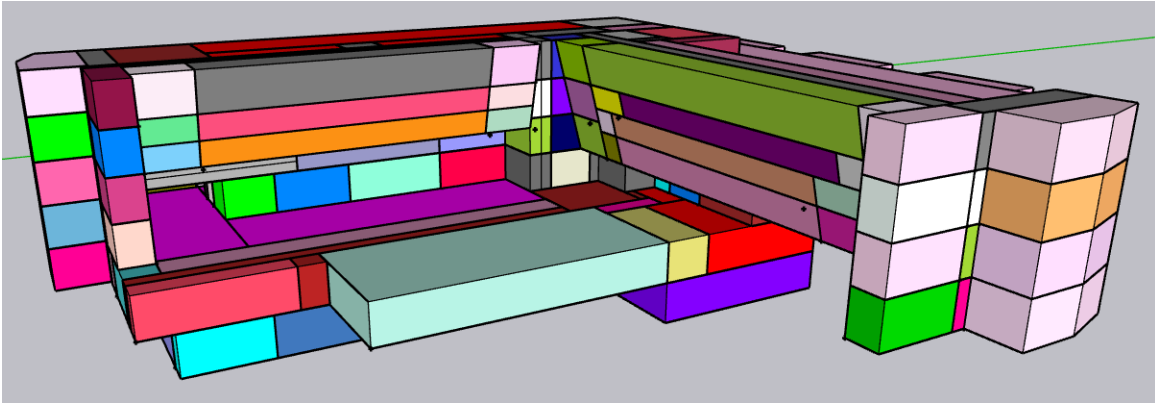


Figure 3.15 Geometry rendered by thermal zones

The third and fourth floors are allocated for labs and offices, each following specific thermal zoning criteria.

In this case study, 129 thermal zones were created, with those sharing the same schedule and function, such as offices on separate levels, compiled into a zone list to be placed in their specific section of the EnergyPlus tool. Meanwhile, some zones, like classes with different schedules, were not categorized with others and were used individually. Table 3.1 shows the names of the zone lists.

Table 3.1 Thermal zone lists

9 thermal zone lists according to Montpetit Hall building spaces

| | | |
|-------------------------|-------------------------|---------------------|
| - Office level 0 | - Office level 3 | - Exercise level 00 |
| - Office level 1 | - Office level 4 | - Exercise level 0 |
| - Office level 2 | - Mechanical room level | - Exercise level 1 |

00

As mentioned in the NECB, spaces with no specific schedules were defined as adjacent spaces and categorized in those zone lists. For example, washrooms and corridors are adjacent to offices on levels 1, 2, 3, and 4 or to mechanical rooms on level 00.

3.3.2. OpenStudio

OpenStudio is an open-source plugin developed for SketchUp that enables work on various parameters of energy modelling, including daylight assessment and determining materials and construction to aid in creating energy-efficient building designs (Yu et al. 2013). In this study, a crafted 3D model in SketchUp was imported into OpenStudio to identify materials along with their characteristics and incorporate them into the construction of the building (Figure 3.17).

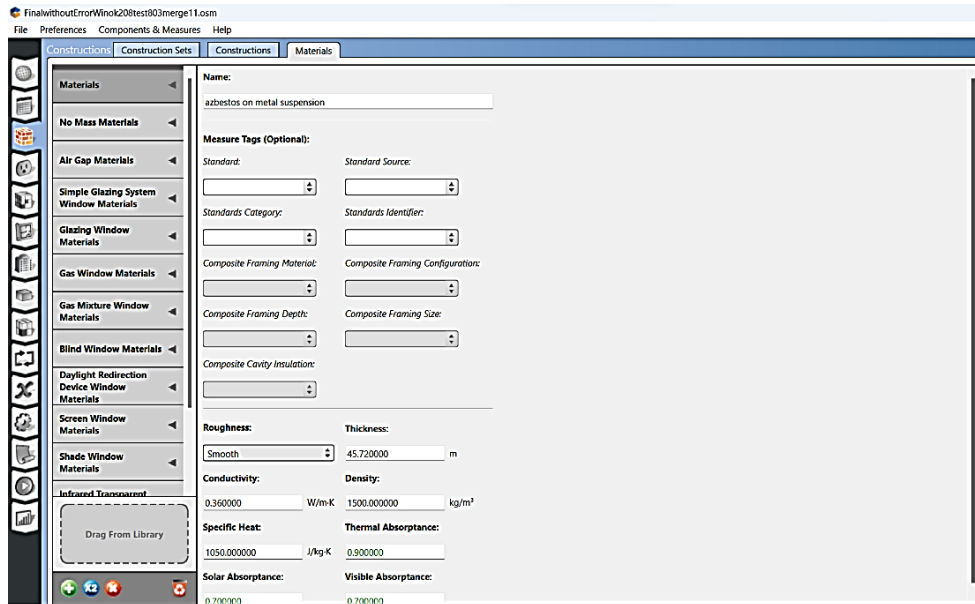


Figure 3.17 OpenStudio space

Table 3.2 shows materials for the building envelope, specified in OpenStudio and organized into layers for constructing walls, floors, and ceilings. The university-provided files are used as references for obtaining building materials layer by layer.

Table 3.2 Material and construction of Montpetit Hall

| Constructions and materials | | | | | |
|--|----------------------|------------------------------------|---------------------------|-------------------|-----------|
| Exterior walls and Basement walls | Interior wall | Floors and ceilings | Basement floor | Roof | |
| Exposed concrete walls | Plaster board. | Carpet | Tile | Built-up roofing | Skylights |
| Rigid insulation | Metal studs | Cement topping | Cement topping | Rigid insulation | Windows |
| Plasterboard (Gypsum board) | Plasterboard | Structural slab | Structural slab | Slopping concrete | |
| | | | | Structural slab | |

Characteristics were determined based on comprehensive reference sources. These characteristics include thermal conductivity, thickness, roughness, density, and conductivity. Additionally, specific characteristics related to glazing window materials were identified, such as solar transmittance, front-side solar reflectance, back-side solar reflectance, visible transmittance, front-side visible reflectance, and back-side visible reflectance (see Tables 3.3 and 3.4).

Table 3.3 Characteristics of the material's envelope

| Material | Roughness | Thickness (mm) | Density(kg/m³) | Conductivity (W/m-K) |
|-----------------------------|------------------|-----------------------|----------------------------------|-----------------------------|
| Aluminum | Medium rough | 0.002 | 2700 | 136.0 |
| Carpet | Medium smooth | 0.0127 | 288 | 0.06 |
| Cement topping | Medium rough | 0.3556 | 1600 | 0.97 |
| Concrete wall | Medium rough | 0.254 | 2400 | 0.5 |
| Gravel | Smooth | 0.152 | 1840 | 0.4 |
| Gypsum board | Medium smooth | 0.019 | 800 | 0.16 |
| Lean concrete | Medium rough | 0.0508 | 640 | 0.19 |
| Heavyweight concrete | Medium rough | 0.1016 | 2240 | 1.95 |
| Plastic finish | Smooth | 0.1 | 920 | 0.2 |
| Precast concrete | Medium rough | 0.0762 | 2400 | 0.1 |
| Quartz stone | Medium rough | 0.1524 | 2880 | 10.4 |
| Rigid insulation | Medium rough | 0.0254 | 43 | 0.03 |
| Slopping concrete | Medium rough | 0.10 | 2400 | 0.5 |
| Structural slab | Medium rough | 0.203 | 2400 | 0.5 |
| Vinyl Asbestos tile | Medium rough | 0.003 | 2000 | 0.85 |
| wood | | 0.02 | 640 | 0.16 |

Table 3.4 Glazing window material characteristics.

| Solar transmittance | Front-side solar reflectance | Back-side solar reflectance | Visible transmittance | Front-side visible reflectance | Back-side visible reflectance |
|----------------------------|-------------------------------------|------------------------------------|------------------------------|---------------------------------------|--------------------------------------|
| 0.837 | 0.075 | 0.075 | 0.898 | 0.081 | 0.081 |

Notably, the windows are double-glazed, and the gas window material is air, with its thickness considered a defining characteristic (see Table 3.5). This determination was grounded in the materials utilized in Canadian construction practices in 1973.

Table 3.5 Gas window material characterization

| Gas window material | Thickness (cm) |
|----------------------------|-----------------------|
| Air | 0.013 |

Subsequently, the dataset was exported to the EnergyPlus software (Figure 3.19) as an IDF file to enhance its parameters before starting the model simulation.

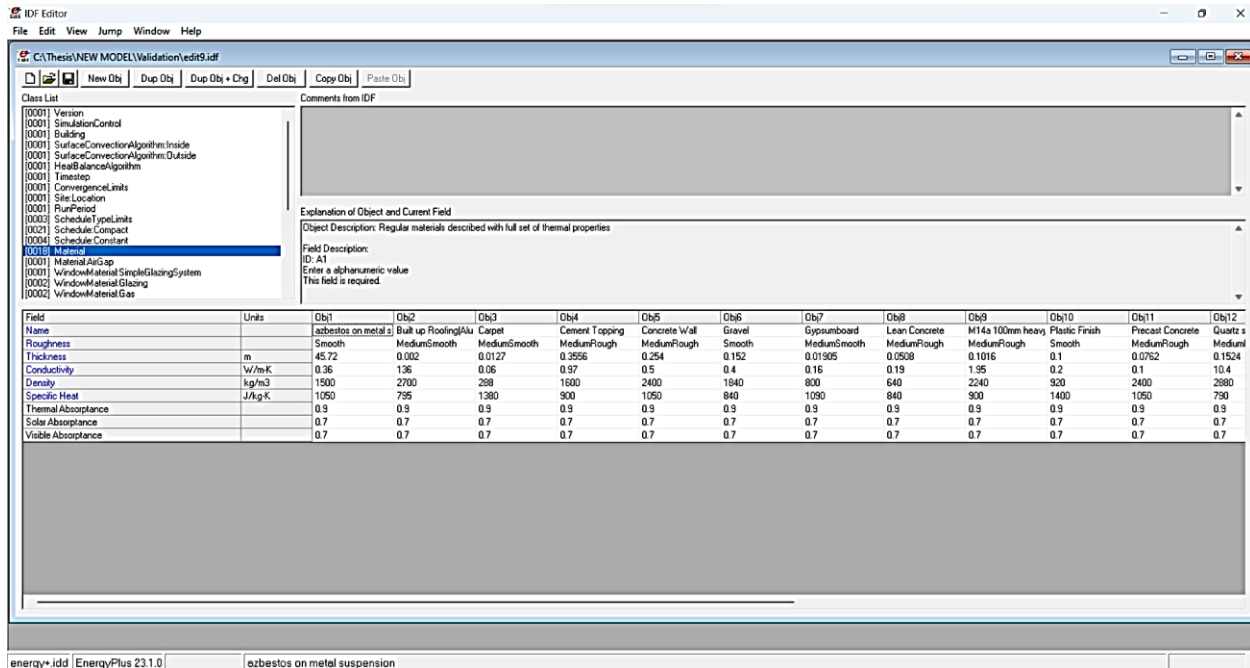


Figure 3.19 EnergyPlus tool space

3.4. Energy modelling

The second stage of this process involves building energy modelling. This involves creating a computer-based model of a building to simulate its energy performance. The goal is to understand how different components of the building and its systems interact and contribute to overall energy usage. The IDF file is exported from the geometry model to the EnergyPlus tool at this stage. Data integration is needed in the IDF file. The model requires various data inputs to accurately simulate the building's energy performance. The data is gathered from different sources and integrated into the EnergyPlus model. These data inputs include:

- Occupancy data: Information about the number of people in the building.
- Lighting data: Details about the lighting systems in the building.
- Electrical equipment data: Information on electrical devices and equipment.

- Mechanical equipment data: Details about the HVAC (Heating, Ventilation, and Air Conditioning) systems.
- Schedules: Timing and usage schedules for different building components.
- Infiltration data: Information about air leakage into and out of the building. The collected data for this part is from the (Moradi and Kavgic 2022) article.
- Weather file: Data related to the climate and weather conditions in the area where the building is located.

The information and details were collected from the university and standards like NECB to account for data that may not be readily available. This approach helps ensure the accuracy and reliability of our modelling efforts.

Finally, the outcomes of the energy simulation and actual energy consumption data are extracted from utility bills obtained from the building facility office. A reliable source is then employed to authenticate the model. In cases where inconsistencies emerge in the results, adjustments are made to the model. Otherwise, the process is repeated until a satisfactory level of accuracy is achieved.

This study focuses on exploring buildings' energy systems, mainly by conducting a detailed energy audit of Montpetit Hall at the University of Ottawa. This research aims to highlight Montpetit Hall on the university campus to conserve energy, minimize emissions, and reduce operational and capital costs.

3.4.1. Weather file

The additional data allocated to the model for simulation in EnergyPlus includes the weather file, sourced from typical weather data available in the EnergyPlus software files

and the NSRDB website, and the weather file from the university. These datasets were specifically chosen for the location, Canada, ON, Ottawa, and 2017 was considered a typical year. The file format used is "epw," initially converted to Excel files for data transfer. The final file is converted back to the "epw" format following necessary manipulations, facilitating integration with the EnergyPlus software.

Table 3.6 displays the data transferred from the downloaded file of the NSRDB website to the Typical Weather Data format in the EnergyPlus file, intended for use in simulations.

Table 3.6 Data from NSRDB for weather file

| Data Transferred from NSRDB to EnergyPlus Weather File |
|---|
| Dry Bulb Temperature (C) |
| Dew Point Temperature (C) |
| Relative Humidity (%) |
| Atmospheric Pressure (Pa) |
| Global Horizontal Radiation (Wh/m2) |
| Direct Normal Radiation (Wh/m2) |
| Diffuse Horizontal Radiation (Wh/m2) |
| Wind Direction (deg) |
| Wind Speed (m/s) |

3.4.2. Schedule

Regarding schedules, the data source for classes was documented from the University of Ottawa, while NECB was utilized for the rest. Additionally, two types of schedules are integrated into the EnergyPlus tool for simulating and assessing energy consumption:

compact and constant. The compact schedule, represented by fractional numbers, determines the schedule for the typical year. On the other hand, the constant schedule maintains the same pattern throughout the year and is represented by any number. Each schedule is created for occupancy, equipment, lighting, electrical, and mechanical facilities. Subsequently, specific zones are identified, necessitating the establishment of zone lists, as explained in the following section.

3.4.3. Occupancy

The university's shared data obtained the number of people in the Montpetit Hall building level by level (see Table 3.7). So, in terms of occupancy of the building in the EnergyPlus tool for simulation, the unit of this data was provided to people per floor area. It is clear that the peak occupancy is at level 0, which is used for various gyms and pool spaces; these data are gathered from the university.

Table 3.7 Occupancy

| Level | Average Occ. Load | Area(m ²) |
|-----------------------|-------------------|-----------------------|
| TOTAL LEVEL 00 | 43 | 3656.25 |
| TOTAL LEVEL 0 | 2266 | 6783.73 |
| TOTAL LEVEL 1 | 432 | 1646.94 |
| TOTAL LEVEL 2 | 917 | 2795.09 |
| TOTAL LEVEL 3 | 205 | 2795.09 |
| TOTAL LEVEL 4 | 254 | 1625.76 |
| TOTAL LEVEL 5 | 0 | 0 |

3.4.4. Lighting

Light data must be put in the EnergyPlus tool to continue simulating. For this part, Table 3.8 shows the annual consumption for each floor considered. This summary is generated

by considering the lamp count completed for each space, organized on a per-floor basis. To export the data to the IDF file, the unit of Watts per Zone Floor Area (W/m²) was determined by dividing the annual consumption of floors by the area of each floor.

Table 3.8 Lighting data.

| Approximate lighting load per floor (Chiasson 2020) | | | | |
|--|-------------------------|------------------|---------------------------------|--------------------------------|
| Level | T8 Fixture Count | Load (kW) | Annual consumption (kWh) | Annual consumption (GJ) |
| Level 00 | 417 | 10.4 | 60,882 | 219 |
| Level 0 | 1367 | 34.2 | 199,582 | 718 |
| Level 1 | 340 | 8.5 | 49,640 | 179 |
| Level 2 | 826 | 20.7 | 120,596 | 434 |
| Level 3 | 690 | 17.3 | 100,740 | 363 |
| Level 4 | 446 | 11.2 | 65,116 | 234 |
| penthouse | 5 | 0.1 | 730 | 3 |
| Total | | 102.3 | 597,286 | 2,150 |

3.4.5. Other equipment

The data for other equipment is within the electrical equipment group in the IDF file. Due to the absence of data from the university, the NECB standard was the source.

Concerning electrical equipment, the Peak Receptacle Load per occupant (W/m²) from NECB was applied to each thermal zone list.

3.4.6. HVAC

In this research, during the simulation process to assess energy consumption and optimize envelope variables, details of an ideal air load system for cooling and heating the building were examined considering the HVAC system. This system includes carefully set temperatures designed for the specific needs of Canadian locations, allowing for the execution of detailed simulations. Additionally, the verification of setpoint temperatures for summer and winter and adjustments for the thermostat were added to EnergyPlus.

3.5. Optimization process

As explained in previous sections, a building's energy consumption can be optimized to enhance efficiency through active and passive strategies. This research assesses and implements the optimization process by creating an energy-efficient building envelope as a passive design, as further detailed in the following sections.

3.5.1. Identifying decision variables for multi-objective optimization

Optimizing a single index while considering a set of parameters is the goal of a single-objective optimization problem. Determining the hypothetical solution to an optimization problem using just one index is impossible due to their interdependence and interrelation. An optimization issue, commonly called multi-objective or multi-criteria optimization,

requires the simultaneous definition of numerous objective functions (Taghdisian, Pishvaie, and Farhadi 2015).

In this study, focusing on optimizing building energy efficiency, critical areas for improvement include building envelope elements. We pick decision variables by considering building energy performance, climate conditions, criteria from stakeholders, and what's available in the market. These variables fit into the categories of insulation and windows. Regarding insulation, choices are made considering type, thickness, cost, energy efficiency, and carbon footprint. Likewise, selections for windows are based on U-value, heat gain coefficient, and whether they have double or triple-pane glazing.

3.5.2. Objective functions

In this process, the focus is on identifying and formulating objective functions, which serve as the criteria for optimization. These objective functions can be categorized into two perspectives: environmental and financial, minimizing primary energy consumption and minimizing cost. The environmental objective functions aim to assess and enhance the ecological impact, while the financial ones are oriented toward economic considerations, explained in the following sections.

The next step involves systematically employing optimization algorithms to evaluate and refine these objective functions. These algorithms are computational methods designed to analyze and improve the given processes. The goal is to identify the most optimal result through a comparative analysis of the outcomes generated by these functions. This approach allows for a balanced consideration of both environmental and financial factors, ensuring a comprehensive and informed decision-making process in pursuing the best overall outcome.

3.5.2.1. Environmental objective function

Within the outlined framework, the environmental aspect of building energy retrofit assessment relies on energy consumption (EC). Using primary energy factors, EC for heating and cooling is determined through energy consumption (A. Safari, 2022). Specifically, dynamic energy simulations using the EnergyPlus software obtain detailed information on monthly energy consumption. It is important to note that, within the provided framework, insulations are regarded as a retrofitting measure. The energy produced is subtracted from the overall energy usage, decreasing the energy demand.

3.5.2.2. Economic objective function

A cost-effective energy retrofit project aims to reduce overall expenses over its lifespan by making appropriate initial investments in implementing Energy Retrofit Measures. This leads to decreased electricity, natural gas, and renewable energy costs.

3.5.2.2.1. Net present value (NPV)

In energy retrofit projects the NPV of an energy retrofit project can be calculated as follows:

$$NPV = IC + EC + GC \quad (1)$$

Where IC is the investment cost, dEC and dGC are the present value of savings in electricity and natural gas bills during building service time.

IC includes profits earned from decreased gas and energy expenses. The following sections explain the calculations for each of the above terms.

3.5.2.2.2. Investment cost

Investment cost or IC is the total cost of implemented energy retrofit measures for each scenario or building configuration. In this regard, calculating the investment cost of an energy retrofit project is necessary, and it can be as follows:

$$IC = \sum_{i=0}^I \sum_{j=0}^J C_i^j \cdot K_i^j \quad (2)$$

This framework C_i^j signifies the cost of incorporating the i th decision variable type with the j th alternative measurement. The variable K_i^j is a binary digit, set at 1 when implementing measure (i, j) and 0 when not opting for measure (i, j) . In fact, I is the

number of decision variables, and J is the number of alternatives for each decision variable.

3.5.2.2.3. Cost of electricity and natural gas

Here is how to compute the present value of the costs associated with gas and electricity use during building maintenance:

$$r = \left(\frac{i - i_e}{1 + i_e} \right) \quad (3)$$

$$EC = EC_1 * \frac{(1+r)^{n-1}}{r*(1+r)^n} \quad (4)$$

$$GC = GC_1 * \frac{(1+r)^{n-1}}{r*(1+r)^n} \quad (5)$$

$$n=50$$

$$i=5\%$$

$$i_e=3\%$$

In the base situation, EC1 represents the cost of electricity. In the base case and the proposed retrofitted building, GC1 represents the natural gas costs. The project service time in years are n, the discount rate (i), and the energy price inflation rate (ie). r is the difference between energy price inflation and discount rates. In fact, Because the inflation rate of energy (ie) and overall inflation (i) can be different, each is discounted to the present time at a different rate.

In these mathematical formulas, n is considered to be 50, ie is considered to be 3%, and i is considered to be 5%.

The discount rate is a critical factor in the life cycle cost analysis. By factoring in the difference between the discount rate and the inflation of energy prices, more accurate results can be obtained when calculating the net present value (NPV) of energy retrofit projects.

3.5.3. Multi-objective optimization

After establishing objective functions, the formulation of multi-objective optimization can be outlined as shown below:

Energy consumption: [Minimize] $F_1(x) = \text{PEC}$

Price: $\begin{cases} \text{Investment cost} \\ \text{Cost of energy} \end{cases}$: [Minimize] $F_2(x) = \text{NPV}$

Subject to:

$x \in X$

$F_1(x) \leq \text{PEC}_0$

$\text{IC}(x) \leq \text{Available budget}$

Here, PEC_0 represents the primary energy consumption of the original building in the first year, x is the set of decision variables representing different retrofit scenarios, and X is the feasible range of decision sets. Notably, the optimization objective is governed by two constraints. Specifically, to ensure the efficacy of an energy retrofit strategy without compromising energy efficiency, all solutions leading to an increase in PEC compared to the initial configuration are disregarded. Additionally, obstacles to executing energy retrofit

projects include elevated investment expenses, energy costs, and inadequate financial resources (A. Safari, 2022).

The introduced problem is addressed by using a simulation-based multi-objective optimization method. This process aims to identify the optimal values for decision variables that minimize both PEC and NPV.

Genetic algorithms are frequently used for building energy optimization because they don't rely on derivatives. This allows simulation-based optimization with a balance between computational efficiency and reliability. Therefore, in this study, the Genetic Algorithm is employed. This approach, commonly applied in prior research on optimizing building energy, aims to achieve a practical solution. The proposed simulation-based multi-objective method consists of the following main components:

Optimization Engine: The NSGA-II code acts as the optimization engine.

Input Data File: Integral to the process, the Parametric EnergyPlus input data file (.idf) assumes a pivotal role.

Communication Module: This module generates specific EnergyPlus files (.idf) adjusted to any given vector of decision variables (x) using the parametric EnergyPlus model. It then autonomously runs simulations for the generated (.idf) files and extracts results from (.csv) files.

Post-Process Module: This module assesses simulation outcomes to calculate natural gas and electricity costs based on Canada's utility tax policy. It also determines PEC and NPV using the formulas explained in the preceding sections, assuming 0.045 CAD/kWh for the gas unit and 0.129 for the electricity unit.

In-depth, NSGA-II operates as an optimization algorithm within the MATLAB framework alongside EnergyPlus, which functions as a dynamic energy simulation engine. The chosen software demonstrates proficiency in handling text-based inputs and outputs, enabling efficient communication across diverse environments (A. Safari, 2022).

NSGA-II is a highly effective evolutionary algorithm and multi-objective genetic algorithm. It follows a step-by-step process involving fitness-based creation, crossover, mutation, and selection to improve a group of individuals referred to as chromosomes. These chromosomes represent solutions to the optimization problem. Specifically, potential building configurations or retrofit strategies are encoded using a bit-string format in the vector of decision variables (x). NSGA-II prefers individuals with better fitness values (objective function values) and those contributing to a higher average crowding distance, supporting population diversity.

The highlights of this optimization method are:

- An answer that no other explanation is better than has more points. Answers are ranked and ordered based on the number of better answers.
- Merit is assigned to the answers according to their rank and non-predominance of other answers.
- The fitness-sharing method is used for close answers so that the dispersion of the answers can be set favourably, and the answers will be distributed uniformly in the search space. Figure 3.20 shows the sorting of the answers in this algorithm.

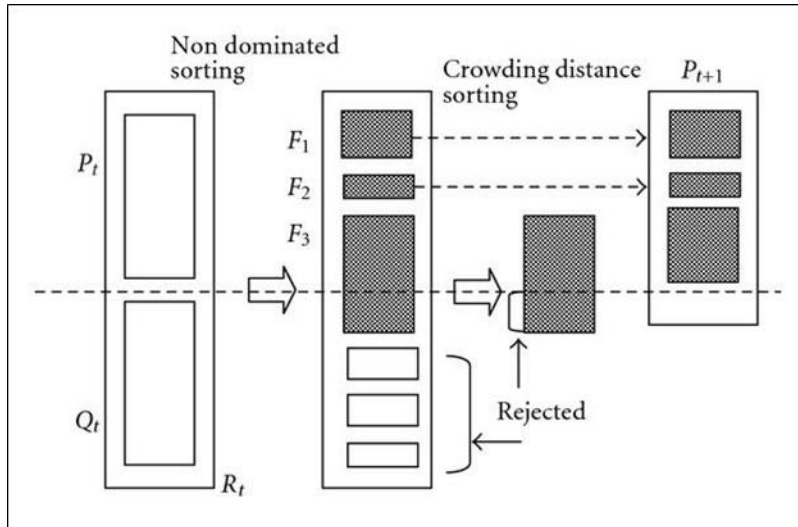


Figure 3.20 Sorting of the answers in this algorithm

Variations of this method are on selection operators. The quality of the answers should be measured; if it is not met, it should be repeated according to the order. Figure 3.20 shows how this choice is made. By adding two necessary operators to the average single-objective genetic algorithm, this algorithm has become a multi-objective algorithm, which, instead of finding the best one-dimensional solution, gives a set of best solutions known as the Pareto front. These two operators are:

- An operator who assigns a superiority criterion (rank) to the members of the population based on non-superiority sorting and fronting.
- An operator that preserves the variety of answers and their dispersion among answers with equal rank. This parameter is called the crowding distance.

The crowding distance parameter indicates the proximity distance of the target sample to other members of the population, and a significant value of this parameter will lead to better divergence and range in the set of population members. The crowding distance for a member is obtained by dividing the difference between the objective function value of

the following member and the previous member by the difference between the maximum and minimum values of the function. To determine the ranking, the first Pareto front is considered first, and then the ranking continues among other Pareto fronts. If there is a need for a more accurate ranking on a Pareto front, any member with a greater crowding distance will be ranked higher.

The NSGA-II optimization algorithm, implemented in the MATLAB environment, requires simulating each building retrofit model corresponding to an energy retrofit strategy to assess each one. Therefore, a communication platform is crucial for connecting the MATLAB optimization code with the EnergyPlus simulation engine. In pursuit of this goal, a parametric model for EnergyPlus is formulated by incorporating information from the energy retrofit strategies database and the baseline building model. When the optimization algorithm evaluates an individual within the population, the communication module transforms the mentioned parametric model of EnergyPlus into a designated building model aligned with the decision variable vector (x) to examine the simulation results. The post-processing module, equipped with a cost calculation algorithm based on the utility tax policy in Canada, computes values of objective functions (EC and NPV) for each one in the population and conveys these values back to the optimization algorithm.

In addition, to enhance computational efficiency, a method is employed to store the outcomes of each EnergyPlus simulation, uniquely labelled for reference. During optimization, if a previously assessed scenario recurs, the system retrieves the stored simulation results using the unique label, thus avoiding the need to repeat the simulation. Throughout the optimization process, NSGA-II consistently refines the building models

until reaching a specified stopping point, defined here as the maximum number of iterations (referred to as generations in the context of the genetic algorithm). Ultimately, the optimization algorithm produces a set of preferred solutions, the Pareto front, addressing various objective functions.

3.5.4. Multi-criteria decision making.

Every point on the Pareto front represents a potential solution to the optimization problem. All solutions on the Pareto front are regarded as valid without requiring subjective preference information. Consequently, employing a multi-criteria decision-making method to choose the optimal solution from the Pareto front becomes essential, aligning with mutually contrasting criteria.

3.5.5. Energy efficiency measures

After a comprehensive market examination involving key stakeholders through a focused group, a series of strategies was used. These strategies are outlined as decision variables within the EnergyPlus and MATLAB platforms to direct a simulation-based multi-objective optimization process. A summary of these suggested Energy Efficiency Measures (EEMs) is presented in Table 3.9.

Table 3.9 Characterization of investigated energy efficiency measures

| Decision Variables | Investigated options | Number of discrete options |
|------------------------|--|----------------------------|
| Wall insulation | Material: fibreglass, extruded polystyrene, expanded Polystyrene Thickness: 1" - 8.5" | 20 |
| Roof insulation | Material: fibreglass, extruded polystyrene, expanded Polystyrene Thickness: 1" - 8.5" | 20 |
| Windows glazing | Insulated Dual Clear Air Filled High Altitude Insulated Dual Low-E Advanced Low-E Insulating Glass Air Filled High Altitude Insulated Dual Low-E NaturalSun Low-E Insulating Glass Argon Non-High Altitude Insulated Dual Low-E SunDefense™ Low-E Insulating Glass Argon Non-High Altitude Insulated Dual Low-E AdvancedComfort Low-E Insulating Glass Argon Non-High Altitude | 6 |

Examining this in detail, the initial step in proposing measures to enhance the building's energy efficiency involves establishing a performance benchmark. Suggesting solutions to reduce energy loss through surfaces and prevent air infiltration can elevate its overall performance. Applying thermal insulation within the building envelope is a practical step

to minimize heat transfer. Various proposed insulation materials and their thicknesses are outlined in Table 3.10.

Table 3.10 Insulation variables

| Insulation walls and floors | | | | | |
|------------------------------------|--|---------------------------|--|------------------|--------------|
| Component | Type | Thermal Resistance | | Thickness | price |
| Fiberglass | Building Insulation/Batt | R8 | | 2.5" | \$69.99 |
| Fiberglass | Building Insulation/Batt | R12 | | 3.5" | \$79.99 |
| Fiberglass | Building Insulation/Batt | R20 | | 6" | \$159 |
| Fiberglass | Fiberglass insulation | R28 | | 8.5" | \$90.99 |
| Extruded Polystyrene | rigid insulation Panel-XPS 20 | R5 | | 1" | \$26.99 |
| Extruded Polystyrene | rigid insulation Panel-XPS 20 | R7.5 | | 1.5" | \$77.46 |
| Extruded Polystyrene | rigid insulation Panel-XPS 20 | R10 | | 2" | \$64.99 |
| Extruded Polystyrene | rigid insulation Panel-XPS 30 | R15 | | 3" | \$89.99 |
| | "ComfortBatt" Insulation | R14 | | 3.5" | \$88.18 |
| | "ComfortBatt" Insulation | R22 | | 5.5" | \$90.11 |
| | "ComfortBatt" Insulation | R28 | | 7.25" | \$88.84 |
| Expanded Polystyrene | Isofoam Rigid Insulation Panel | R5.6 | | 1.5" | \$35.99 |
| | CertainTeed Fibreglass Batt Insulation | R12 | | 3.5" | \$51.00 |
| | CertainTeed Fibreglass Batt Insulation | R20 | | 6" | \$74.95 |
| | CertainTeed Fibreglass Batt Insulation | R28 | | 8.5" | \$67.00 |
| Extruded Polystyrene | Rigid Insulation SM XPS | R5 | | 1" | \$26.74 |
| Extruded Polystyrene | Rigid Insulation SM XPS | R5 | | 2" | \$57.98 |
| Extruded Polystyrene | Rigid Insulation SM XPS | R5 | | 2.4" | \$63.35 |
| | Rigid Mineral Wool Insulation | R4 | | 4" | \$86.12 |
| | Rigid Mineral Wool Insulation | R4 | | 1.5" | \$81.00 |

Moreover, external windows play a significant role in influencing the energy performance of the building by facilitating natural lighting and the transfer of heat between indoor and outdoor spaces. Various window options under consideration are presented in Table 3.11.

Table 3.11 Window variables

| Number | Size | Glass material | Gas | U-value (W/m ² ·K) | SHGC |
|--------|------|--|-------|----------------------------------|------|
| 1 | 6*4 | Insulated Dual Clear Air Filled High Altitude | Air | 2.725 | 0.69 |
| 2 | 6*4 | Insulated Dual Clear Air Filled High Altitude Upgrade To 4mm | Air | 2.668 | 0.67 |
| 3 | 6*4 | Insulated Dual Low-E Advanced Low-E Insulating Glass Air Filled High Altitude Upgrade To 5mm | Air | 1.816 | 0.32 |
| 4 | 6*4 | Insulated Dual Low-E NaturalSun Low-E Insulating Glass Argon Non-High Altitude Upgrade To 6mm | Argon | 1.646 | 0.57 |
| 5 | 6*4 | Insulated Dual Low-E SunDefense™ Low-E Insulating Glass Argon Non-High Altitude Upgrade To 6mm | Argon | 1.533 | 0.24 |
| 6 | 6*4 | Insulated Dual Low-E AdvancedComfort Low-E Insulating Glass Argon Non High Altitude Upgrade To 6mm | Argon | 1.305 | 0.31 |

3.6. Summary

In summary, this research investigates the deep energy retrofitting of a commercial building in Ottawa, leveraging advanced tools like SketchUp with the OpenStudio plugin, EnergyPlus, and MATLAB. The methodology involves modeling the building's geometry with SketchUp and simulating its energy performance with EnergyPlus. Optimization follows in multiple stages: identifying key variables, creating objective functions, and

performing multi-objective optimization using NSGA-II in MATLAB to refine the model and find optimal solutions. The final step involves selecting the most effective optimization strategy. This methodology is visually outlined in Figure 5.1.

4. Results and discussion

4.1. Introduction

This chapter aims to demonstrate, via a case study, how insulation and window efficiency advancements work. This chapter analyzes in detail the results of Chapter 3. Section 4.2 assesses the predictions made by the EnergyPlus model by comparing the base model's energy consumption with actual data from the university. Section 4.3 compares The Typical Weather Data (TWD) and Actual Weather Data (AWD) across four critical factors to make an assessment. After that, Sections 4.4 explore the optimization solutions, and Sections 4.5 and 4.6 explain selected insulation and window variables. Finally, Section 4.7 examines how to create the best possible optimization plan while assessing the costs of execution and the effect of envelope retrofitting on energy usage.

4.2. Base model evaluation

To evaluate the model-designed predictions by EnergyPlus, the energy consumption of the base model is compared with actual data collected from the university. Table 4.1 displays the energy intensity of the base model and actual data, facilitating a comparison to estimate the model. Based on the ASHRAE standard, the designed model should be assessed using NMBE and CV (RMSE) formulas. For monthly assessment with NMBE, the difference between the designed model and actual data should be within a range of $\pm 5\%$, and with CV (RMSE), this difference of up to 15% is acceptable, which for the NMBE the result of this project was -3.9%, and for CV (RMSE) it was 14.5%. The model was designed for 2012-2013 by AWD for this period and then assessed with the actual data of this year.

Table 4.1 Total energy consumption and EUI of the base model and the actual one

| | Designed model (2012-2013) | Actual (2012-2013) | Actual (2011-2012) | Actual (2009-2010) | Actual (2007-2008) | Area (m²) |
|------------------------------------|---------------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-----------------------------|
| Total energy (kWh) | 4,789,741 | 4,948,960 | 5,513,798 | 5,874,449 | 6,085,349 | 17,096.2 |
| EUI (kWh/m²) | 280.16 | 289.48 | 325.5 | 343.6 | 355.8 | |

The provided Energy Use Intensity (EUI) values for the actual and designed models result from energy consumption data obtained from the output of EnergyPlus for the model and actual data from the university's sustainable office, as presented in the tables below. In Table 4.2, EnergyPlus presents monthly figures for the building's cooling, heating, and electricity energy utilization. Meanwhile, the university's sustainable office has data on energy consumption.

Table 4.2 Energy consumption of the base model

| | Cooling (kWh) | Heating (kWh) | Electricity (kWh) | Total (kWh) |
|--------------------|----------------------|----------------------|--------------------------|--------------------|
| January | - | 378,283 | 228,722 | 607,005 |
| February | - | 281,624 | 206,053 | 487,677 |
| March | - | 204,094 | 185,610 | 389,704 |
| April | - | 115,106 | 115,330 | 230,436 |
| May | - | 34,890 | 151,356 | 186,246 |
| June | 228,920 | - | 170,132 | 399,052 |
| July | 318,678 | - | 177,277 | 495,955 |
| August | 274,494 | - | 177,034 | 451,529 |
| September | 178,767 | - | 176,153 | 354,920 |
| October | - | 100,090 | 160,385 | 200,475 |
| November | - | 180,029 | 217,942 | 397,971 |
| December | - | 300,894 | 227,867 | 528,761 |
| Total (kWh) | 1,000,860 | 1,595,014 | 2,193,866 | 4,789,741 |

Additionally, Table 4.3 provides monthly data for heating and electricity, along with annual cooling energy usage in the building (monthly cooling energy consumption of actual data is not available), as obtained from the sustainable office of the university.

Table 4.3 Energy consumption by actual data.

| | Heating (kWh) | Cooling(kWh) | Electricity(kWh) | |
|--------------------|---------------|--------------|------------------|-----------|
| January | 322,026 | | 188,655 | |
| February | 242,314 | | 190,095 | |
| March | 201,506 | | 224,657 | |
| April | 123,429 | | 112,328 | |
| May | 37,473 | | 208,816 | |
| June | - | | 208,816 | |
| July | - | | 161,292 | |
| August | - | | 161,292 | |
| September | - | | 171,373 | |
| October | 112,764.79 | | 195,855 | |
| November | 211,541.20 | | 226,098 | |
| December | 283,380.73 | | 221,777 | |
| Total (kWh) | 1,534,436 | 1,143,462 | 2,271,061 | 4,948,960 |

The data in this section shows that the energy intensity of the model compared to the actual data is underestimated, which means that the energy savings from the retrofit would be higher.

4.3. Actual and typical weather data

Typical weather data and actual weather of 2012-2013, which was available and covered the time before COVID-19, were used to verify and optimize the model. Four critical meteorological parameters—global horizontal irradiance (W/m^2), relative humidity, wind speed (m/s), and dry-bulb air temperature ($^{\circ}C$)—that have a substantial impact on

building energy performance were included in the statistical analysis (Moradi et al. 2023). These parameters were provided for AWD and TWD in the ensuing sections for a thorough discussion and comparison.

Figure 4.1 compares the temperature of actual weather data and typical weather data. Also, December, January, and February are the coldest months for both cases.

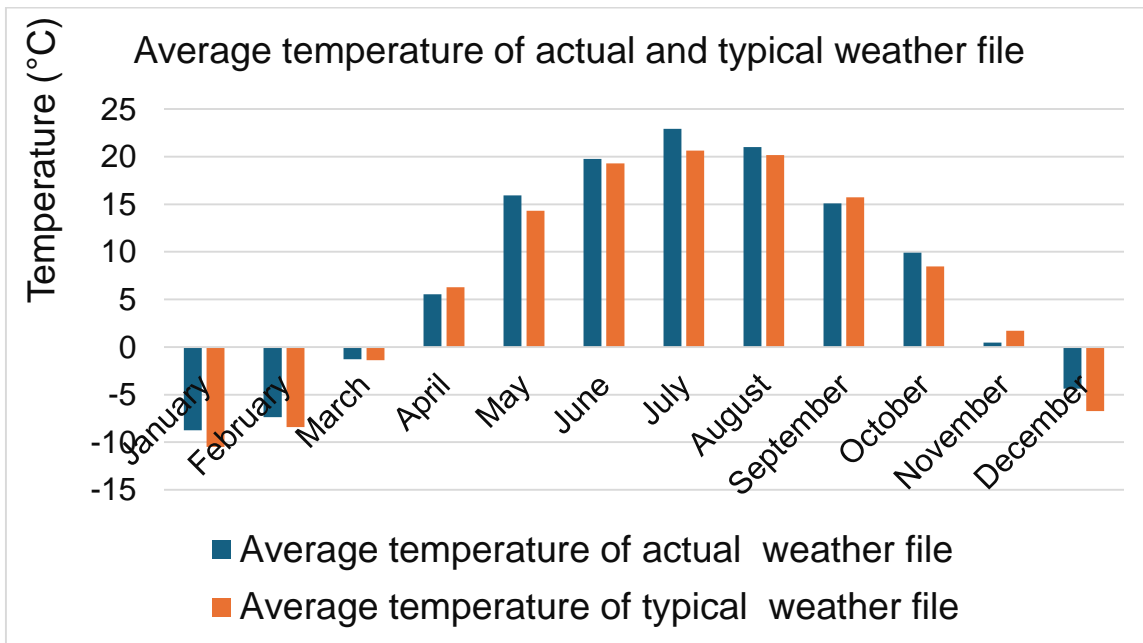


Figure 4.1 Temperature of actual weather data and typical weather data.

The quantity of terrestrial irradiance falling on a surface horizontal to the earth's surface is known as global horizontal irradiance or GHI. Concerning the frequency of sunny days, this parameter (GHI) provides an all-encompassing assessment of the solar radiation incident on a horizontal surface. Figure 4.2 compares the Global Horizontal Irradiance of AWD and TWD, showing that their differences are insignificant. However, during the cold months, the average Global Horizontal Irradiation of typical weather data is higher than that of the actual weather data. In contrast, in the warm months, it is almost the opposite.

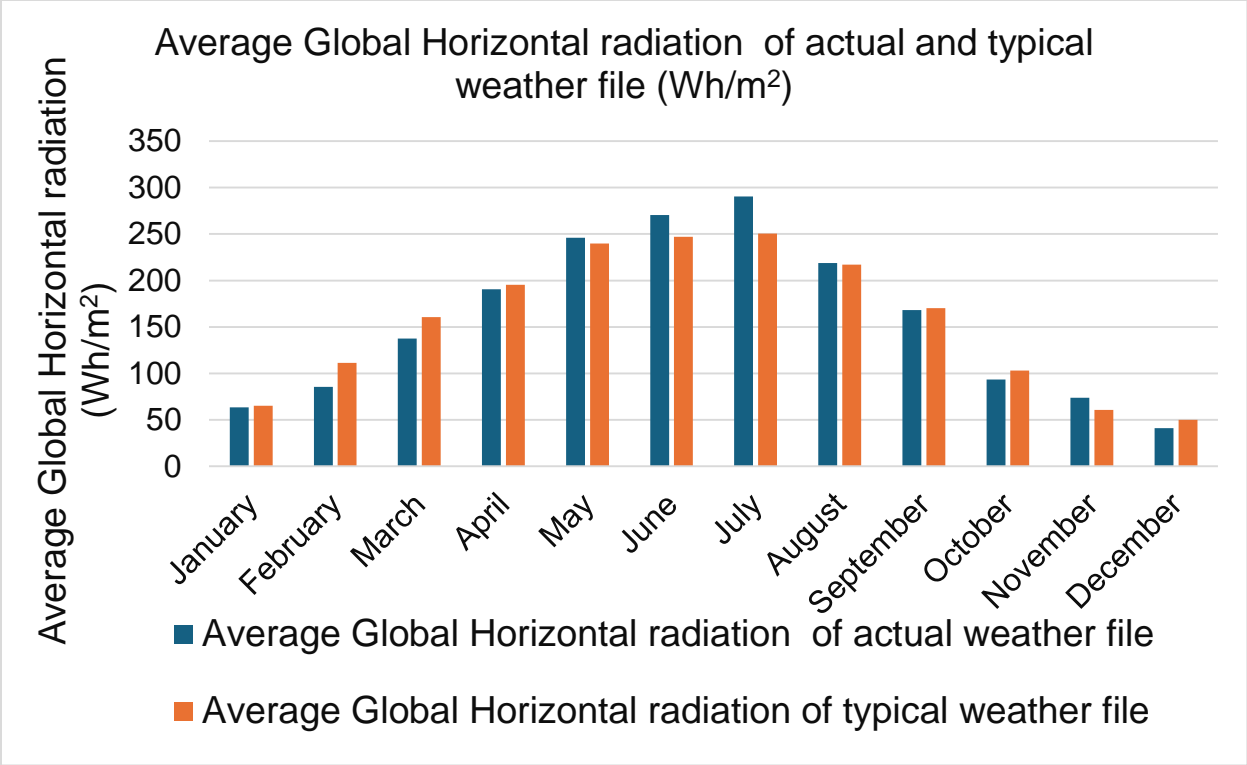


Figure 4.2 Global Horizontal Irradiance of AWD and TWD

The ratio of the quantity of atmospheric moisture present to the amount that would be present if the air were saturated is known as relative humidity and is stated as a percentage. Relative humidity is a function of temperature and moisture content because the latter is temperature-dependent. Figure 4.3 shows that the difference in Relative Humidity is more significant in December than in other months. The Relative Humidity of actual weather data for this month is 86%, while typical weather data is 76%.

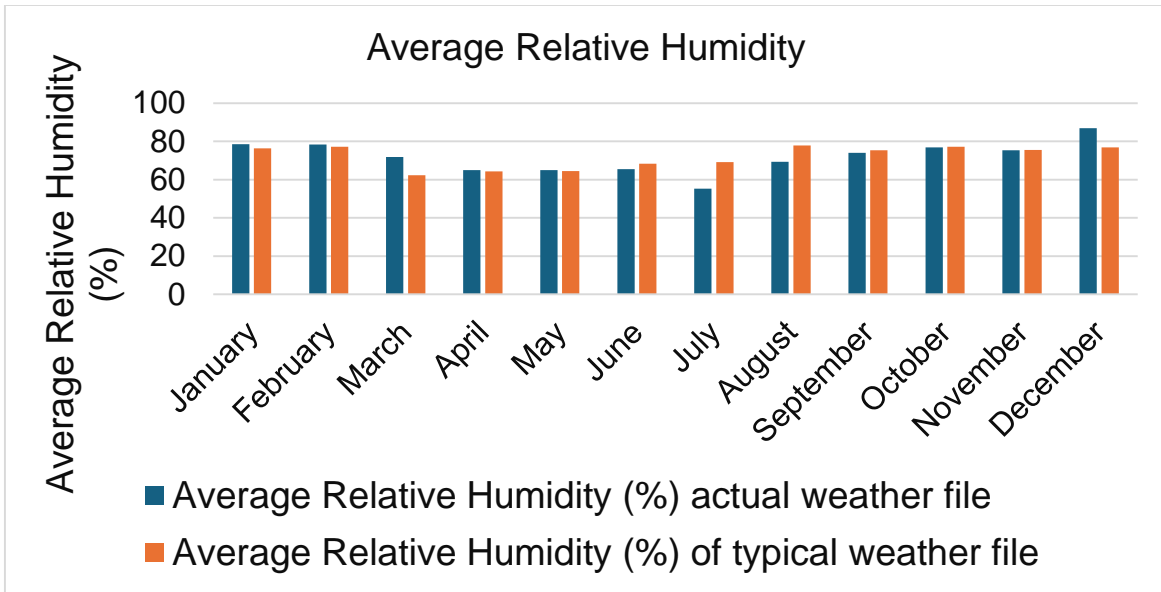


Figure 4.3 Average relative humidity of AWD and TWD

Figure 4.4 shows that wind speed in typical weather data is greater than in actual weather data, and the differences between them are noticeable. In December and October, the difference between them is maximum. 4.6 m/s for TWD while 11.8 m/s for AWD.

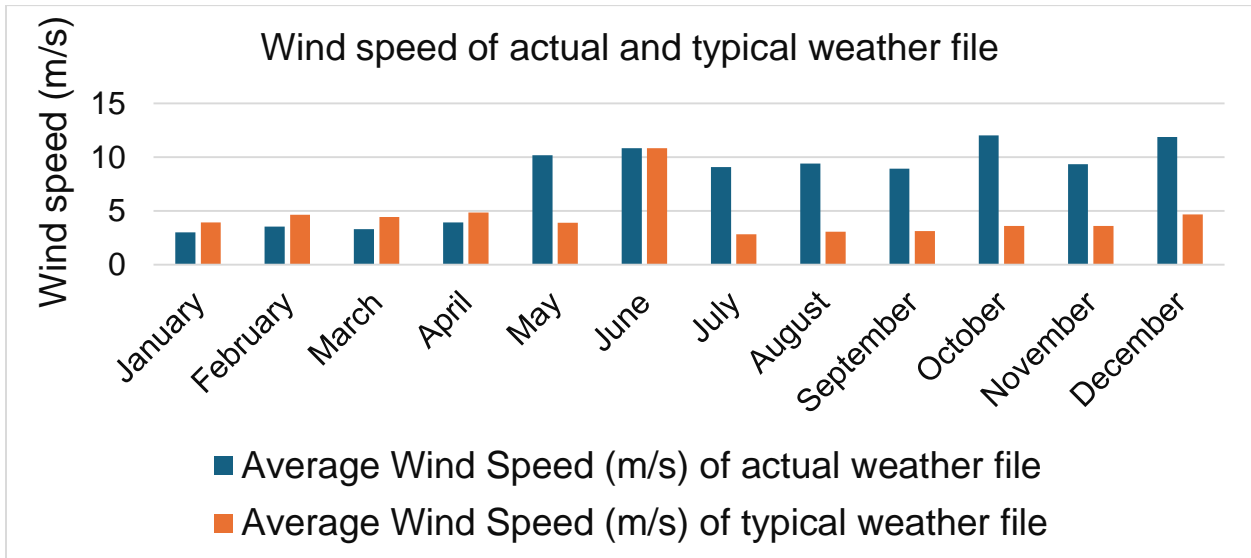


Figure 4.4 Wind speed of AWD and TWD

4.4. Solutions

The findings of each factor, such as the Pareto front, the chosen alternatives for decision variables, and the values of the objective functions and their evaluations, are explained in the following sections. Considering the status of utility pricing, Figure 4.5 displays the Pareto front resulting from a simulation-based approach to multi-objective optimization. Also, there is a range of solutions for multi-objective optimization and NSGA-II. It reveals 50 optimal solutions. Furthermore, this figure illustrates the Pareto front in a two-dimensional format, showing an inverse relationship between NPV (cost) and total primary energy.

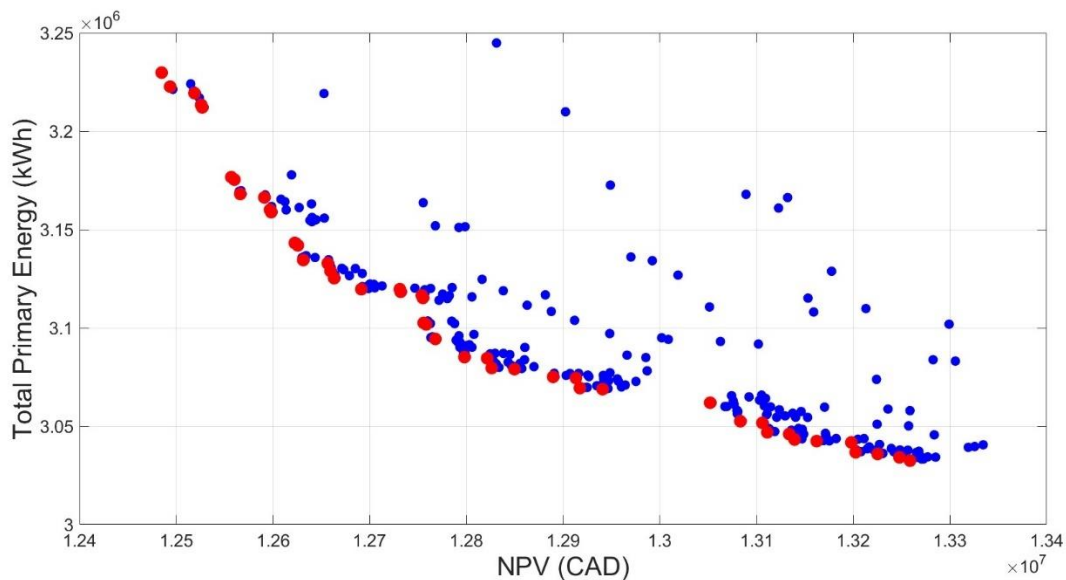


Figure 4.5 Pareto Front and non-selected variables.

This project's total primary energy consumption exhibits variability among different options, ranging from 3,032,519 to 3,244,902 kWh. This fluctuation underscores the impact of diverse factors on overall energy consumption within the study's context.

Additionally, the total primary energy consumption of the 50 proposed options in the Pareto front ranges from 3,032,519 kWh to 3,229,814 kWh. In contrast, the total primary energy consumption of the base model is 3,335,188 kWh. This means that optimizing the envelope will decrease the total primary energy consumption by around 10%.

The following examines three options out of a total of fifty solutions. The first option has the lowest energy consumption, the second option has the lowest cost, and the third option was obtained using the sum weight method, which will be briefly explained in the analysis of Case 3.

- **Case 1:** The solution with the least energy consumption is examined for this case. In Figure 4.6, a comparison of the monthly energy consumption of the building after and before the optimization of one of the selected options among 50 solutions in the Pareto front is shown. This comparison is presented monthly; while the total energy consumption before optimization in the cold and warm months is higher than in other months, the optimization, specifically in January, February, October, November, and December, is up to 24%. It is more notable than in other months.

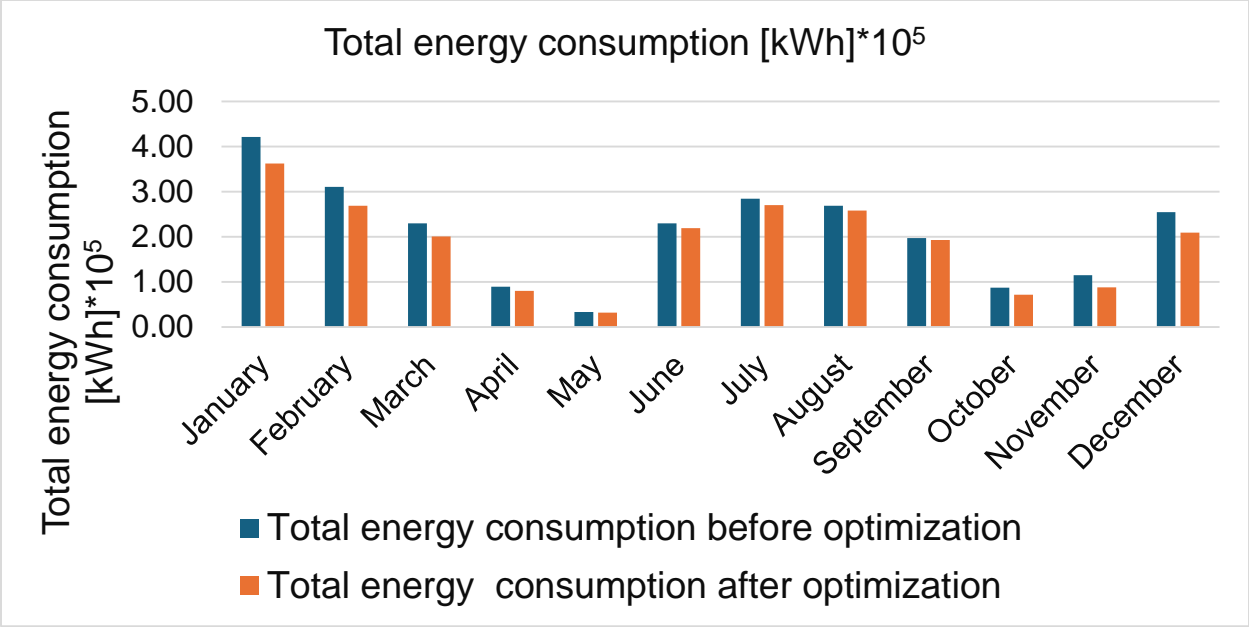


Figure 4.6 Comparison between total energy consumption before and after optimization.

Additionally, according to data from the sustainability office, thermostats are set differently based on demand. For heating in winter, temperatures range from 19°C to 22°C. Moreover, since the number of occupants is lower in summer than winter, the settings remain stable. Therefore, there can be broader setpoint ranges for summer, leading to variations in energy consumption. Table 4.7 shows sensitivity analysis for different temperatures of summer setpoints along with their effects on energy consumption.

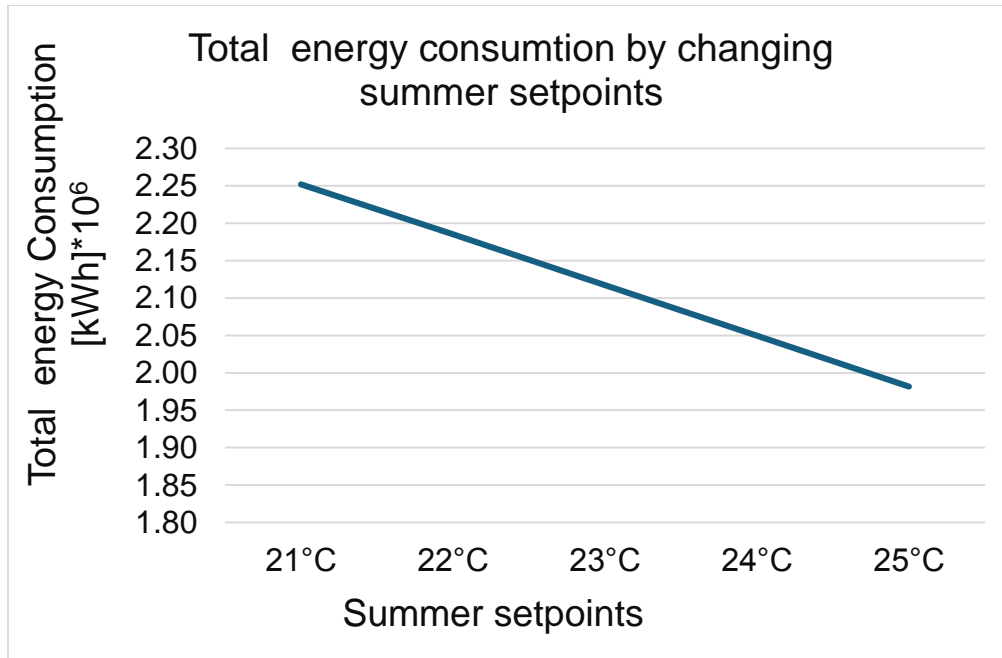


Figure 4.7 Comparing total energy consumption(kWh) with different summer setpoint points.

Changing the cooling setback in summer does not affect total energy consumption. Additionally, as the cooling setpoint increases by 1°C, the effectiveness on energy efficiency is between 3% to 12% for 25°C. So, the best cooling setpoint to the least energy consumption between 22, 23, 24, and 25°C is 25°C (figure 4.7).

Figure 4.8 shows energy consumption differences with different winter setbacks. It demonstrates that decreasing the heating setback by 1°C in winter has a 6% effect on total energy consumption.

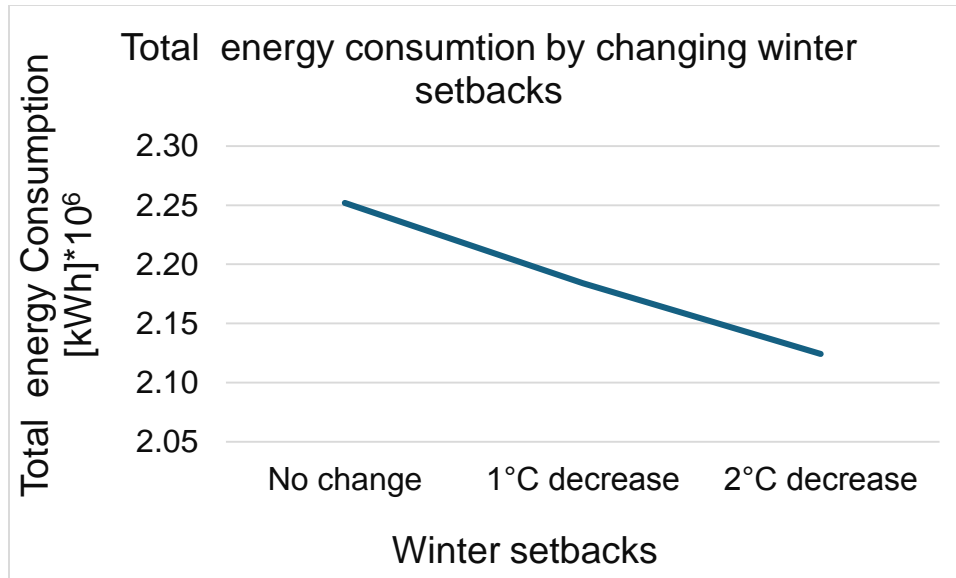


Figure 4.8 Comparing total energy consumption(kWh) with different winter setbacks.

Therefore, to assess total energy consumption, a 2°C decrease in heating setbacks and a 25 °C adjustment for the cooling setpoint were selected.

Figure 4.9 compares the total energy consumption of the base model with TMY in each month of that selected option of the Pareto front model after optimization, where the setpoints and setbacks are adjusted to the mentioned values in the same selected solution of the Pareto front. This shows that for this solution, the total energy consumption is decreased by about 10%; after changing setpoints and setbacks by the mentioned values, the optimization is about 30%.

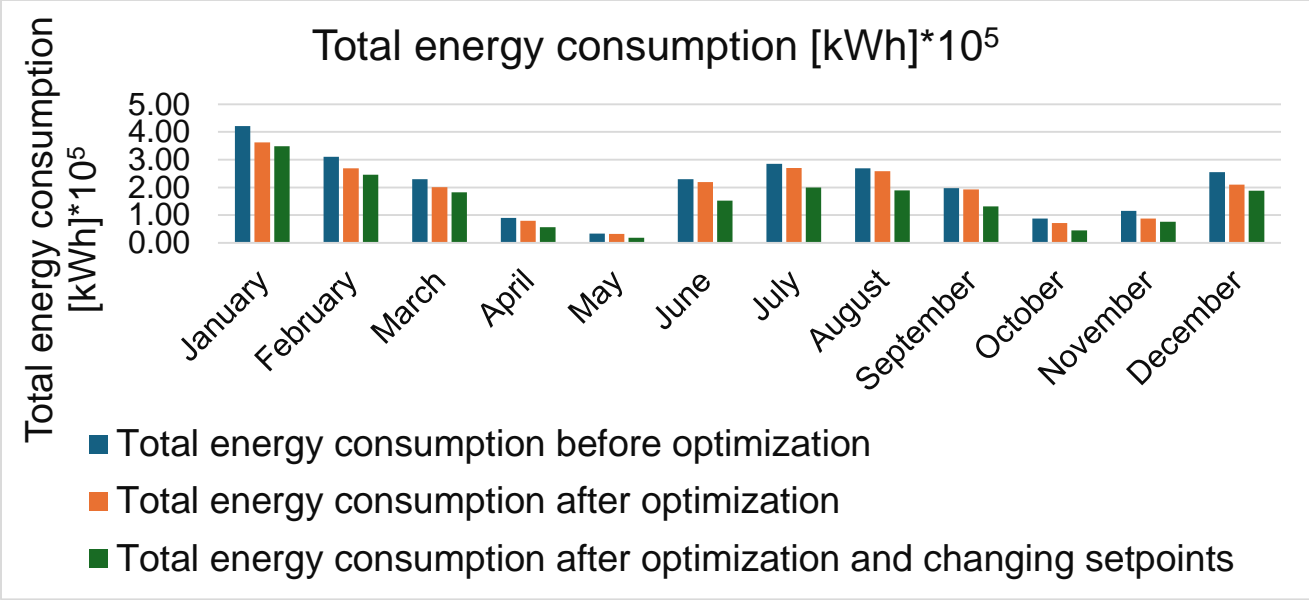


Figure 4.9 Comparing the total energy consumption of the base-model and a solution (kWh)

As mentioned, energy efficiency increases by 24% during January, February, October, November, and December, and after adjusting the new setpoint and setback, it will increase to 48% in October.

Figures 4.10 and 4.11 outline the total energy consumption on the coldest and warmest days of the year before and after optimization. After retrofitting and adjusting setpoints and setbacks to the mentioned values during extreme winter days, total energy efficiency increases by 20%.

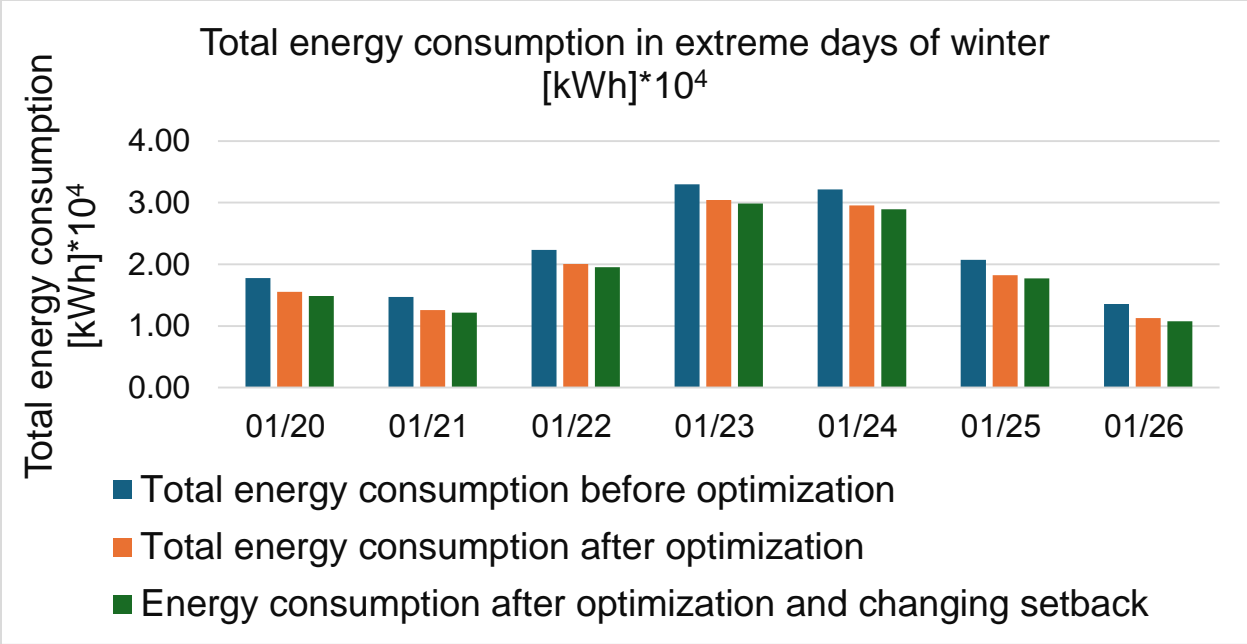


Figure 4.10 Comparing energy consumption in extreme days of winter(kWh) before(base-model) and after optimization.

For this solution, the highest energy consumption during the coldest days is 33,000 kWh before optimization, occurring on January 23rd. After retrofitting, this energy consumption decreases to 30,400 kWh (7.7%), while again, by changing setpoints and setbacks, it will decrease to 29,800 kWh (10%). Moreover, energy efficiency on January 26 after retrofit increased by 17%, while after retrofitting and adjusting new setpoint and setbacks increased by 20%. Furthermore, the highest energy consumption during the warmest days of the year was 17,600 kWh before retrofitting on July 15th, reduced to 16,700 kWh (5.2%) after retrofitting and 12,800 kWh (27%) after retrofitting and changing setpoints and setbacks.

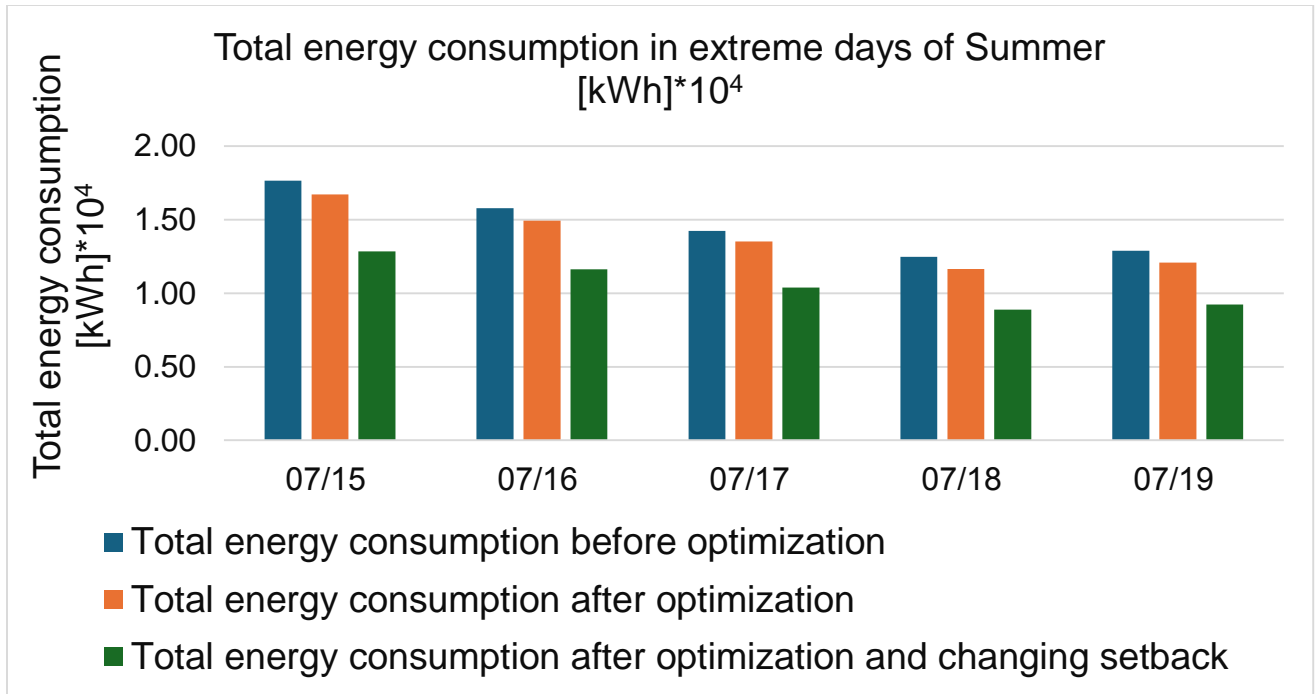


Figure 4.11 Comparison of energy consumption in extreme summer days before and after optimization.

- Case 2:** This case examines the solution with the least cost. In Figure 4.12, a monthly comparison of the building's energy consumption before and after optimization for this selected option from the Pareto front (among 50 solutions) is presented. Before optimization, total energy consumption was higher in cold and warm months. There is a notable reduction, especially in January, October, November, and December, with savings of up to 12% after optimization.

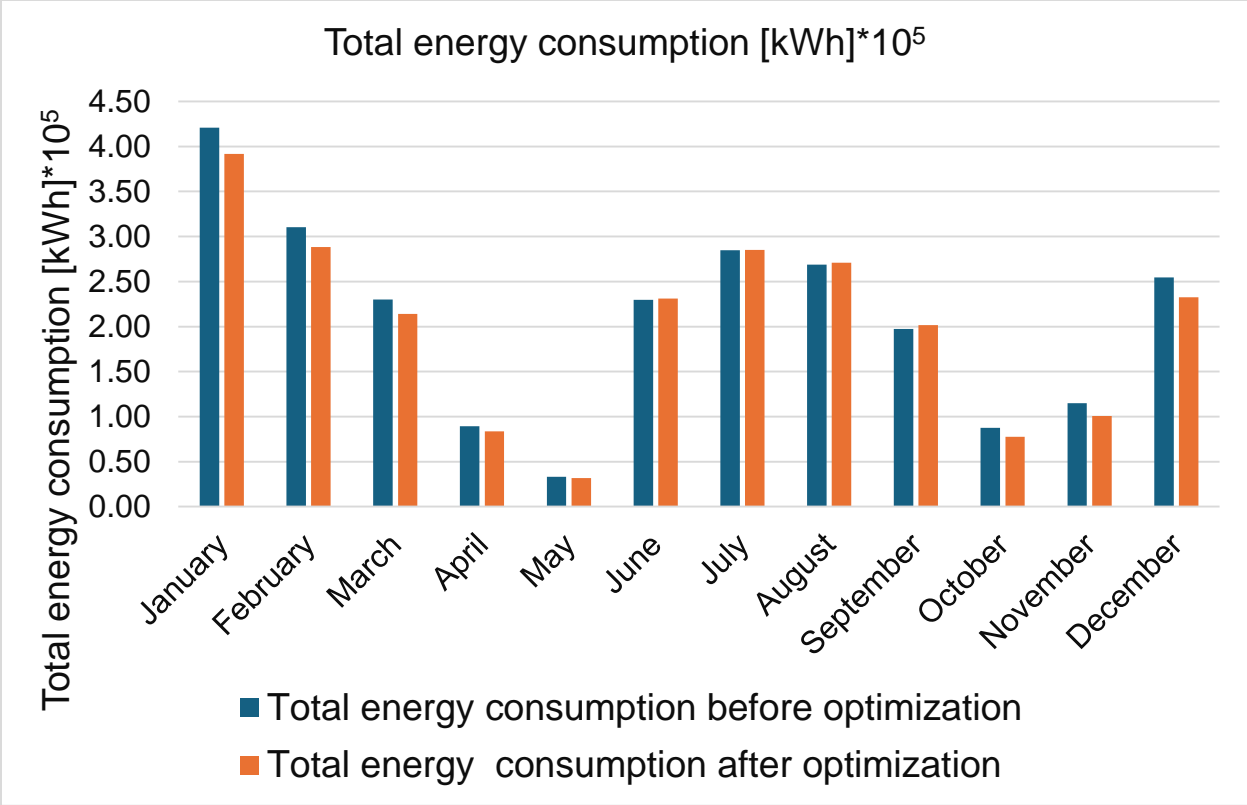


Figure 4.12 Comparison between total energy consumption before and after optimization.

Figure 4.13 compares the monthly total energy consumption of the base model using TMY with that of the selected optimized option from the Pareto front. The setpoints and setbacks were adjusted according to the values in the chosen Pareto front solution. This adjustment resulted in a roughly 12% reduction in total energy consumption, and with the changes in setpoints and setbacks, the optimization achieved around 42% savings in October.

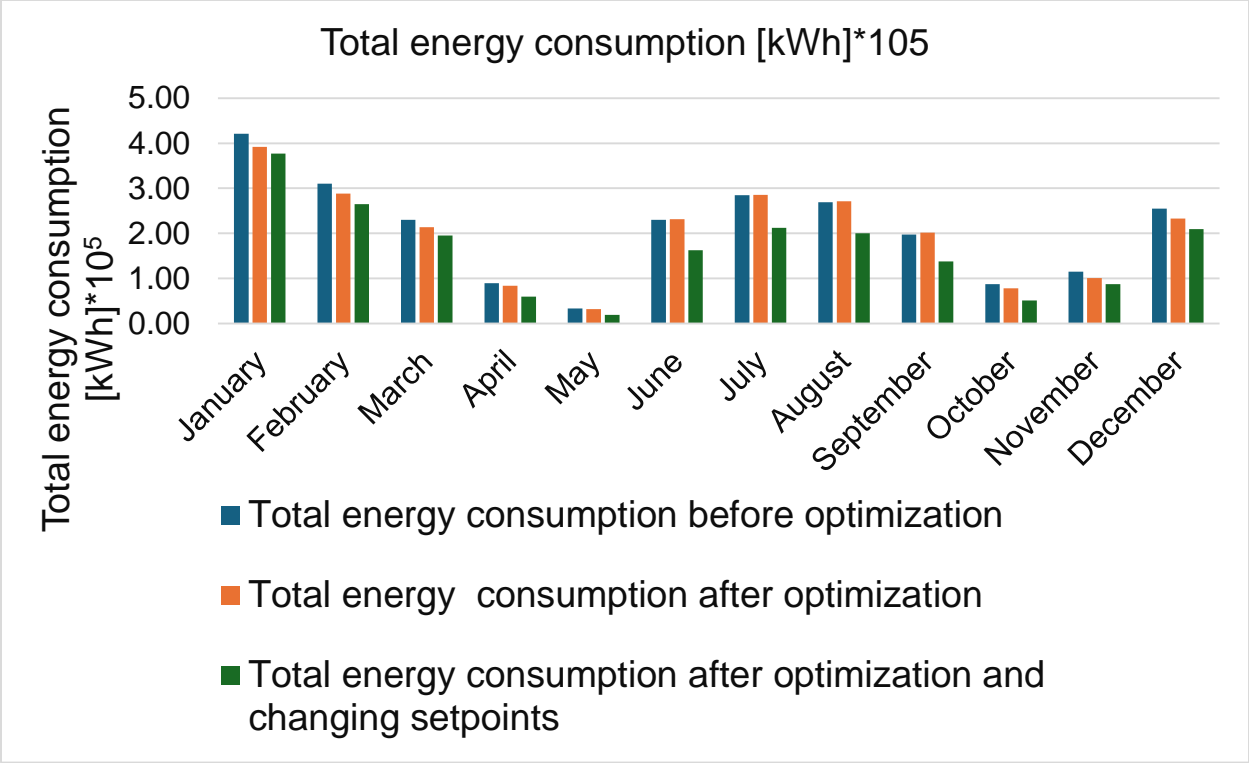


Figure 4.13 Comparison of the total energy consumption of the base model and a solution (kWh).

Figures 4.14 and 4.15 outline the total energy consumption on the coldest and warmest days of the year before and after optimization. After retrofitting and adjusting setpoints and setbacks to the mentioned values during extreme winter and extreme summer days, total energy efficiency increases by 90%.

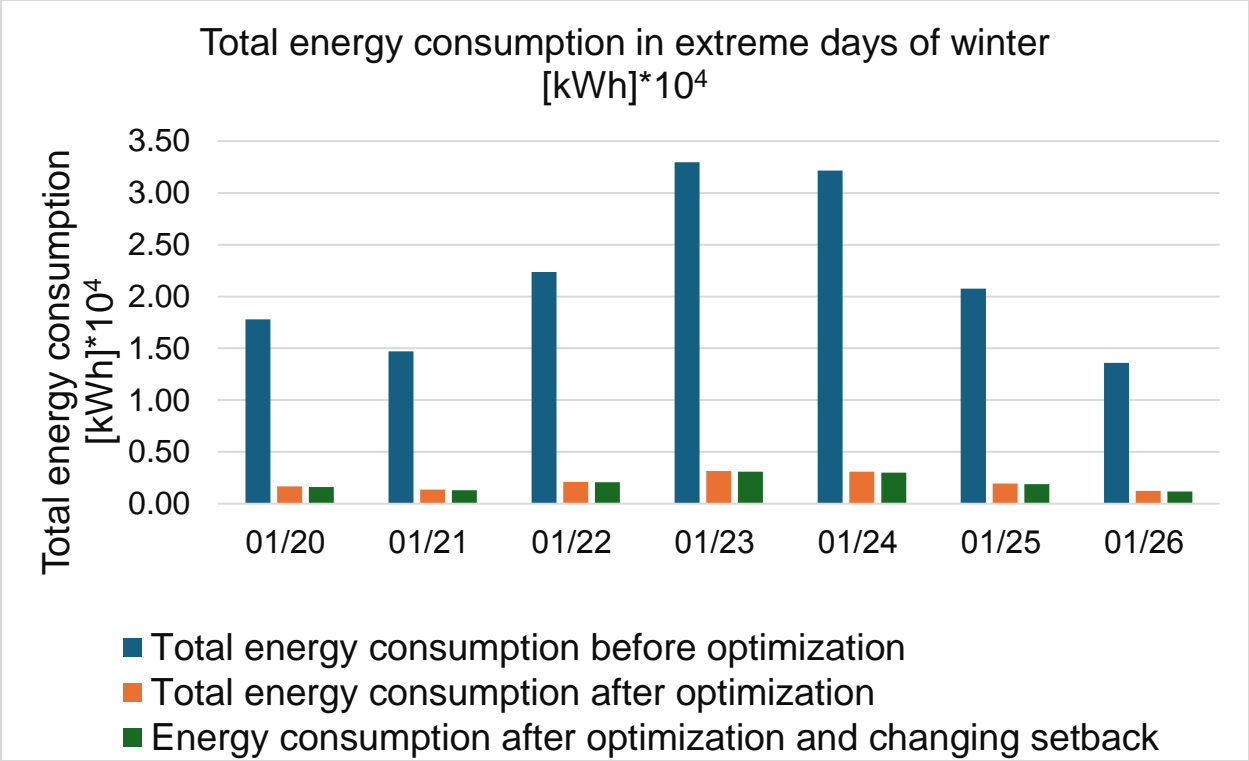


Figure 4.14 Comparison of the energy consumption in extreme days of winter before and after optimization.

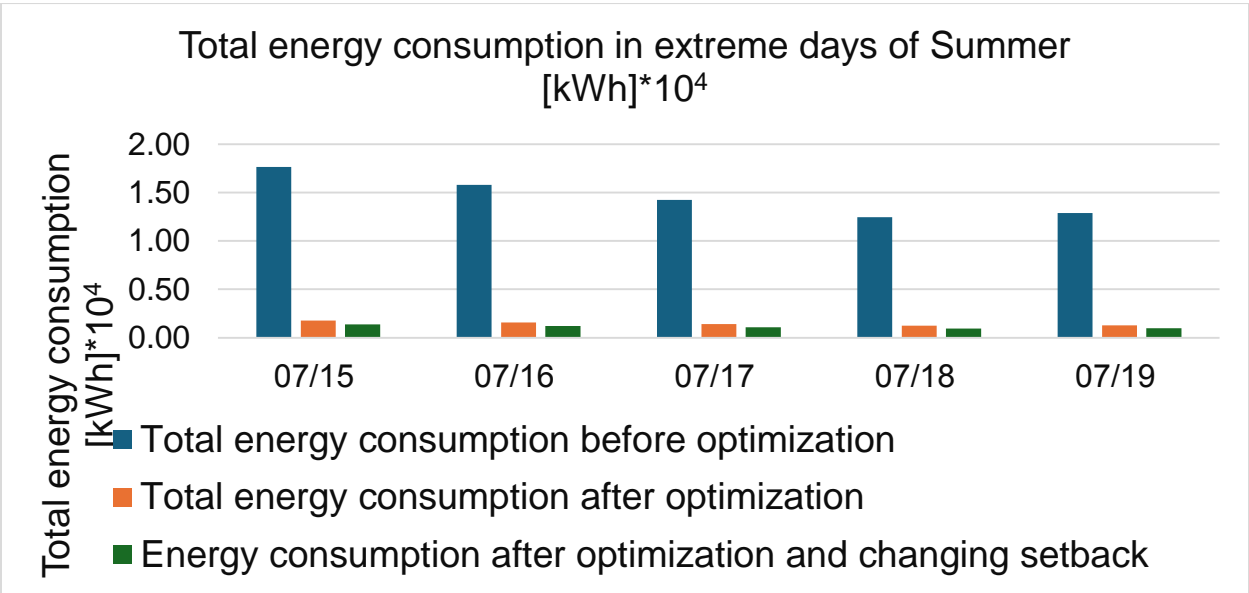


Figure 4.15 Comparison of the energy consumption in extreme days of summer before and after optimization.

Case 3: The third option was selected using the sum weight method. This method and its results related to the selected option are explained below.

Multi-criteria decision analysis is a subfield of operations research that transparently evaluates conflicting criteria in a decision. Conflicting criteria are common in the assessment of options.

In the context of building energy optimization, after performing multi-objective optimization and obtaining the set of Pareto front solutions, it is necessary to select a final solution from this set. Since the Pareto front solutions are mathematically equally good, the problem must be solved using the decision-maker's priorities. Nowadays, there are many transparent and structured methods for multi-criteria decision-making. One of the most well-known methods used in this thesis is the weighted sum method.

In this method, the optimal point of the objective function is obtained using weighting coefficients.

$$F_{ws}(\vec{x}) = \sum_{i=1}^k w_i \frac{f(x)_i - f(x)_i^{min}}{f(x)_i^{max} - f(x)_i^{min}}$$

$$w_i = 0.5$$

Figure 4.16 presents a monthly comparison of the building's energy consumption before and after optimization for a selected solution by sum weight method from the Pareto front (out of 50 solutions). Before optimization, energy consumption was higher in cold and warm months. After optimization, significant reductions, especially in January, October, November, and December, achieved savings of up to 22%.

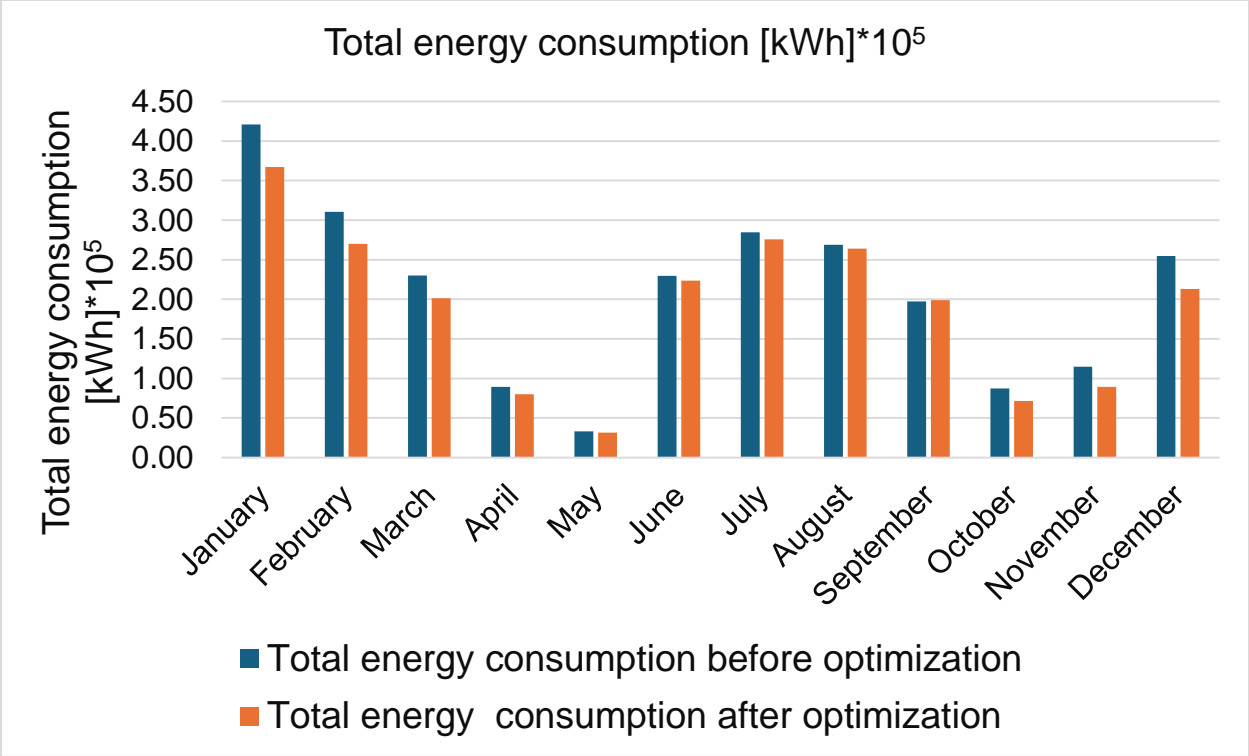


Figure 4.16 Comparison between total energy consumption before and after optimization.

Figure 4.17 compares the monthly total energy consumption of the base model using TMY with the selected optimized option from the Pareto front. Adjustments to the setpoints and setbacks based on the chosen Pareto front solution resulted in approximately a 22% increase in energy efficiency, changing the setpoints to the mentioned values and increasing it to 47% in October.

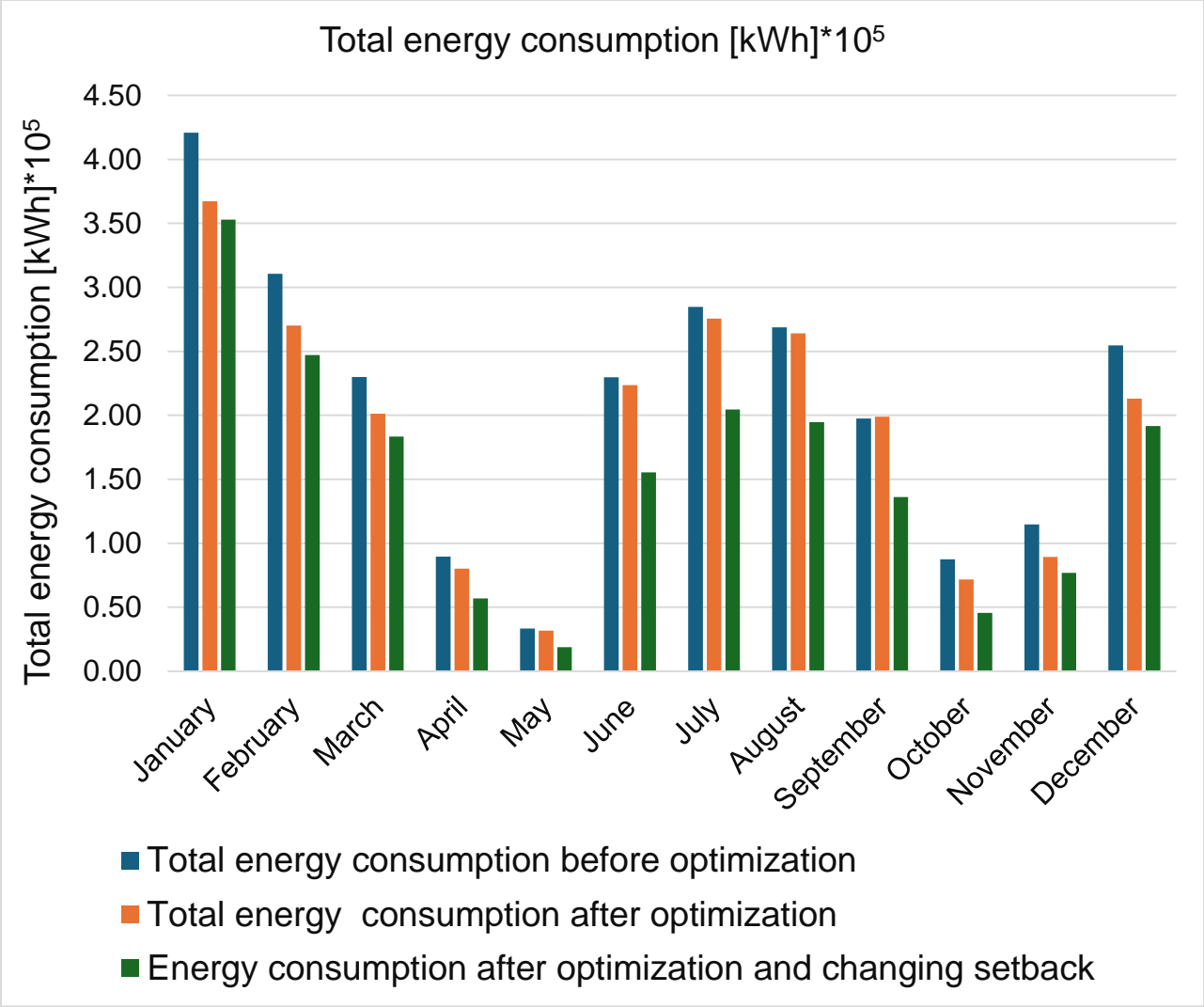


Figure 4.17 Comparison of the total energy consumption of the base model and a solution (kWh).

Figures 4.18 and 4.19 illustrate the total energy consumption on the coldest and warmest days of the year, both before and after optimization. After retrofitting and adjusting setpoints and setbacks to the specified values, total energy efficiency increased by 90-92% during extreme winter and summer days.

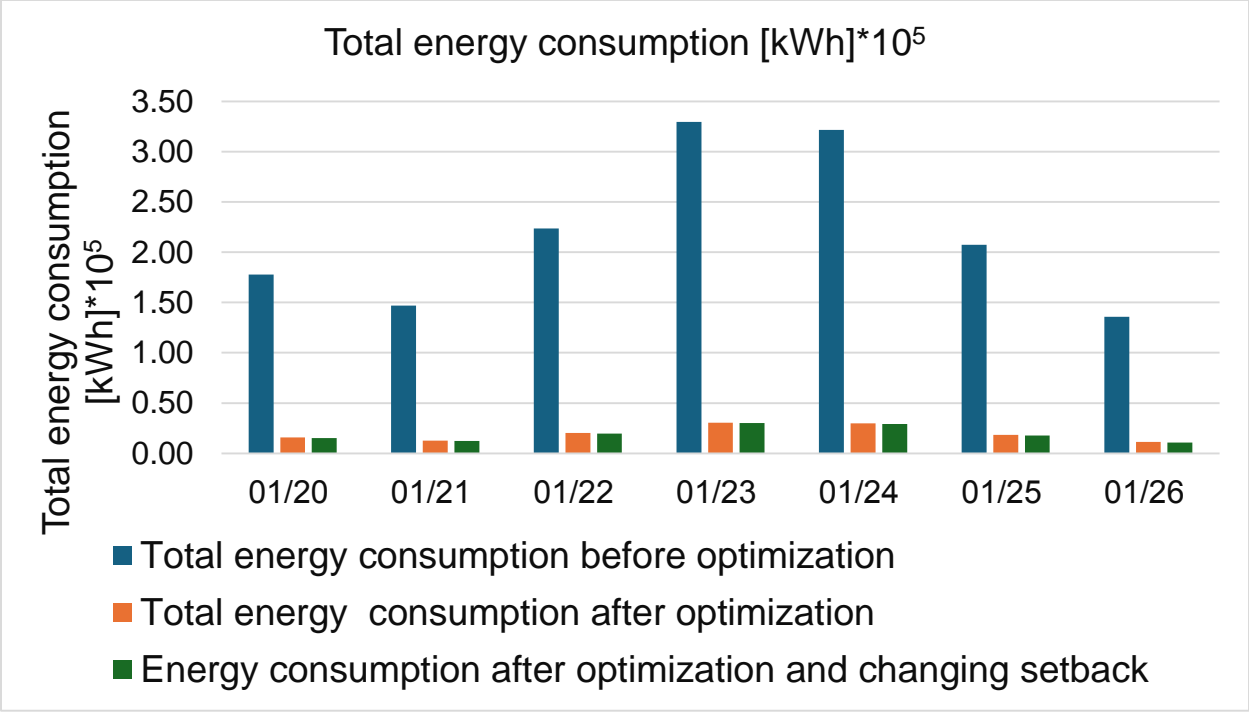


Figure 4.18 Comparison of the energy consumption in extreme days of winter before and after optimization.

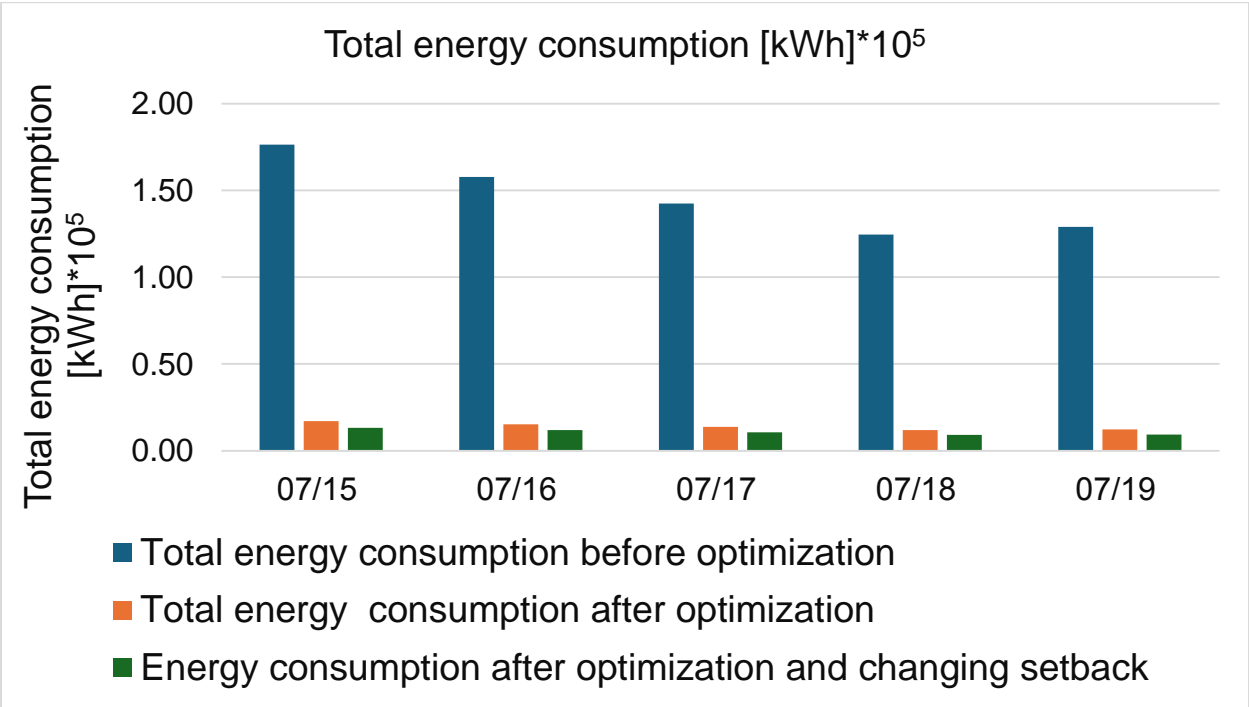


Figure 4.19 Comparison of the energy consumption in extreme summer days before and after optimization.

4.5. Insulation variables

In energy-efficient solutions, roof insulation and exterior wall insulation, particularly CertainTeed Fibreglass Batt Insulation, with a thermal conductivity of 0.043 and a thickness of 0.21 meter, is recommended, constituting 100% of Pareto solutions.

For floor insulation, CertainTeed Fibreglass Batt Insulation with a thermal conductivity of 0.043 and a thickness of 0.15 meters is highly recommended, constituting 76% of solutions. Additionally, Building Insulation Batt with a thermal conductivity rating of 0.045 and a thickness of 0.06 meters (6% of solutions), along with CertainTeed Fibreglass Batt Insulation featuring a thermal conductivity of 0.028 and a thickness of 0.025 meters (18% of solutions), are also suggested.

Furthermore, for roof insulation, CertainTeed Fibreglass Batt Insulation with a thermal conductivity of 0.043 and a thickness of 0.15 meters comprises 16% of solutions. Comfortbatt Insulation with a thermal conductivity of 0.037 and a thickness of 0.18 meters is the predominant choice (72% of solutions). Rigid Insulation with a thermal conductivity of 0.022 and a thickness of 0.05 meters (12% of solutions) is recommended.

Table 4.4 shows the construction of the selected walls, roof, and floors with selected insulation variables in the Pareto Front.

Table 4.4 Selected insulation variables are in the Pareto front during the construction.

| Wall 15 | Roof 11 | Roof 14 | Roof | Floor 14 | Floor 3 | Floor 13 |
|---|-------------------------------|---|-------------------------|---|----------------------------------|---|
| Finishing | Built-up roofing | Built-up roofing | Built-up Roofing | Structural slab | Structural slab | Structural slab |
| CertainTeed Fibreglass Batt insulation | ComfortBatt Insulation | CertainTeed Fibreglass Batt Insulation | Rigid insulation | Lean concrete | Lean concrete | Lean concrete |
| Exposed concrete walls. | Slopping concrete | Slopping concrete | Slopping concrete | Quartz stone | Quartz stone | Quartz stone |
| Rigid insulation | Structural slab | Structural slab | Structural slab | Cement topping | Cement topping | Cement topping |
| Plasterboard (Gypsum board) | | | | CertainTeed Fibreglass Batt Insulation | Building Insulation/ Batt | CertainTeed Fibreglass Batt Insulation |
| | | | | Wood floor | Wood floor | Wood floor |

Table 4.5 shows the characterization of selected insulation used to construct exterior walls, roofs, and floors of the Pareto front.

Table 4.5 Characterization of selected insulation variables in the Pareto front

| Name | Thermal conductivity(metric) | Thickness (m) |
|--|------------------------------|---------------|
| CertainTeed in the wall15 | 0.043 | 0.21 |
| CertainTeed Fibreglass Batt Insulation in Roof14 and Floor14 | 0.043 | 0.15 |
| ComfortBatt Insulation in Roof11 | 0.037 | 0.18 |
| Building Insulation/Batt on Floor3 | 0.045 | 0.06 |
| CertainTeed Fibreglass Batt Insulation in Floor13 | 0.028 | 0.025 |
| Rigid Insulation in Roof | 0.022 | 0.05 |

4.6. Windows variables

This section discusses the chosen windows in the Pareto front. Moreover, Table 4.6 outlines the characterization of windows in the Pareto front. The grammar is mostly correct, but the sentence can be clearer and more concise. Notably, since this project involves building energy retrofits, the window sizes cannot be changed, so they are not considered.

Table 4.6 Characterization of selected windows in the Pareto front.

| Name | Glass material | Gas | U-value (W/m²·K) | SHGC |
|--------------------------|--|------------|--|-------------|
| Window 5 | Insulated Dual Low-E SunDefense™ Low-E Insulating Glass Argon Non-High Altitude Upgrade To 6mm | Argon | 1.533 | 0.24 |
| Window 6 | Insulated Dual Low-E AdvancedComfort Low-E Insulating Glass Argon Non High Altitude Upgrade To 6mm | Argon | 1.305 | 0.31 |
| Simple window | Insulated Dual | Air | 2.669 | 0.7 |

8% of the proposed windows for the south sector with a 23-degree angle are double-glazed windows with a U-factor of 1.305 W/m².K, a 0.31 Solar Heat Gain Coefficient, and argon-filling gas, 18% of the selected windows for this side of the building are double-glazed windows with a U-factor of 1.533 W/m².K, a 0.24 Solar Heat Gain Coefficient, and argon-filling gas. Additionally, 74% of the proposed windows for those locations are double-glazed windows with air-filling gas, a U-factor of 2.669 W/m².K, and a 0.7 Solar Heat Gain Coefficient.

For windows in the East sector with a 23-degree angle, 24% of the chosen ones are double-glazed windows with argon-filling gas, a U-factor of 1.305 W/m².K, and a 0.31 Solar Heat Gain Coefficient. Also, 42% of them are double-glazed windows with air-filling gas, a U-factor of 2.669 W/m².K, and a 0.7 Solar Heat Gain Coefficient, and 34% are double-glazed windows with argon-filling gas, a U-factor of 1.533 W/m².K and a 0.24 SHGC. Concerning the rest of the windows in the East (straight ones), 24% are double-glazed windows with argon-filling gas, a U-factor of 1.533 W/m².K, and a 0.24 SHGC, 2% of the chosen ones are double-glazed windows with argon-filling gas, a U-factor of 1.305

W/m².K, and a 0.31 Solar Heat Gain Coefficient. The remaining 74% are double-glazed windows with air-filling gas, a U-factor of 2.669 W/m².K, and a 0.7 Solar Heat Gain Coefficient.

For the remaining windows in the south sector, 2% of the chosen ones are double-glazed windows with argon-filling gas, a U-factor of 1.305 W/m².K, and a 0.31 Solar Heat Gain Coefficient, 28% are double-glazed windows with argon-filling gas, a U-factor of 1.533 W/m².K and a 0.24 SHGC, and 70% are double-glazed windows with air-filling gas, a U-factor of 2.669 W/m².K, and a 0.7 Solar Heat Gain Coefficient.

For the north sector, 28% of those locations are double-glazed windows with air-filling gas, a U-factor of 2.669 W/m².K, and a 0.7 Solar Heat Gain Coefficient. Furthermore, 72% of the selected windows are double-glazed windows with argon-filling gas, a U-factor of 1.533 W/m².K, and a 0.24 Solar Heat Gain Coefficient.

For the west sector, 80% of the selected windows are double-glazed windows with argon-filling gas, a U-factor of 1.533 W/m².K, and a 0.24 Solar Heat Gain Coefficient. Additionally, 20% of the proposed windows for those locations are double-glazed windows with air-filling gas, a U-factor of 2.669 W/m².K, and a 0.7 Solar Heat Gain Coefficient.

Tables 4.7 and 4.8 provide all 50 solutions, along with their NPV and total energy consumption, the selected insulation for their roof, floor, and external walls, and the selected windows.

Table 4.7 NPV and Total Primary energy consumption of 50 solutions with their selected insulation for their roof, floor, and external walls

| Numbers of solutions | Net_Present_Value | Total_Primary_Energy | ExternalWall | Roof | Floor |
|-----------------------------|--------------------------|-----------------------------|---------------------|-------------|--------------|
| 1 | 13,258,695.69 | | Wall15 | Roof11 | floor 14 |
| | | 3,032,519.58 | | | |
| 2 | 13,247,794.34 | | Wall15 | Roof11 | floor 14 |
| | | 3,034,193.17 | | | |
| 3 | 13,225,155.79 | | Wall15 | Roof11 | floor 14 |
| | | 3,035,918.93 | | | |
| 4 | 13,202,522.19 | | Wall15 | Roof11 | floor 14 |
| | | 3,036,785.80 | | | |
| 5 | 13,197,981.13 | | Wall15 | Roof11 | floor 14 |
| | | 3,041,767.61 | | | |
| 6 | 13,162,170.19 | | Wall15 | Roof11 | floor 14 |
| | | 3,042,450.67 | | | |
| 7 | 13,139,349.39 | | Wall15 | Roof11 | floor 14 |
| | | 3,043,270.84 | | | |
| 8 | 13,133,746.30 | | Wall15 | Roof11 | floor 14 |
| | | 3,046,050.26 | | | |
| 9 | 13,111,120.95 | | Wall15 | Roof11 | floor 14 |
| | | 3,046,918.56 | | | |
| 10 | 13,105,970.65 | | Wall15 | Roof11 | floor 14 |
| | | 3,051,720.65 | | | |
| 11 | 13,083,263.23 | | Wall15 | Roof11 | floor 14 |
| | | 3,052,558.67 | | | |
| 12 | 13,052,065.81 | | Wall15 | Roof11 | floor 14 |
| | | 3,061,957.52 | | | |
| 13 | 13,052,065.81 | | Wall15 | Roof11 | floor 14 |
| | | 3,061,957.52 | | | |
| 14 | 12,940,842.25 | | Wall15 | Roof11 | floor 14 |
| | | 3,068,832.08 | | | |
| 15 | 12,940,842.25 | | Wall15 | Roof11 | floor 14 |
| | | 3,068,832.08 | | | |
| 16 | 12,917,360.63 | | Wall15 | Roof11 | floor 14 |
| | | 3,069,420.90 | | | |
| 17 | 12,913,208.35 | | Wall15 | Roof11 | floor 14 |
| | | 3,074,535.66 | | | |
| 18 | 12,889,661.69 | | Wall15 | Roof11 | floor 14 |
| | | 3,075,107.32 | | | |
| 19 | 12,889,661.69 | | Wall15 | Roof11 | floor 14 |
| | | 3,075,107.32 | | | |
| 20 | 12,849,710.55 | | Wall15 | Roof11 | floor 14 |
| | | 3,079,036.15 | | | |
| 21 | 12,849,710.55 | | Wall15 | Roof11 | floor 14 |
| | | 3,079,036.15 | | | |
| 22 | 12,826,200.52 | | Wall15 | Roof11 | floor 14 |
| | | 3,079,620.27 | | | |
| 23 | 12,821,540.43 | | Wall15 | Roof11 | floor 14 |
| | | 3,084,592.92 | | | |
| 24 | 12,798,024.43 | | Wall15 | Roof11 | floor 14 |
| | | 3,085,171.79 | | | |

| | | | | | |
|----|---------------|--------------|--------|--------|----------|
| 25 | 12,767,914.79 | | Wall15 | Roof11 | floor 3 |
| | | 3,094,390.16 | | | |
| 26 | 12,758,426.24 | | Wall15 | Roof11 | floor 14 |
| | | 3,101,814.63 | | | |
| 27 | 12,755,840.50 | | Wall15 | Roof11 | floor 13 |
| | | 3,102,554.21 | | | |
| 28 | 12,755,073.45 | 3,115,251.45 | Wall15 | Roof11 | floor 14 |
| 29 | 12,753,928.64 | 3,116,500.41 | Wall15 | Roof11 | floor 13 |
| 30 | 12,732,097.32 | 3,118,359.21 | Wall15 | Roof14 | floor 14 |
| 31 | 12,731,196.81 | 3,119,680.21 | Wall15 | Roof14 | floor 13 |
| 32 | 12,691,333.20 | 3,119,692.07 | Wall15 | Roof11 | floor 14 |
| 33 | 12,663,295.36 | | Wall15 | Roof11 | floor 14 |
| | | 3,125,291.98 | | | |
| 34 | 12,659,464.32 | | Wall15 | Roof11 | floor 14 |
| | | 3,128,952.34 | | | |
| 35 | 12,656,660.51 | | Wall15 | Roof11 | floor 14 |
| | | 3,132,897.23 | | | |
| 36 | 12,631,328.96 | | Wall15 | Roof11 | floor 14 |
| | | 3,134,535.31 | | | |
| 37 | 12,625,741.53 | | Wall15 | Roof11 | floor 3 |
| | | 3,141,962.17 | | | |
| 38 | 12,622,570.98 | | Wall15 | Roof11 | floor 13 |
| | | 3,143,197.46 | | | |
| 39 | 12,598,210.40 | | Wall15 | Roof14 | floor 14 |
| | | 3,158,856.19 | | | |
| 40 | 12,596,994.25 | | Wall15 | Roof14 | floor 13 |
| | | 3,160,086.09 | | | |
| 41 | 12,591,110.24 | | Wall15 | Roof14 | floor 14 |
| | | 3,166,362.62 | | | |
| 42 | 12,566,205.68 | 3,168,112.11 | Wall15 | Roof14 | floor 14 |
| 43 | 12,560,115.79 | | Wall15 | Roof14 | floor 3 |
| | | 3,175,421.75 | | | |
| 44 | 12,556,966.68 | | Wall15 | Roof14 | floor 13 |
| | | 3,176,664.21 | | | |
| 45 | 12,526,862.13 | | Wall15 | Roof | floor 14 |
| | | 3,212,137.40 | | | |
| 46 | 12,526,862.13 | | Wall15 | Roof | floor 14 |
| | | 3,212,137.40 | | | |
| 47 | 12,525,802.58 | | Wall15 | Roof | floor 13 |
| | | 3,213,417.75 | | | |
| 48 | 12,518,847.47 | | Wall15 | Roof | floor 14 |
| | | 3,219,406.86 | | | |
| 49 | 12,493,726.80 | | Wall15 | Roof | floor 13 |
| | | 3,222,674.87 | | | |
| 50 | 12,484,933.96 | | Wall15 | Roof | floor 13 |
| | | 3,229,814.69 | | | |

Table 4.8 Selected windows for all 50 solutions for all sides of the building

| Number s of solution s | SouthAngle | EastAngle | East | South | North | West |
|---------------------------------|-------------------|-------------------|---------------|-------------------|-------------------|-------------------|
| 1 | SimpleWindo w6 | SimpleWindo w6 | SimpleWindow5 | SimpleWindo w6 | SimpleWindo w5 | SimpleWindo w5 |
| 2 | SimpleWindo w6 | SimpleWindo w5 | SimpleWindow6 | SimpleWindo w6 | SimpleWindo w5 | SimpleWindo w5 |
| 3 | SimpleWindo w5 | SimpleWindo w6 | SimpleWindow5 | SimpleWindo w5 | SimpleWindo w5 | SimpleWindo w5 |
| 4 | SimpleWindo w5 | SimpleWindo w5 | SimpleWindow5 | SimpleWindo w5 | SimpleWindo w5 | SimpleWindo w5 |
| 5 | SimpleWindo w5 | SimpleWindo w6 | SimpleWindow5 | Simple window | SimpleWindo w5 | SimpleWindo w5 |
| 6 | SimpleWindo w6 | SimpleWindo w6 | Simple window | SimpleWindo w5 | SimpleWindo w5 | SimpleWindo w5 |
| 7 | SimpleWindo w6 | SimpleWindo w5 | Simple window | SimpleWindo w5 | SimpleWindo w5 | SimpleWindo w5 |
| 8 | SimpleWindo w5 | SimpleWindo w6 | Simple window | SimpleWindo w5 | SimpleWindo w5 | SimpleWindo w5 |
| 9 | SimpleWindo w5 | SimpleWindo w5 | Simple window | SimpleWindo w5 | SimpleWindo w5 | SimpleWindo w5 |
| 10 | SimpleWindo w5 | SimpleWindo w6 | Simple window | Simple window | SimpleWindo w5 | SimpleWindo w5 |
| 11 | SimpleWindo w5 | SimpleWindo w5 | Simple window | Simple window | SimpleWindo w5 | SimpleWindo w5 |
| 12 | SimpleWindo w5 | SimpleWindo w5 | Simple window | Simple window | Simple window | SimpleWindo w5 |
| 13 | SimpleWindo w5 | SimpleWindo w5 | Simple window | Simple window | Simple window | SimpleWindo w5 |
| 14 | Simple window | SimpleWindo w6 | SimpleWindow5 | SimpleWindo w5 | SimpleWindo w5 | SimpleWindo w5 |
| 15 | Simple window | SimpleWindo w6 | SimpleWindow5 | SimpleWindo w5 | SimpleWindo w5 | SimpleWindo w5 |
| 16 | Simple window | SimpleWindo w5 | SimpleWindow5 | SimpleWindo w5 | SimpleWindo w5 | SimpleWindo w5 |
| 17 | Simple window | SimpleWindo w6 | SimpleWindow5 | Simple window | SimpleWindo w5 | SimpleWindo w5 |
| 18 | Simple window | SimpleWindo w5 | SimpleWindow5 | Simple window | SimpleWindo w5 | SimpleWindo w5 |
| 19 | Simple window | SimpleWindo w5 | SimpleWindow5 | Simple window | SimpleWindo w5 | SimpleWindo w5 |
| 20 | Simple window | SimpleWindo w6 | Simple window | SimpleWindo w5 | SimpleWindo w5 | SimpleWindo w5 |
| 21 | Simple window | SimpleWindo w6 | Simple window | SimpleWindo w5 | SimpleWindo w5 | SimpleWindo w5 |
| 22 | Simple window | SimpleWindo w5 | Simple window | SimpleWindo w5 | SimpleWindo w5 | SimpleWindo w5 |
| 23 | Simple window | SimpleWindo w6 | Simple window | Simple window | SimpleWindo w5 | SimpleWindo w5 |
| 24 | Simple window | SimpleWindo w5 | Simple window | Simple window | SimpleWindo w5 | SimpleWindo w5 |
| 25 | Simple window | SimpleWindo w5 | Simple window | Simple window | Simple window | SimpleWindo w5 |
| 26 | Simple window | SimpleWindo w5 | Simple window | Simple window | Simple window | Simple window |
| 27 | Simple window | SimpleWindo w5 | Simple window | Simple window | Simple window | Simple window |
| 28 | Simple window | Simple window | SimpleWindow5 | Simple window | SimpleWindo w5 | SimpleWindo w5 |

| | | | | | | |
|----|---------------|----------------|---------------|----------------|----------------|----------------|
| 29 | Simple window | Simple window | SimpleWindow5 | Simple window | SimpleWindo w5 | SimpleWindo w5 |
| 30 | Simple window | SimpleWindo w5 | Simple window | Simple window | SimpleWindo w5 | SimpleWindo w5 |
| 31 | Simple window | SimpleWindo w5 | Simple window | Simple window | SimpleWindo w5 | SimpleWindo w5 |
| 32 | Simple window | Simple window | Simple window | SimpleWindo w5 | SimpleWindo w5 | SimpleWindo w5 |
| 33 | Simple window | Simple window | Simple window | Simple window | SimpleWindo w5 | SimpleWindo w5 |
| 34 | Simple window | Simple window | Simple window | SimpleWindo w5 | Simple window | SimpleWindo w5 |
| 35 | Simple window | Simple window | Simple window | Simple window | SimpleWindo w5 | Simple window |
| 36 | Simple window | Simple window | Simple window | Simple window | Simple window | SimpleWindo w5 |
| 37 | Simple window | Simple window | Simple window | Simple window | Simple window | Simple window |
| 38 | Simple window | Simple window | Simple window | Simple window | Simple window | Simple window |
| 39 | Simple window | Simple window | Simple window | Simple window | SimpleWindo w5 | SimpleWindo w5 |
| 40 | Simple window | Simple window | Simple window | Simple window | SimpleWindo w5 | SimpleWindo w5 |
| 41 | Simple window | Simple window | Simple window | Simple window | SimpleWindo w5 | Simple window |
| 42 | Simple window | Simple window | Simple window | Simple window | Simple window | SimpleWindo w5 |
| 43 | Simple window | Simple window | Simple window | Simple window | Simple window | Simple window |
| 44 | Simple window | Simple window | Simple window | Simple window | Simple window | Simple window |
| 45 | Simple window | Simple window | Simple window | Simple window | SimpleWindo w5 | SimpleWindo w5 |
| 46 | Simple window | Simple window | Simple window | Simple window | SimpleWindo w5 | SimpleWindo w5 |
| 47 | Simple window | Simple window | Simple window | Simple window | SimpleWindo w5 | SimpleWindo w5 |
| 48 | Simple window | Simple window | Simple window | Simple window | SimpleWindo w5 | Simple window |
| 49 | Simple window | Simple window | Simple window | Simple window | Simple window | SimpleWindo w5 |
| 50 | Simple window | Simple window | Simple window | Simple window | Simple window | Simple window |

4.7. NPV and optimization

Regarding the discussion of cost or NPV, as depicted in Figure 4.20, it is evident that for the 50 solutions, the cost is higher when the energy consumption is lower. The relationship between NPV and energy is vice versa. Therefore, the highest cost is \$13,258,695, while the lowest cost for solutions with the highest energy consumption in

the Pareto front is \$12,484,933. Notably, the NPV is calculated for the cost over 50 years. By utilizing various multi-objective optimization techniques, industries can choose the best option.

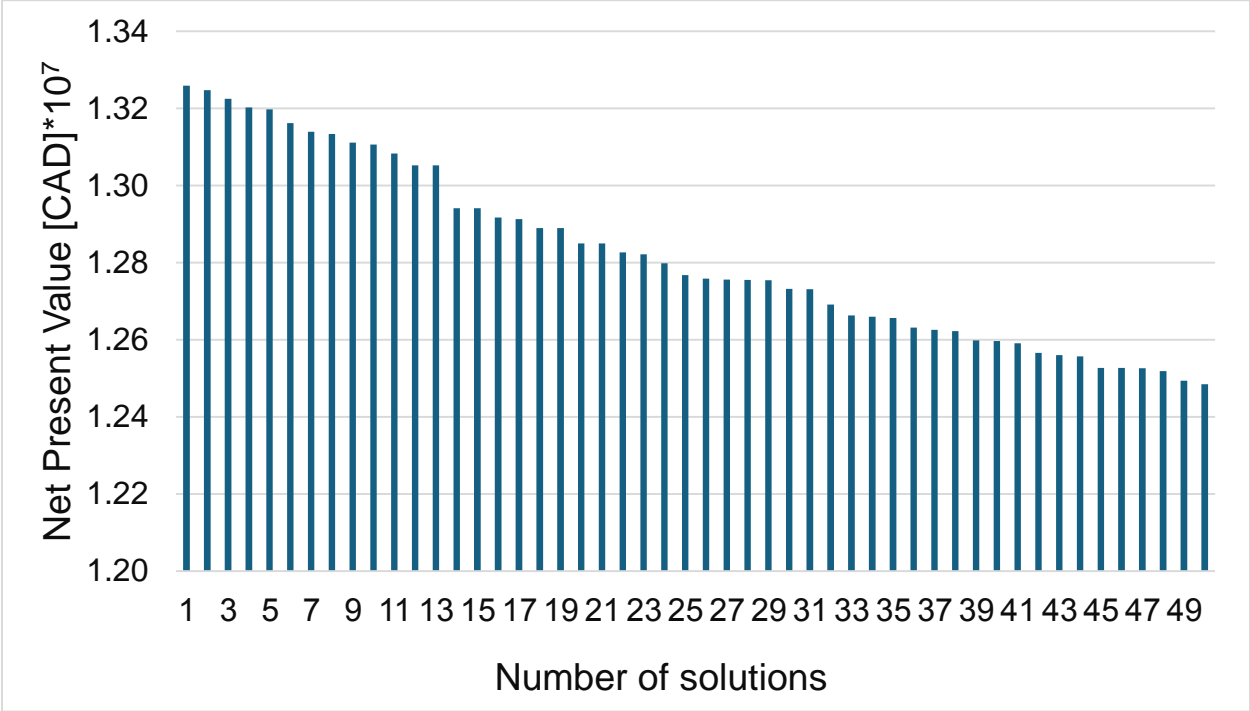


Figure 4.20 Comparison of NPV of the 50 solutions of Pareto front from the least energy consumption to the most.

5. Summary, Conclusions, Future Work

5.1. Introduction

This thesis presents a comprehensive simulation of the Montpetit Hall Building, accomplished using SketchUp, OpenStudio, and EnergyPlus software. Then, it suggests a simulation-driven approach to optimize multiple objectives in retrofitting buildings for increased energy efficiency and economic gains. By installing insulation in the walls, ceiling, and floor, modifying the windows, and setting the ideal heating and cooling setpoints and setback temperature. The optimization of variables was accomplished by utilizing MATLAB software with the NSGA-II algorithm. The optimization algorithm includes a feature to save results, keeping them for potential use in future iterations to prevent repetition. The outcome shows the 50 best solutions.

These measures have led to a reduction in energy consumption by 10-30% for one of the solutions. Certain months experience more substantial reductions of 24-48%, notably on extreme weather days where energy usage decreases by up to 27%. This optimization also positively impacts NPV due to its inverse relationship with energy usage.

- Chapter 3 provides details of the model's whole operation and the several input variables considered during the optimization process.
- In Chapter 4, four distinct features—dry-bulb air temperature ($^{\circ}\text{C}$), global horizontal irradiance (W/m^2), relative humidity (%), and wind speed (m/s)—were compared between actual and typical weather data, along with the outcomes of the entire optimization process shared and discussed between the optimum points.

5.2. Conclusions

This study examined insulation and window variables to evaluate two objective functions—achieving greater energy efficiency and optimizing the Montpetit Hall building. Twenty various insulating materials, seven different glass materials for the walls, roof, and floors, and seven distinct glass materials for the windows were chosen to find the optimal solution. The only goal of this study was to optimize the building envelope; the ideal air load system was intended to be designed into the HVAC system.

The figures and tables in Chapter 4 display assessments for one of the solutions, revealing that the total energy consumption after optimization will decrease by about 10%. It is noteworthy that during cold months, the total energy consumption for this examined solution decreases by 24%. Furthermore, when examining this solution by changing the summer setpoint and winter setback, total energy consumption in cold months can decrease by up to 48%. The second solution evaluated showed the lowest cost, with notable reductions in energy consumption, particularly in January, October, November, and December, achieving up to 12% savings post-optimization. By adjusting setpoints and setbacks, the savings in October increased to 42%. Additionally, overall energy efficiency improved by 90% after retrofitting and adjusting new setpoints and setbacks during extreme winter and summer days. For the third option, using the sum weight method, significant reductions in energy consumption were achieved, especially in January, October, November, and December, with up to 22% savings post-optimization. Adjusting setpoints and setbacks further increased energy efficiency to 47% in October, 31% in September, and 43% in May. Overall energy efficiency improved by 90% and 92%

during extreme winter and summer days, respectively. The two-dimensional Pareto front also illustrated the inverse relationship between NPV and total energy usage.

Additionally, based on these figures and tables, a range of solutions resulted from the optimization process with varying NPV and total energy consumption. This variety is an advantage of multi-objective solutions, allowing companies with a specific budget to make informed decisions and select the best solution for their needs. The conductivities of the six insulations that could be applied in single and double layers are 0.043, 0.037, 0.045, 0.028, and 0.022 W/m.K. Moreover, three types of glass with U-values of 1.533, 1.305, and 2.669 W/m²·K and SHGC values of 0.24, 0.31, and 0.7 are used to achieve maximum energy reduction.

Optimal solutions for industries can be chosen through multi-objective optimization techniques. Costs along the Pareto front range from \$12,484,933 to \$13,258,695, with NPV calculated over 50 years.

However, since the world is moving towards reducing carbon emissions and we need to make buildings net-zero, costs are aligned in this direction. Additionally, among the various objectives, cost is more important for the private sector, while energy consumption is more critical for the government. Since this building is educational and public, the best option is the one with the highest cost and the lowest energy consumption.

5.3. Limitations and future work

Recognizing certain limitations is essential as it sets the stage for future research. The following could be used to characterize this thesis's limitations:

- 1- The outcomes of energy retrofit projects are influenced by uncertainties such as global warming, changes in energy prices, and human behaviour during the building life cycle. These factors are beyond the immediate focus of this study and represent a limitation of the research.
- 2- —Secondly, while this study's findings may offer general guidance for similar buildings, the assumption of a constant HVAC system means further optimization is needed. Consequently, these results may not apply to structures for different purposes, construction technologies, and climates.
- 3- Thirdly, the analysis did not consider factors such as thermal comfort and indoor environmental quality. This limitation means the results may not fully capture all aspects of building performance across different climatic zones and building types. Therefore, this study's results may be limited, and further investigation is necessary to create a comprehensive guide by applying the proposed framework across various climatic zones and types of buildings.
- 4- Another limitation was the availability of data and information required for input into OpenStudio for geometry modelling and EnergyPlus for energy modelling. While some data were available from the University's Sustainability Office, other necessary data were not. In these cases, we had to rely on NECB standards instead of actual data.
- 5- This study used standard weather data to improve the accuracy of forecasts in the retrofitting process. While this approach accounted for seasonal patterns and resulted in more reliable results, it did not consider the potential impacts of climate

change. Consequently, the long-term effectiveness of the retrofit measures may be affected.

The following could be used to characterize this thesis's future works:

- Firstly, as many professionals in the construction and energy sectors may lack expertise in energy simulation, optimization, and programming, simplifying the framework into a user-friendly tool would make it more accessible and ensure widespread use.
- Also, Future research should compare solutions using various weather files, including those from abnormal years and projected weather patterns.
- Additionally, the current framework is notable for its efficient data storage system, allowing for better computational capabilities than traditional methods. This facilitates more in-depth studies, including the design of innovative sustainable buildings with additional design variables and complex case studies.
- Moreover, given the numerical nature of this study, it is possible to consider the HVAC system as one of the objective functions for optimizing the building's energy consumption system by incorporating additional factors in the retrofitting process.
- Finally, in the coming years, evaluating the integration of sustainable energy systems is valuable, particularly by installing solar panels on awnings and rooftops. These solar energy solutions have the potential to significantly decrease the building's dependence on non-renewable energy sources, supporting environmental sustainability and improving the overall energy efficiency of the structure.

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