Evaluating the Relation of BIM and 3D City Models for Energy Demand Assessment

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Abstract

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Climate change awareness and growing urban density drive worldwide demand for higher-performing buildings, prompting designers to pay greater attention to building efficiency. Determining the effects of a design change on a building's overall performance and analyzing how it can be affected by other buildings, is beneficial in the urban building modeling domain. This study intends to address a gap in the literature by establishing a way to measure a building's energy performance that considers the morphology of its surrounding network of buildings.

In this research, a single building is introduced as a case study among 3 different urban density contexts. Each scenario's effect on the target building's energy consumption is estimated and compared with the stand-alone condition. Moreover, several urban morphology indicators are measured for each scenario. The impact of each alternative on building performance was assessed by calculating monthly total energy consumption. The results show that shading due to the nearby buildings plays an essential role in energy demand throughout the year. Increasing the height of the surrounding buildings in winter increases the heating consumption by up to 11%, and a reduction in cooling by up to 37% is seen during summertime.

Therefore, building energy behavior analysis in urban planning can be the theoretical foundation for logical architecture design and energy consumption reduction when efficient cities are constructed. Moreover, the influence of other urban environmental factors, such as meteorological loads, Urban Heat Island (UHI) effects, or urban morphology, could be investigated for future studies.

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Abbreviations

2D Two Dimensional

3D Three Dimensional

ASHRAE American Society of Heating, Refrigerating, and Air-Conditioning Engineers

BCEE Building, Civil, and Environmental Engineering

BCR Building Coverage Ratio

BEM Building Energy Modeling

BES Building Energy Simulation

BIM Building Information Modeling

CAD Computer-aided Design

CEA City Energy Analyst

CityGML City Geographical Markup Language

EPW EnergyPlus Weather

EUI Energy Use Intensity

FAR Floor Area Ratio

GBS Green Building Studio

gbXML Green Building eXtensible Markup Language geoJSON Geographic Javascript Object Notion

GIS Geographic Information System

HDD Heating Degree Days

HVAC Heating, Ventilation, and Air Conditioning

IESVE Integrated Environmental Solution Virtual Environment

IFC Industry Foundation Class

JMSB Jhon Molson School of Business

LEED Leadership in Energy and Environmental Design

LoD Level of Detail

MBE Mean Bias Error

MEP Mechanical, Electrical, and Plumbing

MIT Massachusetts Institute of Technology

NBC National Building Code of Canada

NECB National Energy Code for Buildings

NURBS Non-Uniform Rational B-Splines

open-IDEAS open Integrated District Energy Assessment by Simulation

OSM Open Street Map

OTTV Overall Thermal Transfer Value

R&D Research and Development

RMSE Root Mean Square Error

SC Shading Coefficient

SGW Sir George Williams

SHGC Solar Heat Gain Coefficient

SVF Sky View Factor

TEASER Tool for Energy Analysis and Simulation for Efficient Retrofit

TMY Typical Meteorological Year

UBEM Urban Building Energy Modeling

UHI Urban Heat Island

UMI Urban Morphology Indicator

UMI MIT Urban Modeling Interface MIT

UrbanOPT Urban Renewable and Neighborhood Optimization

USGS United States Geological Survey

UWG Urban Weather Generator

VAV Variable Air Volume

VSC Vertical Sky Component

WWR Window-to-wall Ratio

Chapter 1

Introduction

Efficient buildings can produce economic benefits, reduce environmental impacts, and improve people's quality of life. Cities need to evaluate their current energy use and explore how to compare and contrast the results to propose strategies to reduce energy use and environmental impacts. This chapter explains the importance of buildings in global energy consumption and the interconnectivity between the building sector and the city scale. Moreover, this research's problem statements, objectives, and limitations are discussed.

1.1 Background

As urbanization continues to grow, more people are relocating from rural to urban regions, increasing strain on the city's energy infrastructure as energy resources gradually diminish. Planners and designers need to consider buildings as a component of the urban environment rather than as independent entities since this approach will help to create a more efficient and sustainable metropolis.

Urbanization is a socio-economic process shaped by spatial and urban planning and investments in building and infrastructure. According to the United Nations' World Urbanization Prospects [1], cities were occupied by 55% of the world's population in 2018, predicted to reach 68% by 2050 [2]. Urbanization, particularly mega-city expansion, is generally linked with higher energy consumption and greenhouse gas emissions. Due to the increased pace of urbanization, much of the demand generated by city growth has had to be supplied by more significant usage of fossil fuels, resulting in increased emissions and climate change [3]. As a result, municipalities are responsible for two-thirds of the global energy use and take care of 70% of the carbon dioxide (CO_2) emissions [2]. It emphasizes the significance of future energy use in urban areas.

Various studies have demonstrated that many aspects of cities and urbanization substantially impact energy use and must be considered when developing energy efficiency strategies and policies [3]. Manufacturing industries, transportation, and buildings are the three most significant sources of greenhouse gas emissions [4]. About 34% of the opportunities to increase energy productivity are in residential and commercial buildings. As shown in Figure 1.1, the low-cost emission reductions are the highest for the building sector, meaning that buildings have the most significant possibilities for cost-effective energy and carbon reductions compared to other industries [5].

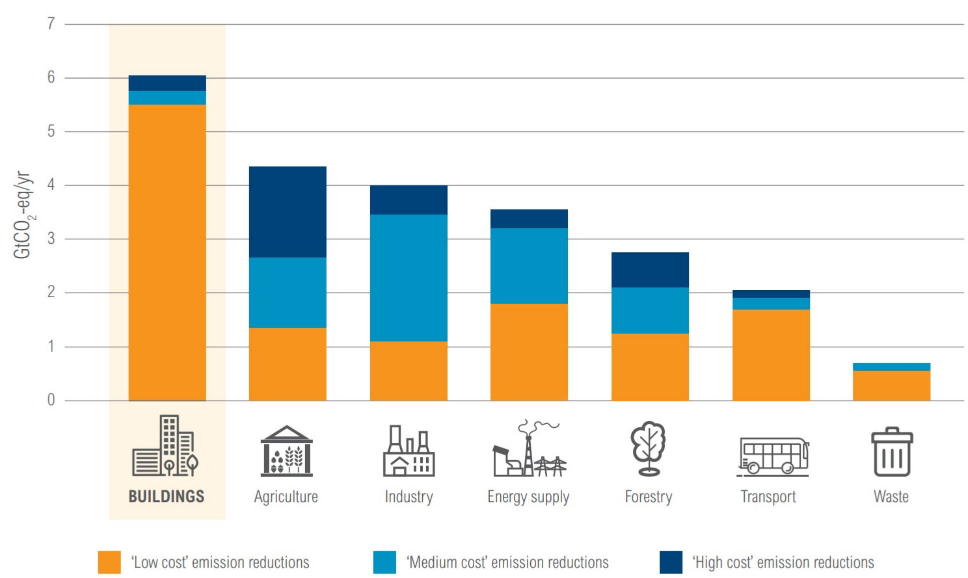


Figure 1.1: Possible Sectoral Economic Mitigation [5]

Buildings are responsible for about 30% of global energy consumption and 15% of CO_2 emissions. If indirect emissions from the production of power and heat are considered, this percentage doubles. Direct emissions from the building sector have increased by 0.5% per year since 2010, despite a progressive move away from fossil fuels due to a rise in the demand for energy services [6]. However, buildings have considerable potential for energy efficiency, both in new and existing buildings. With measures currently available today, the energy efficiency of buildings can be reduced by more than 50% over time. Renovation, improvement, or refurbishment of existing buildings can help to enhance energy efficiency in buildings. Accordingly, a considerable opportunity exists to create and transform cities into a more sustainable environment by improving building energy efficiency [2].

In recent decades, energy crises, rising prices, air pollution issues, and global warming have prompted stricter rules regarding the built environment's energy performance. Because of the problems mentioned earlier, studies in the domain of the construction industry are of interest and have excellent potential for improvement. The development concepts include flexibility, multi-functionality, involvement, and collaboration between buildings and users. Moreover, it is vital to consider different scales from components to systems, buildings, neighborhoods, cities, and territories [7].

Hence, smart cities need creative urban design and development solutions customized to the community's demands. As a result, decision-makers should work with micro-level (building scale) and macro-level (urban scale) simultaneously. This interconnectivity is beneficial in district facility improvements such as energy assessment. These two domains are considered separate scopes, and different information standards, tools, and data sources are deployed for each [8]. Figure 1.2 demonstrates two examples of the data sources for both macro and micro levels of information.

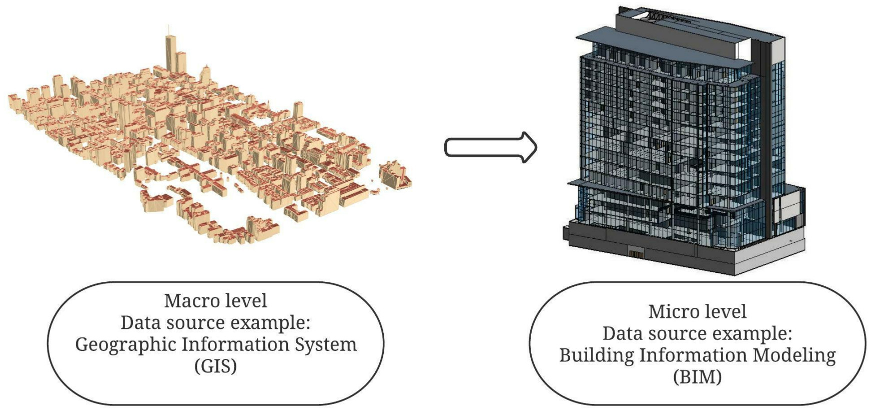


Figure 1.2: Different Information Levels

1.2 Problem Statement

Buildings are the central part of energy consumption globally. Therefore, the building industry has been noted as having significant potential to lower greenhouse gas emissions and improve energy efficiency through various methods and energy-efficient technologies [9]. One of the quickest and most affordable methods to reduce carbon emissions and enhance local economic growth, air quality, and public health is to increase the efficiency of buildings, particularly their energy use in the city context.

Cities with more energy-efficient buildings bring economic benefits, minimize environmental impacts, and enhance people's standard of living. Urban Building Energy Modeling (UBEM) has excellent potential to assist in designing and optimizing urban buildings regarding sustainability, energy efficiency, and resilience. Even though UBEM is gaining traction as an area with considerable and expanding interest, it faces some limitations and challenges regarding interconnected urban systems, big data, workflow, computing resources, and collaboration [2].

The interconnectivity between information from different scales is challenging, especially in the "smart cities" and "digital twins" era. For developments in UBEM, this collaboration across the macro-level (urban scale) and micro-level (building scale) are necessary. This requires information from facilities' design, construction, and operation phases, mainly buildings. Most of the time, these two levels of information are handled as different scopes, and other standards and tools are developed to fulfill each sector's needs. Integrating these two domains would be beneficial in creating a complete urban 3D model with detailed information from buildings [8].

To create a city with low carbon emissions, planners and designers must consider buildings as a component of the urban environment rather than independent entities. This relates to the logical prediction of regional space cooling/heating loads and the design of distributed energy resource systems [10]. However, simulating the energy demand for urban buildings is more difficult at the city size than at the building scale, primarily for three reasons [11]:

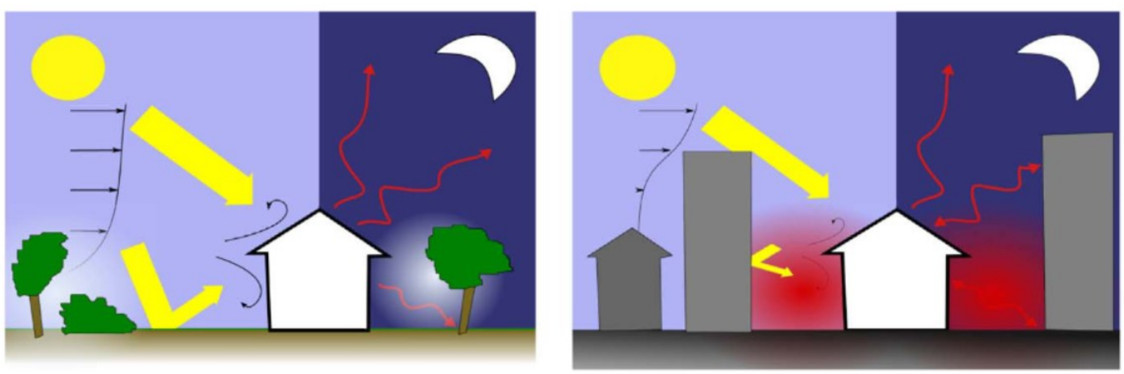
1. Due to the significant scale of the area analyzed, a considerable quantity of information regarding constructed structures (geometry, physical qualities of components, etc.) is required. And yet it is frequently unknown and challenging to gather the information precisely [12]. They must be determined through costly and time-consuming measurements and surveys.

2. The usage of systems and direct activities by occupants significantly influence the energy consumption of buildings. At a larger scale, such as a district level, the temporal variability of occupant behavior results in a difference between the maximal overall power demand and the sum of the individual peak power needs. Due to this variability, unique models based on in-depth research are required [13].

3. Buildings can not be expected to stand alone as is typically anticipated in Building

Energy Models (BEMs) due to the urban context. Urban environment influences on building energy requirements must be considered [14]. Still, external loads, such as meteorological loads, cannot be evaluated in general terms since they are unique to each building.

The meteorological loads on urban buildings and how they behave regarding energy depend on several factors. This includes obstruction and sheltering effects, surrounding surfaces, urban morphology, and the general Urban Heat Island (UHI) effects. Moreover, the general UHI effects depend on different parameters such as high thermal absorptance of urban materials, less evaporative cooling, additional human activity sources, and all the meteorological loads mentioned earlier in this paragraph [11]. Figure 1.3 compares these factors in urban and stand-alone conditions. Although the mentioned factors all have a considerable effect on the energy performance of the buildings, in this research, the main concern is the obstruction and sheltering effects.



(a) Stand-alone building (b) Urban building

Figure 1.3: Adjustments to an Urban Building's Energy Balance as Compared to a Stand-alone Building [11]

1.3 Research Goal and Objectives

Based on the previous research and the gaps from the related literature, the city and building sector scopes are usually considered two separate areas with different information standards, tools, and data sources. Therefore, the main goal of this research is to **find the differences between the building energy simulation outcomes under individual, stand-alone conditions and those under urban-scale situations**.

To reach this goal and to address the mentioned problems and gaps, the four main objectives of this research are:

1. Investigating the UBEM and BEM workflows, approaches, and tools; Elaborating on their advantages and disadvantages regarding the more accurate building energy simulation

2. Comparing and calibrating the Energy Use Intensity (EUI) from UBEM and BEM on a case study; Understanding their relevance and limitations in energy modeling

3. Finding out the impact of shading on the energy consumption of an individual building from nearby buildings under three different urban density scenarios

4. Figuring out the energy-related influence of using different window types on the case study building with and without the existence of the urban context

1.4 Assumptions and Limitations

While some energy simulation programs predict certain building performance factors, others, such as massing-based energy simulations, are intended to indicate a building's overall performance. Energy simulation systems need accurate data collection and assumptions to give precise findings. Generally, a complete set of inputs leads to more accurate results.

Even though energy simulation tools have become easier to use and more time-effective to run, they still take a long time to accomplish accurate results. A vast, underdetermined parameter space can result from the high number of parameters required to conduct an energy simulation for a building and the lack of architectural knowledge early in the design phase [15]. Assumptions are used to fill in the parameter space that is not entirely determined. Accurate assumptions provide accurate building performance simulations, which produce precise energy simulation findings that may be used as a basis for decision-making.

The outcomes of an energy simulation may be unreliable due to faulty assumptions or anticipated load levels. Sometimes, the modeler makes assumptions, but other times, the premises are "deterministic" in nature, which means that the energy simulation program makes such assumptions [16]. Accounting for the software's assumptions is tricky, but strengthening the modeler's assumptions and sharing and using data from earlier comparable projects already operating can help reduce this issue [17]. The general premises and limitations of this study are categorized below.

The assumptions:

1. Simplifying the building geometry in the urban energy models
2. Ignoring the under-ground levels (basements)
3. Sharing the same construction information, schedules, and loads for the surrounding buildings

The limitations:

1. Utilizing some unpopular tools regarding their expenses and the system requirements
2. Generating possible inconveniences caused by using different tools and engines; Working with incompatible workflows could result in data loss or faulty outputs
3. Limited access to some geometrical and non-geometric characteristics of the buildings

1.5 Organization of the Thesis

The outline of this thesis is as follows. Chapter 1 is the introduction. This chapter starts with a brief background on urbanization and energy-efficient buildings and their potential. The following section is the problem statement regarding UBEM, BEM, and their challenges. In addition, the main goal and the four different objectives are introduced in Section 1.3. The assumptions and limitations are also discussed in this chapter. Chapter 2 summarizes the literature about sustainable low-carbon cities, UBEM, BEM, and their integration. The literature gaps are also mentioned in Section 2.6. Chapter 3 introduces this study's framework and the steps of the developed method. Data preparation in boundary selection and geometry fixation is comprehensively described in section 3.4. Moreover, building description, building envelope, Heating, Ventilation, and Air Conditioning (HVAC) systems, building schedules, and weather data are discussed in Chapter 4. The results and discussions about different objectives are mentioned in Chapter 5. In the last section of this chapter. Finally, the summary and impacts of this research and the limitations are proposed in Chapter 6.

Chapter 2

Review of Related Literature

This chapter summarizes the related literature in different criteria, including urban building energy models, building energy modeling, shading influence, and window-type studies on the energy consumption of buildings. Building energy modeling tools, approaches, and workflows are also described on city and building scales. This comprehensive review of the related works finishes with a literature gap summary which inspired this research to propose the methodologies and outcomes.

2.1 Sustainable Low Carbon Cities

An incredible expansion of the built environment will result from rapid urbanization occurring throughout much of the world. The decisions will impact decades of urban services and livability in constructing, designing, and running buildings. Productive, high-performing, and efficient buildings will be crucial in developing sustainable cities, which will help achieve regional and global sustainable development goals [5].

Buildings and their energy use account for many greenhouse gas emissions contributing to climate change. Under a business-as-usual scenario, these emissions will continue to rise. As fossil fuel supplies decrease and the impact of greenhouse gases on the environment grows, it is critical to design buildings with low loads, high efficiency, and as many renewable energy sources as feasible. In order to maximize the performance of a building, the user can assess different energy-saving strategies and determine the ideal combinations of architectural elements by using energy modeling approaches [5].

The purpose of sustainable design is altogether to remove harmful environmental effects through intelligent and attentive design. Sustainable design manifestations employ renewable materials, have a less negative environmental impact, and foster a sense of connection between humans and nature. As illustrated in Figure 2.1, the benefits of a more sustainable built setting could be less adverse effects on the environment, health and comfort of building inhabitants, reduced use of non-renewable resources, reduced waste, and the creation of a healthy, productive ecosystem.

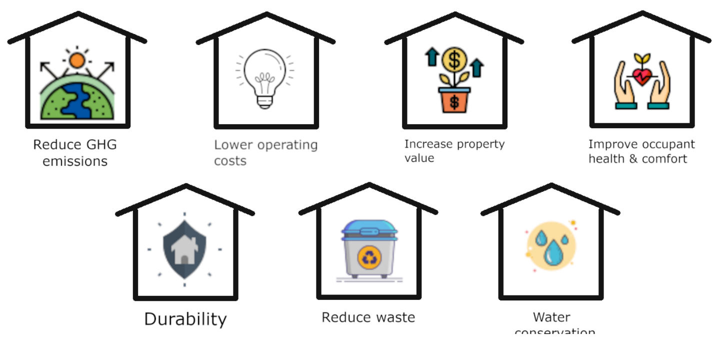


Figure 2.1: Benefits of Sustainable Design

The idea of sustainability in buildings is supported by various factors, including environmental, economic, social, ecological, technical, and technological aspects [18]. Net-zero energy buildings are becoming more and more popular among academia and industry. And due to its importance, many cities have applied regulations and targets toward a more sustainable municipality.

However, building efficiency has numerous obstacles in the scale of cities and governments, which can cause investment priorities to shift away from efficiency. Market, economic, technological, organizational, and awareness-related barriers might limit or discourage people from investing in efficiency. Policies that make pursuing building efficiency a viable option by aligning the interests of all actors at each stage of a building's lifecycle can assist in removing these obstacles. There are eight categories in which local governments might choose to increase the built environment's energy efficiency [5].

(1) Standards and Codes for Efficient Construction

Codes and standards have the potential to significantly reduce energy costs throughout a building's lifecycle when properly planned and executed.

(2) Goals for Efficiency Improvement

To reduce energy use, local governments can set targets that can be applied to their own publicly owned or rented building stock or at the level of the entire city's community.

(3) Certifications and Performance Data

This action allows building managers, owners, and tenants to decide on energy management strategies with knowledge.

(4) Finance and Incentives

They include subsidies and rebates, funding for energy-efficient bonds and mortgages, tax incentives, and priority handling for removing economic obstacles for energy efficiency projects.

(5) Government Leadership by Example

It entails actions made by the government in the form of projects and laws that set a higher standard for market acceptance and demand for energy-efficient buildings.

(6) Engagement of the Owner, Manager, and Tenants of Private Buildings

This includes technical programs, advice, and behavioral tools like competitions and incentives encouraging building stakeholders to form a local partnership for energy-efficient buildings.

(7) Engagement of Technical and Financial Service Providers

Through this interaction, business models and capabilities may be developed more quickly to fulfill the demand for efficiency.

(8) Working with Utilities

Energy usage data can be made more accessible through collaboration with utilities, which can also help them in their mission to help customers use energy more wisely.

2.2 Urban Building Energy Modeling

Urban modeling is an interdisciplinary platform in which city-related fields such as urban planning, civil engineering, transportation, environmental science, economics, and so many others meet computer science to create models in the context of urban spaces [2].

Since the early 1960s, whole-building energy modeling techniques have been used in the design phase to assess buildings' thermal behavior and energy consumption to determine the best design for the building envelope and Heating, Ventilation, and Air Conditioning (HVAC) systems, as mentioned by Waltz [19]. They have recently begun to be employed in the post-occupancy stage for commissioning and energy conservation evaluation. Software tools for simulating energy have undergone significant changes and updates due to technological advancement. To construct a model that closely simulates reality, users must have a comprehensive grasp of the simulation software tools and the physical parameters of the building and the HVAC systems. Their complexity and accuracy have increased over the years.

UBEM is the computational modeling and simulation of a group of buildings' performance in an urban setting, taking into account not only the dynamics of individual buildings but, perhaps more importantly, the effects of other buildings on one another within cities [2]. UBEM tools can significantly improve how well the multidisciplinary components of energy concerns are integrated into the urban planning process. UBEM is frequently used for scenario analysis of technology's potential for energy savings and comparing energy consumption between various urban forms, optimization of energy, and supply and demand management [20].

There are numerous application areas for urban energy modeling. Urban-level energy analysis depends on enhanced geometric and geo-data modeling capabilities, increased accessibility and quality of spatial and non-spatial data, and advancements in these areas [21]. This section focuses on a brief literature review of the urban building energy models, approaches, and popular tools in academia and industry.

2.2.1 UBEM Approaches

The literature generally defines two ways to solve urban energy issues: top-down and bottom-up. Top-down models relate energy consumption to features of the overall housing sector by utilizing estimates of total residential sector energy consumption and other relevant factors. Bottom-up models, in contrast, estimate the energy consumption of a single house or a collection of households and then extend these figures to represent a region or a country [22].

A top-down strategy is often data-driven, with statistical and regression models incorporating building stock data, technology adoption models, and economic models to give high-level building energy policy evaluation and scenario analysis and a roadmap for technology Research and Development (R&D) . Bottom-up approaches, on the other hand, use fully complete dynamic building physics modes (white box), reduced-order dynamic models (grey box), or data-driven models to represent building subsectors or individual buildings (black box). A particular modeling technique often calls for more data to be fed into the UBEM and much more computational power. In summary, the bottom-up approach has been acknowledged as suitable for urban and regional analysis. In contrast, the top-down approach has been considered ideal for large-scale analysis and not for identifying potential improvements in the building sector [2].

For the bottom-up techniques, two distinct strategies are discovered depending on how energy consumption is measured, as illustrated in Figure 2.2. The statistical models, commonly called data-driven models, assess the energy consumption of buildings using data mining and machine learning methods. While the engineering or physics-based models use a thorough thermal characterization to determine how much energy is operated by a building [23].

To estimate energy consumption, simulation-based engineering models combine building, climatic, system data, thermodynamic principles, and simulation tools [24]. The engineering method models energy demand based on the science of building physics and requires precise building characteristic data as model inputs, such as occupancy profile, thermostat setting, air infiltration rate, etc. The most significant benefit of this modeling approach is the ability to generalize and predict system behavior under previously unobserved conditions. As a result, it is frequently used to evaluate and quantify the effects of retrofit measures, future climate scenarios, new technologies, or to support policy making.

Research on physics-based bottom-up urban building energy models may simulate different buildings separately, concentrate on microclimate effects (such as UHI), or combine these two approaches while adjusting the UBEM to consider the microclimate effects. These effects could include shadowing from nearby objects, higher urban temperature due to the UHI effect, and long-wave radiation from neighboring buildings [25]. Aside from this significant statement, this approach is independent of the historical data, calculates the energy consumption for various end uses, and is flexible in using Building Information Modeling (BIM) software tools [24]. The mentioned advantages make simulation-based engineering models the preferred method for this study.

However, this strategy has the drawback of requiring more processing than a statistical approach. The required inputs might vary significantly and may include hundreds of parameters, depending on the modeling objectives and how complicated the underlying calculations or simulation engines are [26]. Common difficulties with this approach are accessibility, quality, resolution, and unpredictability of the model inputs [12]. Also, the urban and human-related simplification and the intensive time-consuming computational simulations are other limitations to this approach [24].

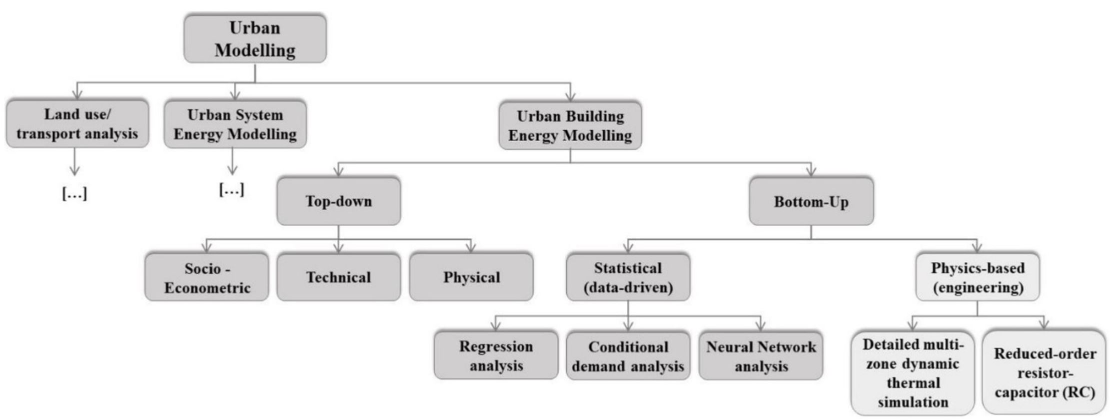


Figure 2.2: UBEM Approaches [23]

2.2.2 UBEM Tools

Different studies comprehensively reviewed UBEM tools in various criteria, including calculation approaches, data formats, and computing platforms [23, 2, 27, 28]. Only the bottom-up physics-based tools designed especially for urban applications and used in various case studies are covered in this review. They enable physics-based detailed simulation of the building stock. Some of the essential tools are introduced and explained in this section. Later, they will be summarized in Table 2.1 according to their release year, approaches, and calculation methods.

In 2009, a decision support tool called CitySim was introduced for urban energy planners to reduce energy consumption and emissions [29]. Based on an equivalent electrical circuit, CitySim's thermal model can consider building subspaces by connecting them with conductance from separating walls. A few years later, in 2013, an urban energy modeling platform, SimStadt, was created to aid the planning of the energy transition at the urban scale [30]. It enables the quick generation of evaluation scenarios utilizing priority indices, time horizons, and refurbishment rates using CityGML [31]. The same year, the Urban Modeling Interface (UMI) for energy performance analysis of neighborhoods was released by the Massachusetts Institute of Technology (MIT) [32]. It was created to evaluate daylighting, outdoor comfort, transit options, and sustainable food production at the neighborhood and city scales. The tool makes use of the Computer-aided Design (CAD) modeling software Rhinoceros® [33]. It is integrated with the Urban Weather Generator (UWG) tool, which considers the effects of urban weather, and Daysim, which accounts for daylight analysis. The web-based data and computing tool, CityBES, was released in 2015 as a platform capable of simulating large-scale building energy performance [34]. The primary use cases of this tool are energy benchmarking, urban energy planning, energy retrofit analysis, building operational management, assessment of solar PV potential, and visualization of urban microclimate [35]. The same year, the open Integrated District Energy Assessment by Simulation (open-IDEAS) was released as an open-source Modelica-based framework [36]. Later in 2016, City Energy Analyst (CEA) , a python-based simulation tool, was released to perform the energy simulation and compare the scenarios directly [37]. Also, in 2016 another program, Urban Renewable and Neighborhood Optimization (UrbanOPT) was introduced [38]. This tool simulates the energy performance of low-energy districts and offers the option for district heating and cooling systems. It relies on EnergyPlus to carry out extensive energy modeling at the level of each building using the OpenStudio platform. Finally, the last tool mentioned in Table 2.1 is the Tool for Energy Analysis and Simulation for Efficient Retrofit (TEASER) [39]. TEASER is another Python-based tool that combines the UBEM and the urban simulation to thoroughly characterize urban energy systems, including distribution, and represent the built environment at the city size.

Even though many additional tools are already in existence or are currently being developed, this study primarily focuses on those that use EnergyPlus as its simulation engine and are compatible with the information gathered from the sources used for the case study of this research.

Table 2.1: Different UBEM Tools

Tool	**Year**	**Approach**	**Calculation method**
CitySim	2009	Physics-based dynamic simulation method	CitySim solver
SimStadt	2013	Reduced-order calculation method	ISO/CEN standards based reduced-order model
UMI	2013	Physics-based dynamic simulation method	EnergyPlus
CityBES	2015	Physics-based dynamic simulation method	EnergyPlus
Open-IDEAS	2015	Reduced-order calculation method	Modelica based reduced order model
City Energy Analyst	2016	Reduced-order calculation method	Tool specific calculation modules
URBANopt	2016	Physics-based dynamic simulation method	EnergyPlus and Openstudio
TEASER	2018	Reduced-order calculation method	Modelica based reduced order model

2.3 Building Energy Modeling

As discussed earlier, the building sector has a significant potential to reduce energy consumption and greenhouse gas emissions by increasing building energy efficiencies, such as by requiring appropriate retrofit measures and planning for net-zero emission buildings and urban districts [40]. Therefore, energy models play an essential role. 3D city models appear to have been primarily utilized for visualization throughout the past few decades. Still, they are increasingly used in various fields and for purposes other than visualization.

BEM involves developing architectural and energy models using computer software to forecast energy usage and enhance building efficiency when occupied. Building owners and operators can identify and diagnose inefficient or broken-down equipment by comparing the expected and actual energy use [41]. Building Energy Simulation (BES) also calculates heat exchanges between various building components and forecasts how energy systems will behave to give comprehensive building energy assessments. The BES has the following scales: the micro-scale refers to building components (systems, façade elements, etc.), and the macro-scale relates to the building itself.

Even though BEMs may simulate building components' behavior and serve as the foundation for explicit urban power modeling, typical BES is not appropriate for the district- or urban-scale simulations. BEM requires upgrades or couplings to incorporate urban influences on urban building energy demand because they were initially developed for stand-alone buildings. Later in this chapter, a few examples from the literature demonstrate how BES was mainly utilized to estimate the energy consumption of a single, frequently hypothetical structure in an urban setting to uncover broad patterns instead of actual case studies. The surrounding buildings are often considered barriers without specifically modeling their thermal characteristics. BES's tools are not intended to model several buildings while fully accounting for their interactions with one another. Performing BES at the urban scale would necessitate a significant computing effort due to the successive computations and coupling procedures.

BES software tools can be expanded to various domains, such as the impact of morphology and urban surroundings on building energy behavior. A few research studies used BESs parametrized with locally generated or recorded meteorological data for a generic building [42, 43, 44, 45].

2.3.1 Building Information Modeling

BIM is a parametric, virtual building model that can store embedded project data [46]. There are several advantages to employing BIM in the building process, some of which improve a project's overall energy efficiency. BIM offers designers the chance to perform clash detection to make sure Mechanical, Electrical, and Plumbing (MEP) plans do not intersect, to carry out quick and accurate quantity takeoffs for estimating, and to extract and analyze large amounts of data about a building design so that designers can base their decision-making process on this information, among other advantages [47]. One significant advantage of keeping data in BIMs is that it may be used to support energy simulations, which are computer analyses that forecast how much energy a design would need. The benefits of using BIM and some possible limitations regarding its implementation in the industry are listed below [47].

The advantages:

1. Automation of energy modeling
2. Storing and organizing buildings' data
3. Better presentation of energy-related outputs
4. Coordination and collaboration
5. Faster drafting without loss of cost and quality
6. Easy maintenance during the lifecycle
7. Schedule and cost optimization
8. Flexibility and customization
9. Risk mitigation and conflict detection

The barriers:

1. Interoperability issues

2. Lack of BIM standards

3. Errors and accuracy issues

4. stakeholder reluctance

5. Time constraints

6. Lack of skilled personnel

7. Organizational issues

The quantities and qualities of building elements, spatial linkages, geographic data, cost projections, material inventories, and project timetables are all represented by BIMs [47]. Users implementing BIM software may quickly create and update geometric models [48]. Contrary to drafting software like AutoCAD, BIM makes it possible to finish drawings more quickly, uses parametric modification technology, and may include vital information in the model [49]. Because BIM can keep and update data about a building throughout the design process, which can then be retrieved and evaluated to enhance decision-making [49], there is a great potential to use the information continued in these models to inform energy simulations.

The costly, laborious process of performing simulations may be made more accessible using BIM-based energy simulation tools [50]. Building performance metrics of a structure may be continually assessed during the design process when BIM software is combined with energy simulation software, ensuring that performance objectives are maximized [51]. Building designers may select a design that maximizes functionality, affordability, and performance by using BIM-based energy modeling, which enables users to quickly forecast several methods' performance quickly [52].

The preparations for data input frequently contain costly and severe errors, such as those involving building geometry and material properties [53]. Additionally, from the perspective of the architect and designer, the majority of the BEM tools are either unsupportive as a design tool or complex in terms of design requirements [54]. Despite being widely employed in their respective industries, BIM and BEM are nonetheless distinct from one another in this regard. Up until recently, the integration of BIM between the many disciplines has received increasing attention by offering a single 3D CAD model containing all pertinent data that can be easily transferred to various function-specific software. Having more situations to consider improves BEM performance by making data input easier. To decrease the complexity and time required to redo the model and modify the simulation parameters on BEM, the data associated with a BIM file can be readily exported as input for the BEM file [55].

2.3.2 BEM Tools

Software tools for simulating energy are gradually becoming more prevalent on the market. While some of these applications are open source, some are commercial. These tools are, however, slightly applied in business or study. Based on the general characteristics of the computer programs, the simulation engine, the performance requirements, and the key advantages and disadvantages, a short list of the most popular BEM tools among the examined articles have been compiled. In Table 2.2, the input data, simulation engine, and selected studies are defined for each computer program.

Table 2.2: BEM tools

Tool	Input data	Simulation engine
DesignBuilder	gbXML, dxf, pdf, bmp, jpg	EnergyPlus Radiance
Green Building Studio (GBS)	gbXML enabled BIM or 3D CAD	DOE 2.2 EnergyPlus
eQuest	gbXML, dwg, dxf	DOE 2.2
IES – Virtual Environment	gbXML, dxf, dwg	Self Radiance
OpenStudio	gbXML, IFC	EnergyPlus Radiance

Architects, engineers, and energy consultants utilize these tools to study and optimize building designs, assess energy-efficient technology, and reach well-informed conclusions regarding the systems and operations of buildings. Which BEM tool is used relies on several variables, including the project's type, the user's skill level, the information available, and the budget. There isn't one BEM tool that is the best or ideal for every project or user. Each tool has strengths and weaknesses; the best depends on the project requirements.

Design Builder is a complete BEM tool with an easy-to-use user experience that combines well with computer programs like SketchUp. It offers a selection of energy, lighting, and thermal comfort analysis options. HVAC systems and controls and renewable energy systems like photovoltaic and solar thermal systems may all be modeled in detail using Design Builder. Like Design Builder, eQuest provides a powerful simulation engine that permits accurate modeling of HVAC systems and supports renewable energy sources. It is a powerful BEM tool intended for larger, more complex constructions.

The IESVE is a comprehensive application that gives various analysis choices for energy, lighting, and thermal comfort, making it one of the most desirable tools in the industry. It comprehensively models HVAC systems, renewable energy sources, daylighting studies, and thermal bridging. It is probably one of the most comprehensive tools for engineers and energy consultants. On the other hand, the GBS , is a web-based energy application that enables users to assess the environmental impact of particular building components early in the design process. Energy and thermal analysis, lighting and shading analysis, and cost assessments are some of the software's main analytical features. The energy and thermal analysis examine energy use, carbon emissions, ventilation, and airflow. GBS is based on an online automated procedure with detailed instructions and minimal preparation requirements. The built-in gbXML error checking of GBS helps to reduce the fallacies in creating energy models. The convenient user interface and the accelerated analysis for LEED compliance are other advantages of this software. On the other hand, GBS has several limitations, including issues with large files or challenging integration of gbXML data to the online database. Also, regarding the HVAC systems, GBS is shown not to be as compatible [56].

The cloud-based tool created for quick conceptual modeling of buildings. It provides a simplified user interface and requires minimal data to construct a model. It does not, however, provide sophisticated HVAC systems or control modeling and is primarily intended for early-stage design study.

Table 2.3: BEM tools' strengths and weaknesses

Tool	Strenghts	Weaknesses
DesignBuilder	User-friendly interface Easy geometry creation detailed HVAC modeling Renewable energy modeling Integration with other software	Commercial, license fee Limited daylighting, thermal bridging, and alternative HVAC systems
Green Building Studio (GBS)	Simplified interface Cloud-based Quick results Integration with Autodesk Optimization capabilities	Limited analysis capabilities Limited customization
eQuest	Robust simulation engine detailed HVAC modleing Customizable Open-source	Difficult-to-use interface Limited support for some analysis limited integration capabilities
IES – Virtual Environment	Comprehensive analysis capabilities Customizable Comprehensive weather data Global/North American compliance	Difficult to use Expensive Resource-intensive
OpenStudio	Free and open-source Easy-to-use interface Extensive library of building components	Limited support of advanced modeling Limited optimization capabilities Limited technical support

Table 2.3 summarizes these tools' strengths and weaknesses. Eventually, it is crucial to assess the capabilities and characteristics of each tool and choose the one that best suits the project's needs. Furthermore, it is critical to guarantee that the user has the necessary knowledge to operate the chosen tool efficiently. While selecting a BEM tool, training and support resources should be considered to ensure the user can provide accurate and reliable results.

2.4 Shading Analysis

Aside from building and thermal features, the urban context influences the accuracy of urban energy modeling. It has been demonstrated that interactions between the city and the individual buildings affect the precision of operational energy use estimates at both the building and urban scales.

BES computer programs could be developed to examine the influence of urban surroundings on building energy behavior. Extending the BES approach, energy models are combined with an urban canopy model to investigate the relationships between urban building energy demand and urban climate. Models are generated for a typical building rather than a specific one in this method to establish its overall impacts on the urban environment and feedback on its energy consumption [11]. The shade of the façade, the solar reflectance of the surrounding buildings based on albedo, and the irradiation on the façade all contribute to the building's solar gain potential. The daylighting performance is significant for office buildings with high lighting consumption and where lighting conditions heavily influence staff productivity [57].

A study in 2021 [58] investigated the impact of nearby shade against solar radiation on the annual heat gain as well as the Overall Thermal Transfer Value (OTTV) of buildings constructed in a group at the same time. The results showed that for 14 multi-block building developments, the annual heat gain between cases with and without adjacent shading effect could differentiate from 4.96% to 43.58%. In a different study, the thermal load of conditioned office buildings in a city with a hot and humid climate was examined concerning the geometry of the urban environment. Based on the results, it was concluded that the geometry of the urban environment could not be disregarded in computational heat transfer simulations of buildings in urban settings, particularly about the floors that are closest to the ground, where it was found that taking the geometry into account resulted in a reduction of the cooling load of up to 29%. According to the study, the denser and more vertical contexts used less energy. The investigation demonstrated the significant impact of urbanization and verticalization on a decline in building energy demand in the climate studied due to shading [59]. Using a parametric method, a study from 2021 forecasted the effect of shadowing on building energy from surrounding buildings. Seven Chinese cities in four thermal climatic zones are used as the building morphology and block simulation cases. The findings show that the impact of shade varies greatly depending on the circumstance and that in particular places, cooling loads can be overestimated by up to 45%, and heating loads can be underestimated by up to 21% [10].

As was reviewed in the literature, various factors influence the effect of the urban context. Building orientation for instants is essential, mainly concerned with solar radiation, shading area, and wind field in a community [60]. The ratio of building height to street width (H/W) is another Urban Morphology Indicator (UMI) . In a study by [61], a 10% difference in dry-bulb temperature is caused by two different H/W numbers. This factor is highly associated with thermal comfort in urban street canyons. As a result, there are typically restricted regulations regarding respecting a desired ratio of H/W in municipalities. Another aspect is the Sky View Factor (SVF) , which is considered an indicator of varying community forms to illustrate the shading effect on the mean radiation temperature [62, 63].

Regarding the relationship between the building and the open area in a district, two factors are usually mentioned in the studies, the Floor Area Ratio (FAR) and the Building Coverage Ratio (BCR) . As shown in Figure 2.3, FAR is the ratio of the built area to the lot area, while BCR indicates the relationship between the ground floor area of the enclosed buildings and the size of the lot. The FAR, the floor space index or plot ratio, represents compactness or urban density [64]. The link between FAR and daylight penetration in neighborhoods was highly negative regarding the vertical daylight factor, also known as Vertical Sky Component (VSC) . However, there is a significant relationship between solar potential and FAR. The same study [63] claims BCR is a closely related morphological geometric indicator to FAR. The BCR metric is also a measure of built urban density. The study demonstrated that BCR corresponds with façade irradiation levels and positively

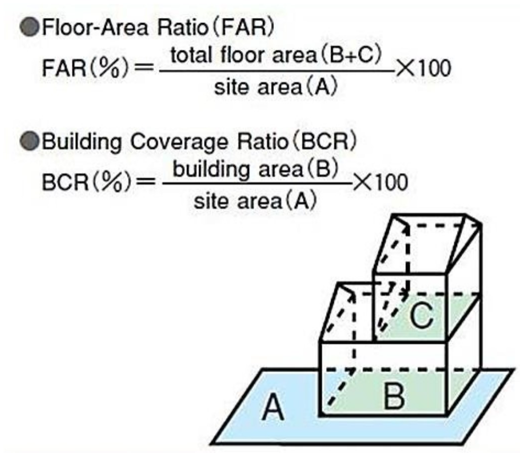


Figure 2.3: FAR and BCR Calculations[65]

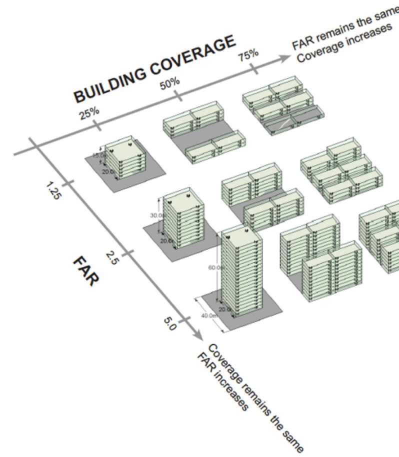


Figure 2.4: The Relationship Between FAR and BCR[10]

affects inside daylight availability. Figure 2.4 perfectly shows the relationship between the floor area and the building coverage ratio [10].

Another critical yet primary factor is the height (H) of the building itself. As [66] utilized building height, interval, orientation, length, and layouts for their studies in 360 cases in the Mediterranean climate zone. Nyuk. W [42] also studied the impact of varying density, the height of the nearby buildings, and vegetation density on the energy consumption of a 3-story office building. Additionally, the weather data and climate are significant components of every energy-related study. Climate directly affects shading, apart from the index parameters and the building layouts. Different examinations have been conducted on shading in multiple cities with different climatic conditions [67, 68, 69, 10].

2.5 Window-type Analysis

The city-level energy-saving effect is proportional to the new construction and regulations for their use of material. This necessitates the improvement of the envelope configurations in the buildings. It is commonly known that windows significantly impact a building's performance, including energy use, internal climate, and visual comfort. Even though many studies have highlighted the importance of heat transfer through windows in improving the thermal performance of fenestrations, research on its effect on the rate of energy consumption reduction at the city scale is minimal.

Windows are linked explicitly to thermal comfort, light convenience, and skin health. They also provide vision, air ventilation, and acoustic comfort and have bio-psychological impacts. Their use as building facades is likewise rising in popularity. Because of their crucial functions, windows must be designed and chosen based on various factors, particularly energy efficiency and visual comfort [70]. As a result, window design is often an optimization problem with multiple elements and objectives. Finding a balance between energy usage, the indoor temperature environment, and visual performance is crucial early in the building design process. This also applies to optimizing window specifications.

Choi et al. (2022) [71] calculated the U-values of various window frames and annual thermal loads based on the window configurations, including the frame, glazing, and cavity in 7 cities in Japan. They confirmed that changing the material of the window frame has a significant energy-saving effect at the city scale. Another study in 2017 [70] declares that the energy loss from windows in residential buildings has been estimated to be between 10% and 25%. In a specific case study of a two-story house with one-third of the exterior surfaces covered by windows, 60% of energy is lost through glazing. Consequently, using energy-efficient windows to reduce heating and cooling is a significant subject. Table 2.4 offers a literature review of the most recent publications that analyzed the effects of different glazing types in addition to other specifications such as Window-to-wall ratio (WWR), orientation, and materials on energy consumption. As it is shown, the thermal transmittance (U-value) of 0.7 to 2 ($^{W}/_{m^2K}$) along with the Solar Heat Gain Coefficient (SHGC) of 0.3 to 0.6, is concluded as the best-performed glazing type in the literature.

Table 2.4: Window-type Literature Review

Reference	Glazing characteristics	Glass-type used	Best performance
[72] 2022	- Thickness - Solar transmittance - Visible transmittance - Infrared hemispherical emissivity - Conductivity - Solar reflectence	- A: 4mm glass (6mm Air) - B: 6mm glass (6mm Air) - C: 4mm low-E glass (13mm Air) - D: 6mm low-E glass (13mm Air)	Glazing D - U-value= 2.01 - Solar transmittance= 0.6
[73] 2021	- U-value - Visible transmittance - SHGC	- Clear single-glazed - Clear double-glazed (Air) - Clear double-glazed (Argon) - Low-E double-glazed (Air) - Low-E double-glazed (Argon) - Low-E triple-glazed (Air) - Low-E triple-glazed (Argon)	Triple-glazed low-E filled with Argon - U-value= 1.058 - SHGC= 0.579
[74] 2019	- SHGC - U-value - R-value - Visible light transmittance	- Single 3mm - Double clear (Air) 6-13mm - Double blue (Air) 6-13mm - Double bronze (Air) 6-13mm - Double green (Air) 6-13mm - Double grey (Air) 6-13mm - Double tinted (low-E) 6-13mm	Double-tinted low-E glass - U-value= 1.772 - SHGC= 0.369
[75] 2017	- Glass thickness - Gas filled - U-value - SHGC	- Three-layer 3 mm low-E - Single-coated glass - Double-coated glass	Double-coated glass filled with Argon - U-value= 0.780 - SHGC= 0.474
[76] 2016	- U-value - SHGC - Visible transmittance	- Single glass - Double glass - Triple glass	Triple glazing - U-value= 1 - SHGC= 0.51

Aside from window type, different parameters could influence the building energy performance. According to a paper in 2021 [77], an analysis is done on a case study to assess the sensitivity of specific parameters to various groups of buildings. The findings indicated a positive correlation between the heating percentage and the WWR. Additionally, the WWR impact will be more significant in buildings where a higher proportion of energy is used for heating as opposed to other purposes, as well as when the facade areas are larger.

We could find one study [71] considering more than one building in the energy-saving effect of changing the materials of the window frames. Aside from that, previous studies have concentrated on single buildings, ignoring the embodied impact of common window types on yearly energy consumption at the city scale. While the effects of the surrounding buildings and the urban canopy could change the shadings and the solar heat gain on the window surfaces.

2.6 Literature Gaps

The chapter reviews several studies about Urban Building Energy Modeling (UBEM), Building Energy Modeling (BEM) and its connection with Building Information Modeling (BIM), the importance of the surrounding buildings and their shading effect, and the window-type configurations. Based on the reviewed literature, gaps, and limitations are found in every topic. In the following paragraphs, these gaps are discussed and later implemented in defining this research's methods and tools.

UBEM and BEM

Urban building energy modeling is still challenging for various reasons, including the uncommon availability of high Level of Detail (LoD) data, inherent simulation uncertainties, computing expense, a dynamic urban microclimate, stochastic occupant behavior, etc. Urban geometry is exceptionally complicated and heterogeneous regarding city-scale energy modeling. As a result, detailed modeling of urban energy consumption requires vast quantities of data that are challenging to collect and high-quality powers that are not available for general use. As a result, simplified methods have primarily been created [11].

The simulation findings of individual buildings are not simply scaled up in larger-scale building energy modeling [2]. Building energy demand can be significantly impacted by inter-building impacts, such as long-wave heat emission, shading, and heat exchange between buildings and the urban environment [20]. As a result, UBEM should consider interactions between buildings and microclimate impacts. A physics-based dynamic simulation method is superior to alternative strategies in this context.

To do extensive energy modeling, many default data and assumptions must be made due to the scarcity of publicly available information about specific city buildings. Appropriately, UBEM results have inherent uncertainty. Urban building energy models are often calibrated using annual energy use data from individual buildings. Technical challenges still exist when modeling interconnected urban system models, including data exchange protocols, coupling techniques, and synchronization control. Additionally, UBEM needs a lot of data, and gathering and then integrating the datasets into a standard format for interoperability demands a lot of work. Another challenge to urban modeling is the workflow for performing urban building simulations on a large scale. This workflow should also provide a visualization ability integrated with 3D GIS, which is not always the case. Computing resources and interoperable collaboration among stakeholders are other difficulties for UBEM, according to the literature [2].

Thermodynamic simulations, on which building physics models are built, have been acknowledged as suitable for energy retrofit assessment and optimization across various spatiotemporal scales. To properly support and produce accurate building physics models, high-quality data and significant computational effort are required [20].

Even though tools and approaches for modeling urban energy usage have received much attention and the promise to provide sustainable routes for city energy management, they still fall short of presenting a realistic urban energy model. The available tools for urban energy modeling frequently concentrate on a single aspect of urban energy usage rather than an integrated approach, while these components are interconnected at several levels. Therefore, the question of enabling an accurate, time-effective, and practical method for integrated urban energy consumption modeling still needs to be answered.

The advantages, trends, dangers, difficulties, and perceptions of BIM in projects have all been recognized in different studies. On the other hand, there is little research that describes how green design stakeholders feel about utilizing BIM to help with the development of energy models and the running of energy simulations. Additionally, there is a shortage of research describing the primary advantages and disadvantages of utilizing BIM to generate energy simulations from the perspective of green design stakeholders.

Since BESs are typically not designed to do simulations at the district or urban scale, even though BEMs can simulate the behavior of building components and are thus the foundation of explicit urban energy modeling. BEMs must be enhanced or coupled because they were initially created for standalone buildings and can not incorporate urban effects on urban building energy consumption. According to the literature, BES was mainly employed to simulate the energy demand of one frequently hypothetical building in an urban setting to detect general patterns, not to investigate an actual situation. Surrounding buildings are commonly presumed to be obstacles without detailed modeling of their thermal characteristics. BES at the urban scale would demand a significant processing effort due to the sequential calculations and the coupling processes. BES tools are not built to model several buildings while accurately accounting for the interactions between each other.

Shading Analysis

As mentioned earlier in this chapter, the geometry of the targeted and neighboring buildings, the length and breadth of the street, and the street's orientation concerning the climate all impact the shading effect. Analysis of building energy behavior in urban and street planning can be a theoretical foundation for logical architecture design and energy consumption reduction when constructing low-carbon cities.

According to the literature research, there are limited studies in which the urban environment is considered a shading element in energy simulations, demonstrating the necessity of including the influence of the urban setting in energy efficiency simulations. Moreover, despite several recent studies examining how buildings interact with their surroundings, a systematic approach to analyzing how a building's energy performance is affected by its surroundings is missing. Few models account for the potential combined inter-building effect and explore how it affects the precision of energy use simulations. Also, the lack of considering a single variable, such as the height of the buildings in energy consumption comparisons of the targeted building affected by shading from the environment, is another gap in the field of shading analysis.

Window-type Analysis

Numerous studies have found that the building's façade, notably its outside windows, has significant energy-saving potential. The window primarily absorbs unwanted heat increases through air infiltration and solar radiation. In terms of heat gain, windows are part of the building that is most vulnerable.

Based on the literature, studies have been conducted on different glass-type alternatives, from single-glazed fenestrations to triple low emissive models filled with Argon. Limited studies consider a large-scale building with numerous floors for the energy demand calculations affected by different window types. The buildings' height is essential, especially in urban contexts where shading affects performance. The lower floors' windows may be covered with shadows throughout the day, while higher floors are not in the shaded area. Moreover, the lack of introducing codes and regulations for window selection in different locations is an essential gap in the literature. Cities with cold weather climates, in particular, mainly have restrictions regarding selecting the facade materials for compatibility and energy efficiency in winter. More importantly, the window-type analysis is primarily performed on a single, individual building while considering a building, among others, may significantly change the absorbed radiation on windows.

Chapter 3

Design and Methodology

This chapter introduces UBEM and BEM developments and presents a methodology overview. In the following, the different steps and research objectives are broken down and explained in detail. The sections include data acquisition, preparation, integration, energy model creation, simulations, and comparisons.

3.1 Framework of Study

To achieve the mentioned objectives in Section 1.3, the first and foremost step is to acquire the building data, more importantly, the geometry of the selected area. Next, the collected data must be presented and ready to use according to the research goal. This step includes data preparation, integration, library creation, geometry fixing, simplification, and attribute modification. Then, with the generated model ready, the simulations are performed, and the results are compared. The flowchart in Figure 3.1 demonstrates the generalized framework of this thesis.

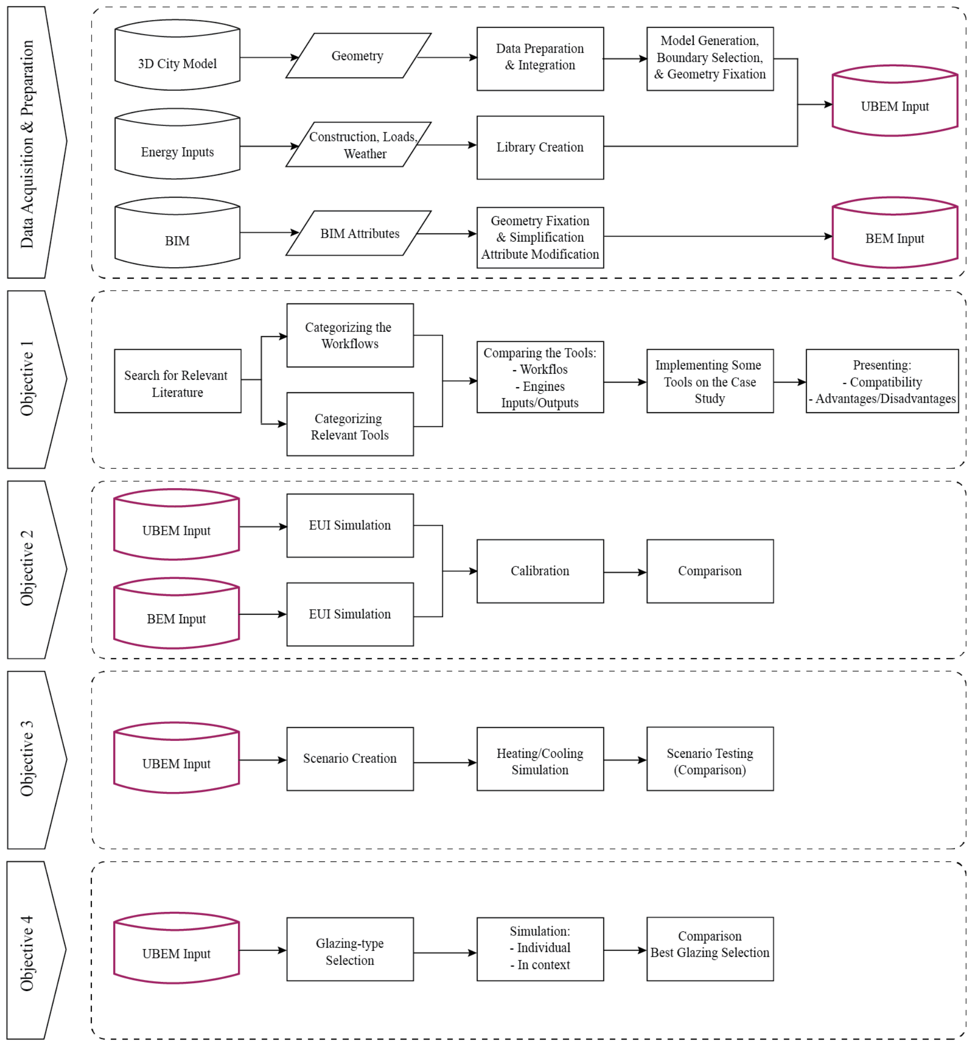


Figure 3.1: The Overview of the Research Methodology

3.2 Steps of the Developed Method

The main goal of this study is to find the differences between the building energy simulation outcomes under individual, stand-alone conditions and those under urban-scale situations. The methodology and steps towards the goals are assigned based on the objectives mentioned in Section 1.3. In this section, the detailed steps of each purpose are described. Following, the primary simulation tools which are used in this study are introduced.

First objective: Investigating the difference between UBEM and BEM approaches; Comparing the tools, workflows, and libraries

The first objective of this research is to familiarize readers with the concept of energy simulation both on an urban scale and building sector. In Chapter 2, a detailed introduction to UBEM, BEM, and their implementations has been stated. For this purpose, a thorough literature review was conducted on the following keywords and their equivalents: Urban Building Energy Modeling (UBEM), Building Energy Modeling (BEM), Building Energy Simulation (BES), Building Information Modeling (BIM), energy simulation tools, UBEM approaches, etc. Concluded from this review, the tools and workflows for this study have been chosen, which are explained in the next section.

Second Objective: Comparing the building energy consumption of individual buildings (BEM environment) with the results from the UBEM environment

Two different workflows are defined for implementing a simulation-based engineering approach to calculate the energy consumption of a case study building in Montréal, Canada. First, the building is assumed as a stand-alone model. The BES approach simulates the heating and cooling consumption of the desired building BIM environment. Figure 3.2 shows the hierarchy of this step.

Next, the mentioned building is considered a part of a district among other entities in downtown Montréal, as it is in reality. This time, the simulations are done in the presence of the surrounding neighborhood and throughout the UBEM process. The second hierarchy is shown in Figure 3.3. Finally, considering all of the assumptions and limitations of each procedure, the comparison between their results is discussed in Chapter 5. This comparison aims to determine in which domain they can provide relevant information for each process to help enrich the energy models. The take-home message of this objective is to investigate whether or not integrating these approaches is feasible or beneficial.

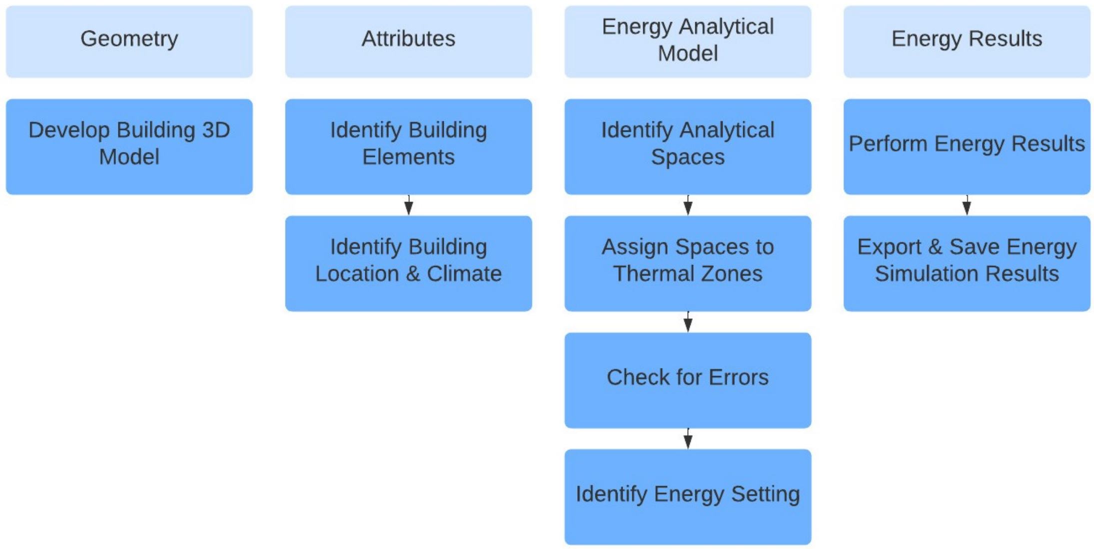


Figure 3.2: BIM Hierarchy Chart

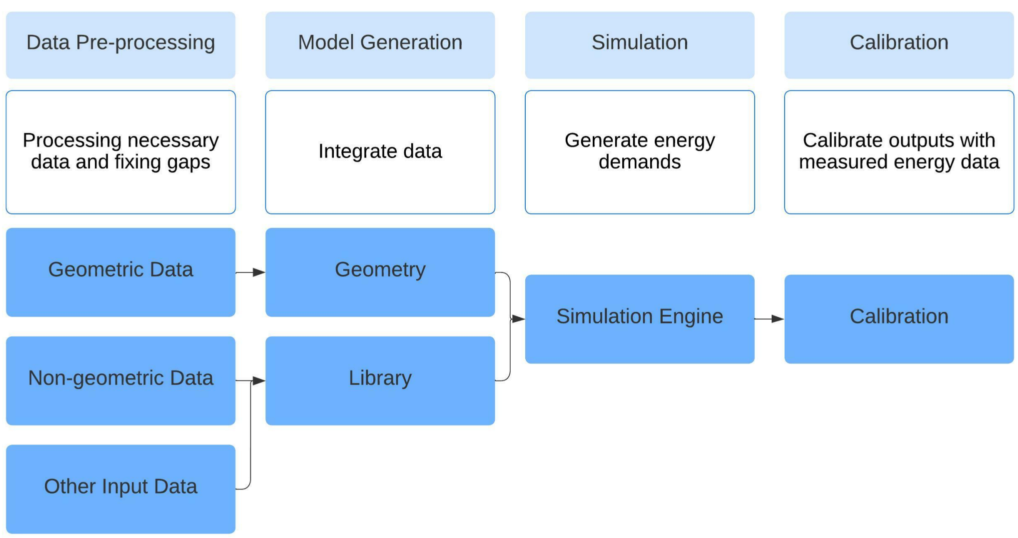


Figure 3.3: UBEM Hierarchy Chart [78]

Third Objective: How the building energy consumption of individual buildings is affected by the surrounding 3D geometry, limited to shading analysis.

This study will analyze the effect of surrounding buildings' shading. The process of the third objective can be divided into the following steps:

1. Determine the selection boundary explained in Section 3.4
2. Select the related morphology and climatic parameters according to the literature review
3. Introducing four different scenarios related to the height of the building; SC1(stand-alone), SC2(complete model), SC3(high-rise), and SC4(low-rise)
4. Establish the building's physical model and context for the defined scenarios
5. Calculate the cooling and heating loads of the targeted building for different scenarios
6. Introduce the value (R) for comparing the reduced or increased energy loads
7. Compare the results and indicate the amount of shade concerning cooling and heating consumptions under various circumstances

Fourth Objective: Finding out the impact of different window types on building energy consumption of the building

In a city context, the energy simulation can be used to assess the effect of various window types on the overall energy performance of a building, taking into consideration factors such as building orientation, shading devices, and the surrounding built environment. For example, a building with south-facing windows may require distinct window types than one with north-facing windows. Glazing is one of the essential elements of a building's façade. Despite having less surface area than the buildings, windows account for most heat gain in buildings. This is because windows also contain radiation gains in addition to conductive increases. The glass qualities of the windows work similarly to insulation in lowering the heat gain or loss. Therefore, as the last objective, the impact of different types of windows on the energy calculations of the desired building in the urban context is considered. The following steps show the clear path to this aim.

1. Investigate the Canadian codes for the glazing characteristics
2. Select glazing systems for the comparison
3. Simulate the heating and cooling for each glazing type in the urban context and as an individual entity
4. Conduct the simulations with four different Window-to-Wall Ratio (WWR)
5. Compare the results and introduce the best performance glazing and the WWR

3.3 Simulation Tools

As mentioned in Section 2, several energy simulation programs enable a computational analysis of energy and daylight in buildings. The overview of the selected tools used in this study is described in this section. The primary drawing tool used in this study is Rhinoceros® ((McNeel R. & Associates.) [33], which is a Computer-Aided Design (CAD), 3D application tool. The reasons for selecting this software are the accessibility of the Rhino file format for the chosen area and the software's compatibility with a range of energy simulation engines such as Energyplus. Moreover, this platform is standard among architects, urban designers, and energy analysts for its' flexible environment and graphical coding editor called Grasshopper.

1. Ladybug Tools

Ladybug Tools [79] is a set of free computer programs that aid in environmental design and education. Their website shows Ladybug Tools is one of the market's most complete environmental design software suites, integrating 3D CAD interfaces to various verified simulation engines. Ladybug, Honeybee, Dragonfly, and Butterfly are the main plug-ins for this tool. Grasshopper can import standard EnergyPlus Weather files (.EPW) through Ladybug. It offers a selection of interactive 2D and 3D climatic visualizations to aid decision-making during the preliminary design stages. Radiation and shadow studies, heating and cooling energy usage, HVAC sizing, passive strategies, airflow simulations, and urban district energy use are feature examples of this application.

2. Urban Modeling Interface (UMI)

UMI (MIT sustainable design lab) [32], is a Free open source, Urban modeling interface. It uses the windows based NURBS modeler Rhinoceros® and its CAD modeling platform, EnergyPlus for thermal building-by-building simulations, Daysim for daylight simulations, and custom Python and Grasshopper scripts for walkability evaluations. Using UWG (Urban Weather Generator), UMI converts an EnergyPlus weather file for a rural weather station into a nearby weather urban center accounting for hourly urban heat island effects. Simplified and fast calculations, adjustable construction details and schedules, and a user-friendly interface make it an ideal early-stage design tool for understanding a building's energy behavior and life-cycle assessment. However, several limitations exist, such as multiple default values and the shoe-box simplification strategy.

3. Green Building Studio (GBS)

Autodesk® Green Building Studio [80] is a versatile cloud-based application enabling building performance simulations to improve energy efficiency and strive toward carbon neutrality earlier in the design process. The capacity to design high-performance buildings at a fraction of the time and expense of conventional approaches will be increased with the aid of Green Building Studio. This program can be used as a standalone web service or to support Autodesk Revit's® entire building energy analysis.

3.4 Data Preparation

Initially, for acquiring geometry for the selected case study, the Open Street Map (OSM) data were extracted from the website [81]. With the help of an add-on for Grasshopper called Elk, the data was transferred to Rhino. Elk is a set of tools to generate maps and topographical surfaces using open-source data from OSM and USGS. However, for the desired district of downtown Montréal, the heights of the buildings were missing. Figure 3.4 shows the footprint of the buildings, highways, and railways of downtown Montréal. Moreover, the Grasshopper algorithm and the visualization for the OSM data are provided in Appendices A.

Figure 3.4: The Boundary of Case Study in Downtown Montréal Extracted from OSM [81]

Consequently, the LoD1 geometry was extracted from the Open portal of Montréal in a .3dm format [82]. After data preparation, as explained later in this chapter, the file is ready to be used in the energy simulation procedures. This is because the energy simulation tools utilize a simplified building model that, most of the time, represents the spaces and zones in the buildings, complicating the data transfer from geometry modeling applications to energy simulation tools. The models, therefore, need to be specially prepared to meet the requirements of software energy simulation tools.

3.4.1 Integration

The first action after acquiring data from the open portal of Montréal was to integrate the whole model and precisely separate the desired location. Figure 3.5 shows the entire island of Montréal divided into numerous tiles, where each tile represents a 3D digital model in different formats.

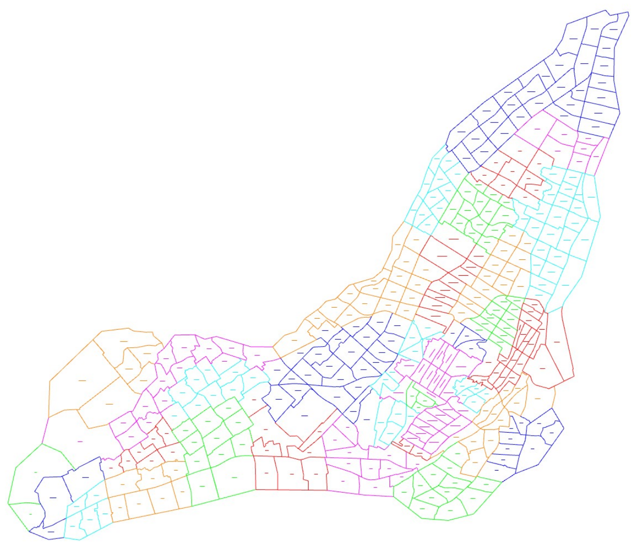


Figure 3.5: Index of Tiles Used for 3D Digital Models Covering the Island of Montréal [82]

The desired location for this study is downtown Montréal, around the intersection of Saint Catherine St. and Guy St., which is identified as tiles VM11, VM07, and VM03. Figure 3.6 shows the plan view of mentioned tiles in Rhinoceros®.

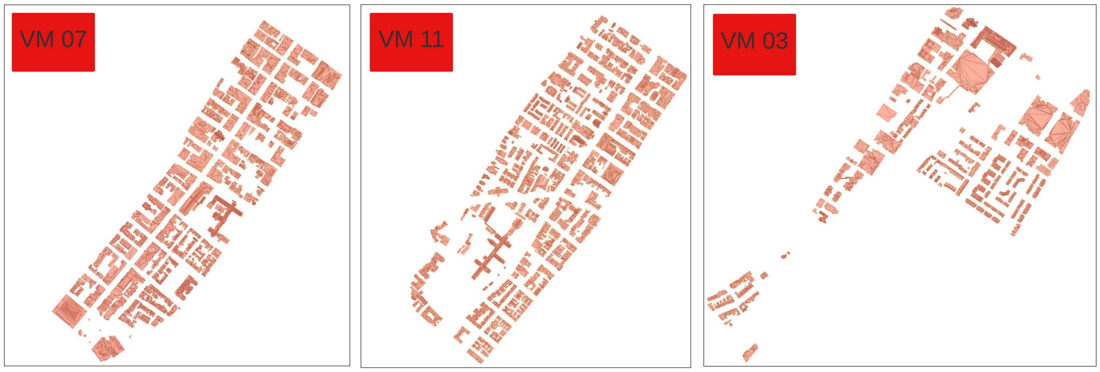


Figure 3.6: Plan View of VM07 & VM11 & VM03

Finally, the three mentioned tiles were merged in Rhinoceros® manually, and since the files were georeferenced, this action did not have any complications. Moreover, further geometry corrections and simplifications must be applied in Figure 3.7.

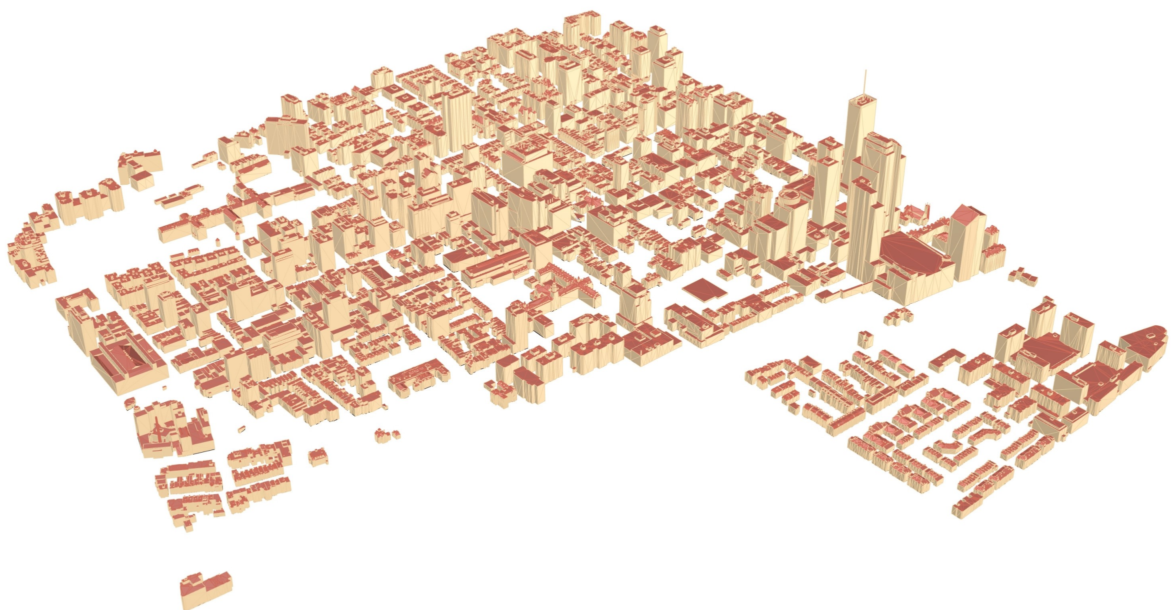


Figure 3.7: Perspective View of Merged File

3.4.2 Boundary Selection

Radiation from the sun carries a large quantity of energy (66 million W/m^2) to Earth. Only a little portion of this energy (1300 W/m^2) makes it to the atmosphere. The atmosphere then absorbs around 15% of this radiation, which is subsequently diffusely radiated in all directions. 6% of the light is reflected into the room. The remaining portion (79%) travels directly from the air to the earth [83].

Solar energy is an essential source of renewable energy. Its technologies are often classified as passive or active solar depending on how it is collected, distributed, or transformed into solar power. Utilizing photovoltaic systems, concentrated solar electricity, and solar water heating are examples of functional solar approaches. However, a building's orientation toward the sun, using materials with good thermal mass, and naturally ventilated rooms are all passive solar solutions. Solar energy implementation has the advantages of decreasing energy consumption, environmental consciousness, high social value, and increasing property's worth.

One of the most important environmental aspects to consider when designing high-performance buildings is how the Earth moves around the sun, which causes solar paths that change throughout the day and the year. By viewing the sun's path, especially during essential days of the year, engineers and architects could take advantage of daylighting, passive heating, natural ventilation, and efficient design ideas in the early stages of building construction. The importance of sun analysis is best acknowledged when possible setbacks occur in a building, such as the impact of glare or overheating caused by the absence of primary studies of the sun's movement.

Since the Earth orbits the sun on an inclined axis, different hemispheres of the planet tilt toward the star at various times during the year. This causes one hemisphere to get more heat and light while the other receives less. At the equinoxes, the celestial equator is crossed by the sun's center as it appears to move along the ecliptic. This indicates that the light reaching the northern and southern hemispheres is equal, making the day roughly equivalent to the night. On solstices, the sun has the greatest declination to the north or south relative to the Earth's equator. As a result, the sun is always at its highest or lowest point on the ecliptic. Figure 3.8 shows the equinoxes and solstices of Montréal in 2022. Moreover, Table 3.1 illustrates the sun's behavior on those days.

Figure 3.8: Equinoxes and Solstices [84]

Table 3.1: Sun Specifications in Montréal, 2022 During Equinoxes and Solstices

Date	Sunrise	Sunset	Daylength	Solar Noon	Altitude at Solar Noon	Term
2022/Dec/21	7:31 am	4:13 pm	8:42:14	11:52 am	21°	Winter Solstice
2022/Sep/22	6:41 am	6:51 pm	12:10:23	12:46 pm	45°	Autumnal Equinox
2022/Jun/21	5:05 am	8:46 pm	15:41:05	12:56 pm	68°	Summer Solstice
2022/Mar/20	6:57 am	7:06 pm	12:09:32	1:01 pm	45°	Vernal Equinox

A shading analysis has been done on the case study building to determine the coverage boundary. Due to the position of the sun and the surrounding objects' heights, the hours that a building receives sunlight vary during the year. According to Equation 3.1, the length of a shadow is related to the height of the building and the latitude of the sun. Therefore, during the winter solstice, the size of the shadow is at its longest. However, due to the position of the sun, the sunlight hours analysis has been executed on December 21^{st}, September 22^{nd}, June 21^{st}, and March 20^{th}.

$$ShadowLength(SL) = H \times ShadowLengthFactor(SLF) \tag{3.1}$$

Where:

$H \quad = Buildingheight$

$SLF = 1 \div \tan(SunAltitude)$

Figure 3.9 and Figure 3.10 illustrate the sunlight hours during the 4 days mentioned earlier, simulated in Grasshopper and Ladybug tools. The process of calculations is shown in Appendices A.3. Considering 21^{st} of December as an example, Figure 3.9 shows during almost 9 hours of day length, the areas in black receive 2.25 or fewer hours of sunlight. On the other hand, the regions in the lightest grey receive sunlight from 6.75 to 9 hours. In this study, however, only areas with less than 6.75 hours of sunlight are considered the effective shading influence of the buildings. The shadow in an area with less than 6.75 hours of daylight is assumed to be less intensive because they have a shorter time with shading coverage. Therefore, Figure 3.11 shows the selected boundary of this study.

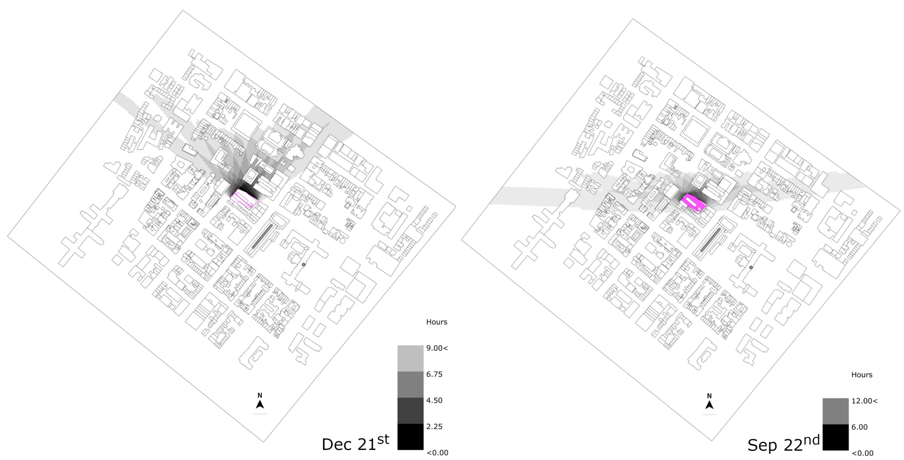


Figure 3.9: Sunlight Hour Analysis on Dec21^{st} & Sep22^{nd}

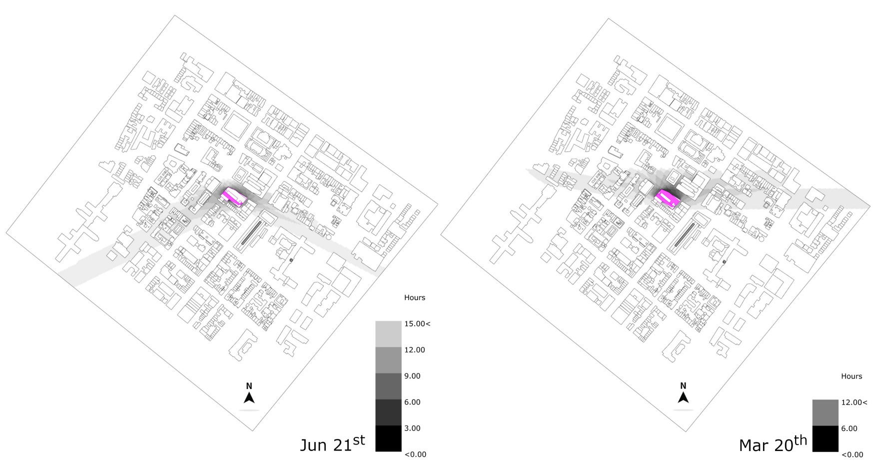


Figure 3.10: Sunlight Hour Analysis on Jun21^{st} & Mar20^{th}

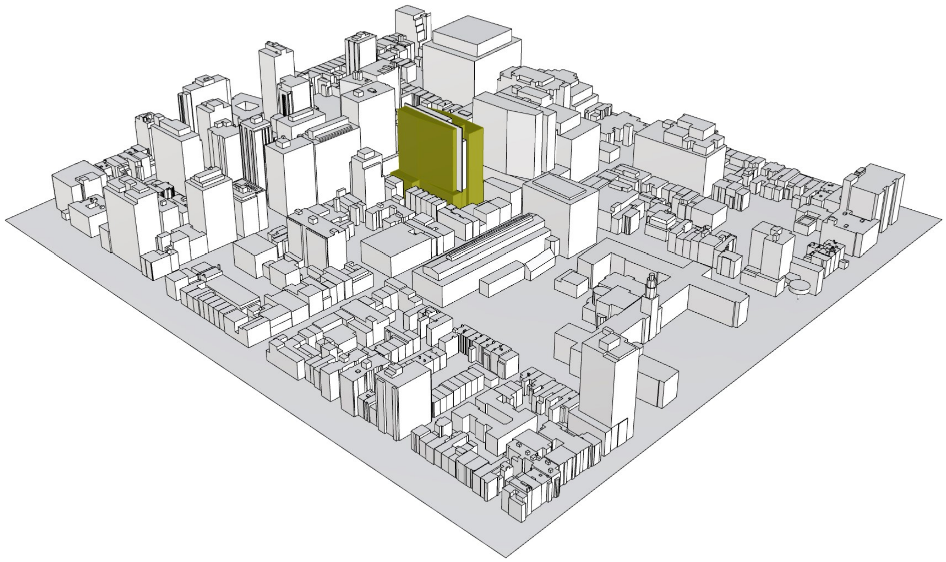


Figure 3.11: Perspective View of the Selected Boundary

3.4.3 Geometry Fixation and Simplification

Most energy modeling tools work with building volumes to calculate the demands. As a result, geometries must be corrected and fixed before being introduced to energy engines. First, all the Mesh geometry is converted to poly surfaces. This could be done with Rhino commands of converting mesh to surfaces. After that, some damaged geometries were found and manually fixed. Figure 3.12 illustrates some examples of damaged geometries ad the repaired version. The process is done by using Rhinoceros®. The BIM file also had some problems and needed minor fixations. At this stage, the geometries were corrected, simplified, and became ready for energy simulations. Some of the issues with the masses were identified as follows:

- Frequent overlapping volumes
- Formation of new unwanted edges
- Open building geometries

- Misaligned surfaces
- Unnecessary architectural elements
- Walls did not reach the ceilings

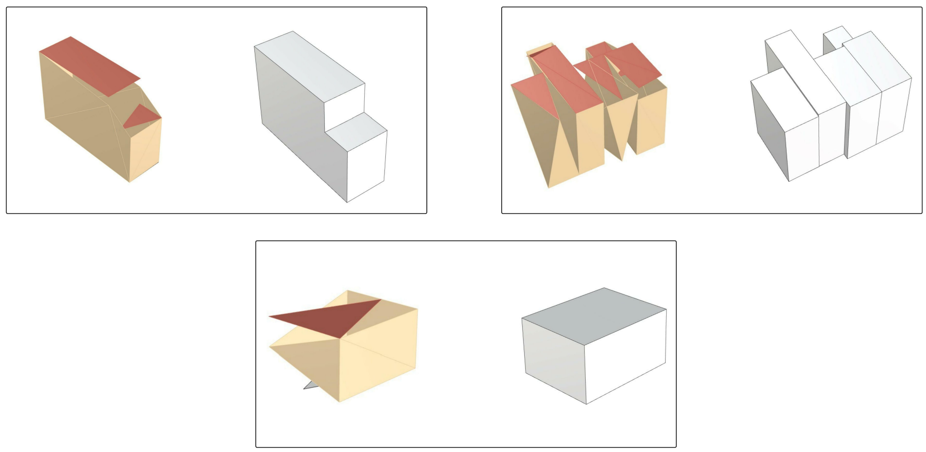


Figure 3.12: Geometry Fixation in Rhinoceros®

We have fixed most of the mentioned issues using different commands inside Rhinoceros. For example, we selected the open-building geometries using the "SelOpenPolySrf" command. After selecting them, using either "Join," "Cap," or "OffsetSrf," commands could connect, fully close, or properly align the surfaces, respectively. Also, the overlapping volumes could be fixed using the "BooleanUnion" command. After fixing an issue in Rhinoceros, we used the "Check" command to identify errors. In rare cases, we had to redraw the whole geometry using OSM and Google Maps. In Revit, gaps and inaccuracies in the model can occur when walls do not reach the ceiling, causing problems during the simulation process. We have selected all the affected walls, checked their properties, and attached them to the top or base to cover the holes. The unwanted elements, such as furniture, structural components, mechanical components, and doors, were also selected by their families and deleted from the analytical model.

Chapter 4

Case Study

This chapter introduces the characteristics of the case study. The building specifications, including the operation manual, the architectural and mechanical drawings, and the electricity consumption, were obtained from the facility management department of the building. The weather data for Montréal was obtained from the Energy Plus website. The geometries of the districts on the island of Montréal were extracted from the Open Portal of the City of Montréal. Also, the BIM file is provided by students in Compleccity Lab at Concordia's BCEE department.

Figure 4.1: Jhon Molson School of Business [85]

4.1 Building Description

The case study of this research is the Jhon Molson School of Business (JMSB) on Sir George Williams (SGW) campus of Concordia University, located in Montréal, Quebec, Canada. There are various reasons why we used this building in the first place. The availability of the BIM file and architectural documents is essential in energy simulation. As mentioned, shading effects are significant for office buildings with high lighting energy consumption and where employee productivity is heavily influenced by lighting conditions [57]. Another reason is the weather and the time zone of Montréal. Regarding the shading effects and the neighbor's shadowing, selecting a cold climate could be better for analyzing the energy efficiency of different urban density contexts. Gaining more sunlight during the winter in cold temperatures could save a lot of energy during the year.

Figure 4.2: Satellite Image of JMSB, Montréal, Québec, Canada [86]

JMSB is in the Ville-Marie borough of Montréal. This building was built in 2009, with 15 stories and two basements. It is an educational building with a total gross area of 37 000 m^2, standing on 3 000 m^2 of land. A Google Earth satellite image of the case study building is represented in Figure 4.2. The estimated height of the building is 77 m. It consists of several modern classrooms, networking spaces, amphitheaters, and two basement levels that connect the building to the subway station and the neighboring buildings, including the Gina Cody School of Engineering and Computer Science. The rooms and spaces based on their usage are described in Table 4.1.

Table 4.1: Rooms and Spaces of JMSB

Rooms	Quantity
Classrooms	45
300-Seat Auditorium	1
150-Seat Amphitheatre	2
120-Seat Amphitheatre	4
Conference Rooms	22
Offices	289
Private Study Rooms	44
Designated Open Study Areas	3
Open Relaxation/Study Areas	8
Waiting Areas	7

The building is pursuing an eco-design and has contributed to social and environmental issues. The Canada Green Building Council awarded it LEED Silver (Leadership in Energy and Environmental Design) certification [87].

JMSB is equipped with a south-facing vertical solar wall helping to reduce the energy consumption of the building. The solar wall is made of perforated metal cladding, with a layer of insulation and black metal that captures the sun's heat behind it. Air is drawn in from the panel's bottom and heated as it travels through the black metal layer. The heated air is then directed into the structure's ventilation system, providing warm air for the heating system. The solar wall is integrated into the mechanical system of the building's framework and is controlled by a building automation system. The system monitors the building's temperature and humidity levels and appropriately adjusts the solar wall's operation. The solar wall's design is functional and aesthetic, with the perforated metal cladding lending a distinct visual aspect to the building's exterior [88].

4.2 Building Envelope

The walls, roof, and glazing construction values are presented in Table 4.2. The values have been extracted from the as-built architectural drawings and the operation manual. The glazing has an average shading coefficient (SC) of 0.24, and the fenestration/wall ratio is 0.54.

Table 4.2: Average Thermal Resistance

Description	Thermal resistance	
	R ($ft^2.h.°F/Btu$)	RSI (m^2. °C/W)
Wall	17.6	3.1
Curtain wall	7.4	1.3
Roofs	21.6	3.8
Glazing	3.4	0.60

4.3 HVAC Systems

All mechanical systems and the generator are located in the mechanical room on level 16, except the main electrical room, the fire pump on level B2, and the mechanical rooms on each floor. The JMSB is a self-contained building for electromechanical systems; for example, the heating systems, cooling systems, fire protection systems, humidification, fresh air ventilation systems, the electrical room, and emergency generator are dedicated to this building. The power supply, the natural gas, and the controlled compressed air come from the Gina Cody Pavilion. Services pass through the tunnel between the two pavilions.

The John Molson School of Business Building comprises classrooms, lecture halls, and teachers' offices. This type of premises contains a lot of people in the exact location, which requires a considerable supply of fresh air to comply with the building code. To meet this demand, the building has VAV ventilation systems, including supply/return fans, filters, cooling coils, and silencers on each floor to ensure ventilation and comfort on the premises. A fresh air unit in the mechanical room on level 16 supplies all the rooms with fresh air. Therefore, classrooms have two volume boxes, one connected to the floor system and the other to the fresh air system. Also, the premises are equipped with motion detectors for lighting control and control over minimum ventilation during unoccupied periods.

Two natural gas condensing boilers of 2,000 MBH, each producing 50% glycol heating water at a temperature of 140 °F. The boilers deliver hot glycol water when the heat recovery system on the chilled water network fails to satisfy the heating demand in the heating coils of the fresh air system or if it is not in operation. Also, two centrifugal compressor-type chillers of 450 tons each and a screw-type chiller of 300 tons making water chilled to 44 °F, are used for cooling.

4.4 Building Loads

The occupancy, lighting, and plug density parameters are extracted from the National Energy Code of Canada for buildings (2020). Also, the ventilation rate is derived from ASHRAE Handbook, HVAC application. Table 4.3 summarizes the mentioned values used in this study.

Table 4.3: Building Loads

Building type	**Lighting density** (W/m^2)	**Occupant density** ($m^2/Occupant$)	**Lighting density** (W/m^2)	**Illuminance levels (lx)**	**Ventilation** ($cfm/Person$)
School / University	7.8	8	5	400	13

4.5 Occupant Schedules

In addition to the earlier descriptions, occupancy schedules are sometimes estimated, naturally less precise, and slightly trickier to predict. Over time, default values based on the kind of facility or activity have changed. Yet, little has been done to evaluate how responsive these operational schedules are, particularly for occupancy in university facilities [89]. An extraction methodology for occupancy indicators from WiFi traffic data is introduced by Alishahi et al. [90]. The proposed system employs several machine learning algorithms and statistical analysis approaches to forecast building occupancy patterns and identify peak occupancy hours. They have validated their framework on the detailed case study of this research but for the first eight floors of the building. Therefore, the actual data written from the WiFi connection counts presented by Alishahi et al. [90] is used in this study for the occupant schedules.

4.6 Weather Data

This study uses an Energy Plus Weather (EPW) file. The file is in TMY format, comprising 35 features for hourly 8760 results from different random years each month. The file consists of two parts, headers, and weather data. Headers typically are location, design conditions, ground temperatures, data periods, regular/extreme periods, holiday/daylight savings, and other comments. There are about 35 variables in the core weather data. However, not all of them are used for energy plus. The primary 13 columns being used during simulations are dry bulb temperature, dew point temperature, relative humidity, atmospheric pressure, horizontal infrared radiation intensity from the sky, direct normal radiation, diffuse horizontal radiation, wind direction, wind speed, present weather observation, present weather codes, snow depth, and liquid precipitation depth.

Some categories mentioned above for Montréal are presented with graphs and charts.

The data is being processed and illustrated by Ladybug tools. The monthly mean minimum and maximum temperatures per hour are shown in Figure 4.3. Also, Montréal's hourly dry bulb temperature and relative humidity are illustrated in Figures 4.4. And last, Figure 4.5 shows the Outdoor Standard Effective Temperature, a commonly used metric to express what temperature the outdoors "feels like."

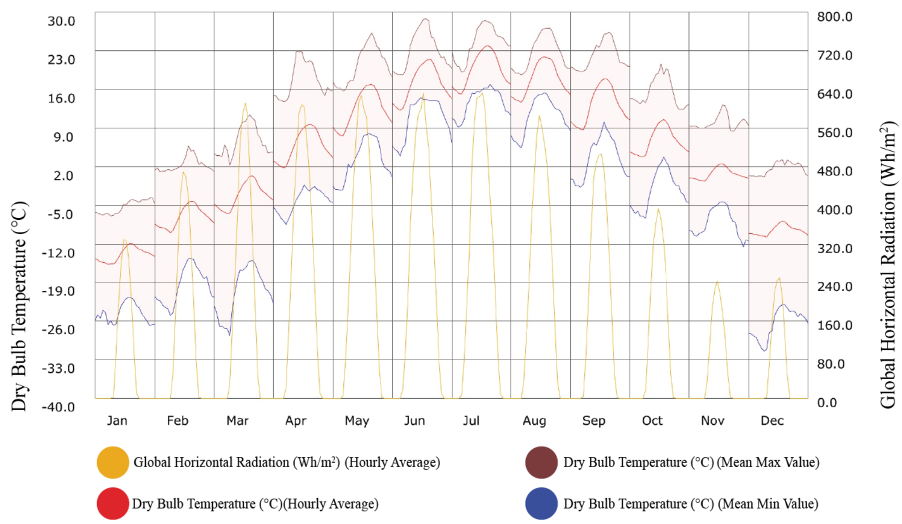


Figure 4.3: Montréal's Monthly Min and Max Temperatures

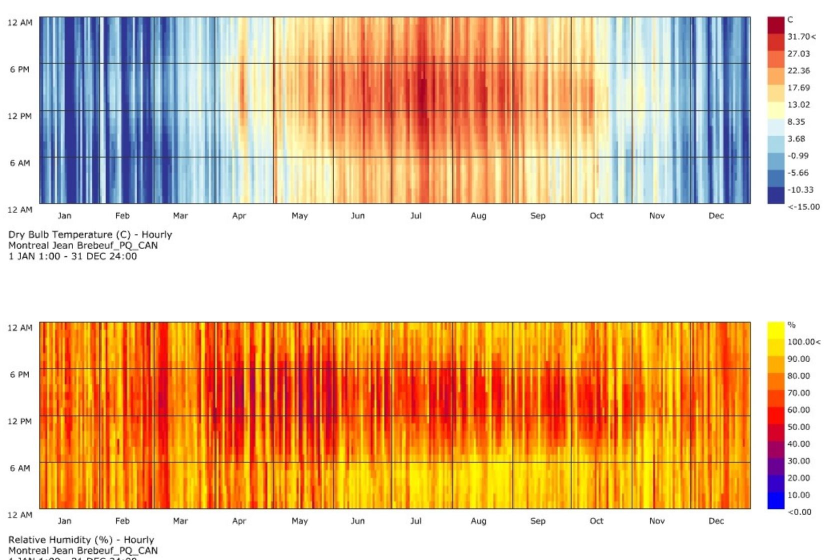


Figure 4.4: Hourly Dry Bulb Temperature (° C) and Relative Humidity (%) of Montréal

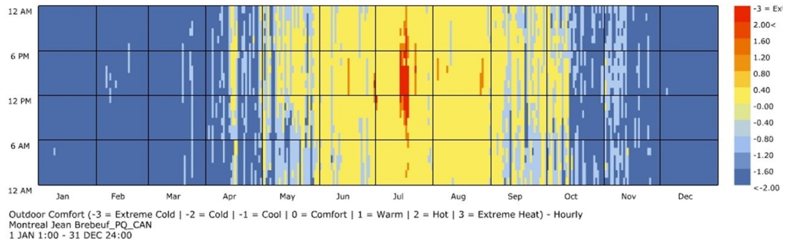


Figure 4.5: Yearly Outdoor Comfort in Montréal

Montréal has a humid continental climate with four different seasons. Summers are hot and humid, and winters are cold and snowy. Figure 4.3 shows that in Montréal, temperatures can vary from around -20°C in the winter to about 30°C in the summer. The average temperature in Montréal in January, the coldest month of the year, varies from -26°C (the mean min value) to -4°C (the man max value). The average temperature in July, usually the warmest month, ranges from 17°C to 26°C. Relative humidity is the quantity of moisture in the air compared to the maximum amount of moisture the air can hold at a given temperature. This is provided as a proportion. The relative humidity in Montréal varies based on the time of day and season. Figure 4.4 illustrates that the relative humidity is more significant in the summer because the air is warmer and can hold more moisture and lower in the winter because the air is colder and drier. The other climatical parameter we discussed here is the yearly outdoor comfort that varies yearly based on the season and weather conditions.

High temps and high humidity levels can impact outdoor comfort during the summer months. Temperatures begin to fall in the autumn, and the air becomes less humid. This can make for pleasant outdoor circumstances, especially early in the season when temperatures are still mild. Winter in Montréal can be brutal for outdoor comfort due to the extreme weather and snowfall. Temperatures rise in the spring, and the city comes to life with blooming flora and trees. The air can be pretty cool and damp early in the season, but outdoor comfort levels improve as spring advances.

Chapter 5

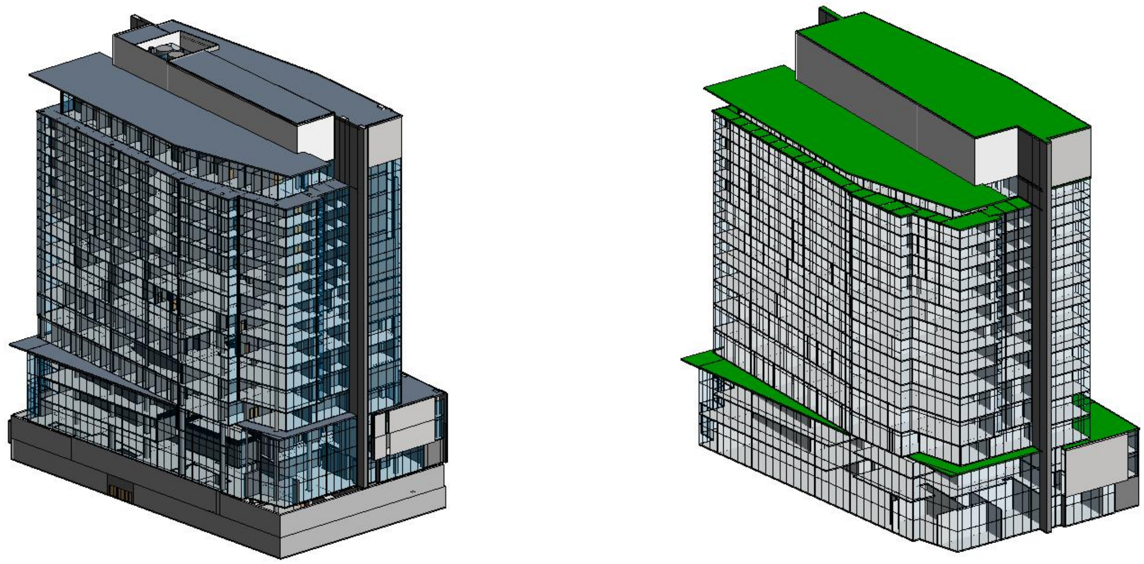
Results and Discussion

In this chapter, the results from different objectives are illustrated and discussed. Results from UBEM, BEM, the shading analysis, and the window-type analysis are the sections of this chapter. The chapter finishes with a comparison and discussion section, summarizing the proposed results.

5.1 Results from BEM

Integrating BIM and BEM from the beginning of architectural design is crucial for energy efficiency and high-performance buildings. To effectively represent buildings as they are or will be constructed, interoperability capabilities of the tools are essential. Data sharing between BIM and BEM applications is rarely a simple process and frequently necessitates manual intervention and data modification. Figure 5.1avisualizes the 3D model of JMSB in Revit® 2023, created by my colleagues in Compleccity lab, Concordia University.

An analytical model was manually created based on the architectural model inside Revit® 2023. All the constructions and inputs mentioned in Chapter 4 were assigned to the model. Figure 5.1b shows the energy model created to be used later in simulations in the BEM environment. BEM tools generate analysis models based on the rooms assigned in the 3D BIM model. They develop an analytical model using spaces and surfaces, which ultimately impacts calculations of building area.



(a) Architectural Model

(b) Analytical Model

Figure 5.1: JMSB Models, Revit® 2023

In the analytical model, the basements are not included. The architectural elements, such as doors and furniture, columns, and other structural drawings, are also excluded. Moreover, the indoor spaces and rooms are simplified, and tiny rooms are merged to create thermal zones. The roofs shown in green are also considered shading elements in some parts of the building.

Two data formats, Industry Foundation Classes (IFC) and Green Building XML (gbXML) , frequently facilitate interoperability between BIM and BEM. Geometrical data can be extracted and transferred from BIM models using both formats. In contrast to gbXML, which has a bottom-up structure and is simple to understand, IFC is object-oriented with a top-down structure, and all information is shown in an ordered manner. This study uses the gbXML format for data exchange because it is more effective for energy modeling by academics and business professionals [54].

One of the main struggles for BIM to BEM translation is defining the thermal zones. A zone is a fundamental component of the input models for the building performance simulation tools. Simulation zones determine the building model's spatial representation, and a zone's air is believed to be perfectly mixed. Internal load attributes can only be considered if interior spaces are defined, as would be the case with a conceptual building design. According to ASHRAE [91], floors could be divided into a core region and a perimeter, with the latter being further divided based on the orientation of the space. However, a thorough building model with one zone per room can be generated if interior areas are defined. This model's simulation results may allow zones to be grouped depending on their simulated behavior [92].

There are various approaches regarding the simulation zone selections in the literature. According to a study on energy analysis of domestic buildings in the UK [93], when comparing to the room-based zoning, the annual heating demand is underestimated by 17% and 26%, respectively, when there is only one thermal zone per level and one zone for the entire house. However, using one thermal zone per level may be an acceptable approach in another project in the conceptual design phase due to the need for more detailed information and computational cost. Therefore, selecting the best zoning approach is a decision that should be made before the energy studies in every project stage.

Several top Computer-Aided Design (CAD) manufacturers currently offer BIM-based design authoring software. It has been proved that BIM software could automatically generate thermal zones in a proposed design and accurately simulate building energy use. For instance, Autodesk Revit® offers tools that automatically divide a building's geometry into perimeter and core zones at each story based on ASHRAE 90.1 [94]. Moreover, it can produce thermal zoning based on previously assigned rooms or spaces in the architectural model, which eases the way for creating the analytical model. We have implemented a zoning strategy based on the designated rooms and spaces for this research.

The accurate model creation is essential to prevent possible geometry issues later. This model underwent several scans for issues and problems, and fixations are done manually inside the software. For example, it is crucial to ensure that walls are perfectly stacked because if they are slightly offset, there would be chances to cause geometry issues when exporting the model to gbXML format. Another example is to assign an offset as the size of the element's thickness when placing the roofs to avoid gaps between walls and roofs. Moreover, the spaces would be designated as thermal zones. A total number of 1188 analytical spaces are assigned in this project automatically inside Revit. It is vital to constantly check the schedules for each floor concerning the name, area, and upper limits of spaces. The spaces less than 5 m^2 in the area are considered unoccupied, and the load inputs are not assigned to them.

After fixing all the problems, assigning the construction attributes to the building elements, and creating the analytical model, the simulation-ready model is translated to gbXML for the energy modeling procedure. This research uses the Green Building Studio (GBS) for energy simulations. As discussed earlier in Chapter 2, this simulation software has limitations, specifically for introducing the HVAC system. However, due to its compatibility with Autodesk Revit, it is acceptable to implement it for the BIM to BEM procedure. Using other simulation computer tools is suggested for further investigation and comparison.

In this process, the data transformation dependability is most significant. Therefore, evaluating the accuracy of the data imported from the BIM to BEM tools is necessary. Table 5.1 illustrates the compatibility of our model with the utilized BEM tool. As shown, not all the attributes were correctly translated. Eventually, the missing parameters should be added later in the energy simulation tools, or the built-in "System Analysis" section in Revit® could facilitate the process.

Figure 5.2 demonstrates the results from the simulated data from BIM, compared to

Table 5.1: The compatibility of the case study model with the BEM tool

Criteria	Compatibility with BEM tool
Location and weather file	$\Diamond$
Geometry	$\checkmark$
Construction and materials	$\Diamond$
Thermal zones	$\checkmark$
Occupancy operating schedule	$\times$
HVAC system	$\times$

$\checkmark$: Compatible $\times$: Not Compatible $\Diamond$: Partially Compatible

the average measured data from Concordia University Facility Management from 2017 to 2021. The higher loads of electricity during winter confirm that the primary heating system is performed by electricity. As mentioned earlier in Chapter 4.3, the gas boilers deliver hot water only when the system fails to satisfy the heating demand. Also, the term normalized electricity refers to the fraction of total electricity usage over the gross floor area of the building. The measured data was also converted to the same unit (kWh/m²) for a better comparison.

Also, the exact figure compares the baseline model to the calibrated model after several simulations. According to Chong et al. (2021), changing the computational model's numerical or physical modeling parameters to improve agreement with experimental findings is called calibration [95]. Numerous studies have followed this process to examine the accuracy of the outcomes, mainly in the Building Energy Simulation (BES) field. A manual calibration as an iterative trial and error procedure has been implemented in this study.

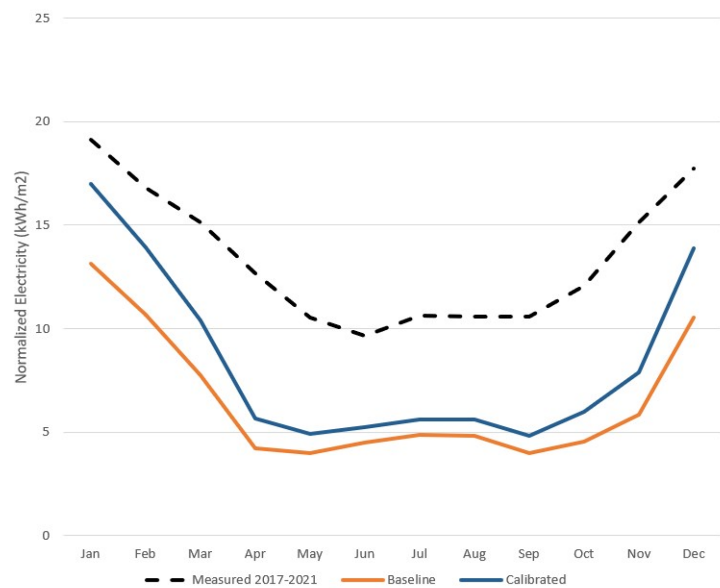


Figure 5.2: The baseline, calibrated and measured electricity data

The energy model went through numerous runs with slightly different changes in inputs. The initial run (baseline) is the model with the translated data from gbXML and the default values of GBS. The ultimate calibrated model is presented after introducing the rest of the attributes missing from the energy model inside the simulation tool. We first calibrated the BEM tool and added the UBEM scenario to the comparison. This is because the BEM is less complex and can be easily adjusted. However, the other way could as well be tested and compared. The UBEM is added to the comparison in the next section, and the results are presented.

5.2 Results from UBEM

This section performs the energy simulation on the targeted building among the other neighbors. The generated model discussed earlier is used as the geometry for this analysis. The calibrated BEM input parameters discussed in the previous section are used for the main building. The surrounding buildings are also introduced as shading elements to consider their impact on the energy loads.

Figure 5.3 compares the results from the individual building, the building in the neighborhood, and the measured data. The figure shows electricity consumption increases by introducing the context geometry, especially during winter. For a more accurate comparison of various scenarios, root mean square error (RMSE) and mean bias error (MBE) analysis were used to determine how well the simulated monthly consumption patterns matched the monitored data [96]. The RMSE and MBE definitions are shown in Equation 5.1 and Equation 5.2, and the results are shown in Table 5.2. The benchmark values for ideal MBE and RMSE, extracted from ASHRAE Guideline 14 (2002), are ±5% and 15%, respectively. However, in this research, we used the same evaluation metrics to compare our models' performance.

$$RMSE(\%) = (\frac{100}{M_{i,av}}) \times (\frac{1}{n} \times [\sum (S_i - M_i)^2])^{0.5} \tag{5.1}$$

$$MBE(\%) = (\frac{100}{M_{i,av}}) \times \frac{\sum (S_i - M_i)}{n} \tag{5.2}$$

where $M_{i,av}$ is average of the measured data, M_i is measured data, S_i simulated data, and n is number of values.

Table 5.2: Calibration results

Scenario	Electricity consumption calibration	
	RMSE (%)	MBE (%)
BEM	38.69	-37.13
UBEM	23.85	-14.47

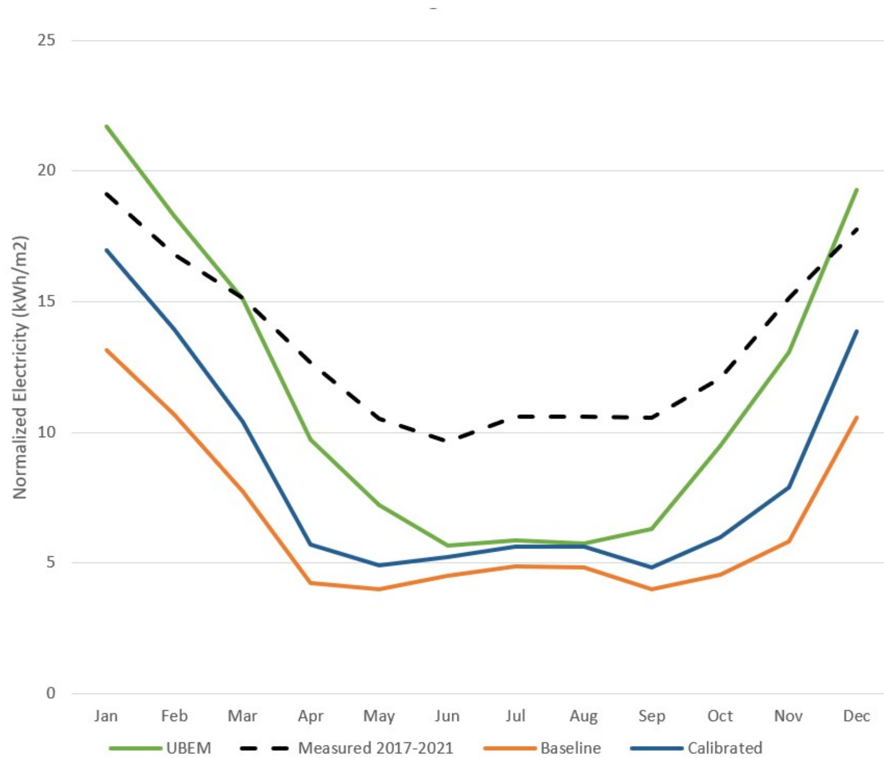


Figure 5.3: The baseline, calibrated, measured, and UBEM electricity data

According to Table 5.2, the results from the calibration confirm that by introducing the surrounding buildings to the energy model, the overall performance of the simulations improves. The main difference between the calibrated model and UBEM is the impact of shading from the urban context. As Figure 5.3 shows, shading contribution to energy consumption is higher during summer. Otherwise, a higher EUI could have been seen in the UBEM, as it is in winter. Considering that the non-geometric variables, location, weather data, and simulation engines are meant to be mainly the same, the environment of the architectural modeling and energy calculations are different. That may explain the general shift in the values reported by UBEM.

It is worth mentioning that the measured data was collected from 2017 to 2021. And COVID-19 affected the university's occupancy schedules during the latter two years. At the same time, we used the same occupancy schedule according to the collected data before the COVID-19 wave. Hence, our reported outputs on each model are slightly (∼15%)

overestimated. Eventually, surrounding buildings could be a determinative parameter of decision-making in energy consideration of a building in a high-density environment.

5.3 Impact of the Surrounding

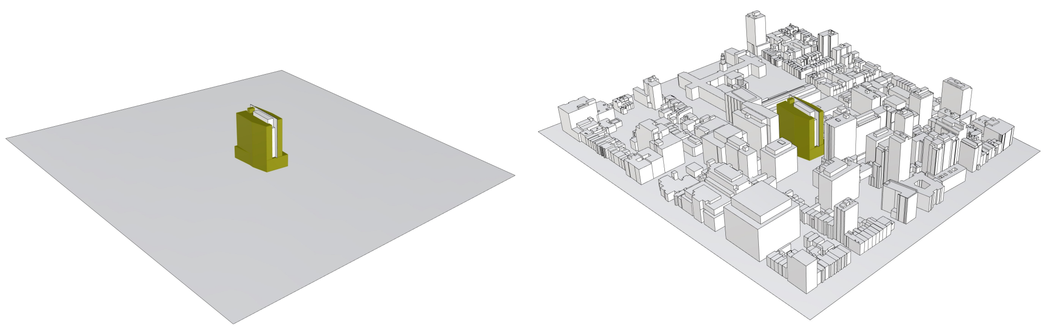
Once the urban block concept has been established, several urban morphological parameters that describe the block and correlate strongly to energy consumption and production can be determined [97]. The urban morphological parameters in this research include average building height (H), floor area ratio (FAR), building coverage ratio (BCR), volume area ratio (V/A), and sky view factor (SVF). The literature on implementing these indicators is available in chapter two. However, Table 5.3 below briefly describes each of the abovementioned parameters.

Table 5.3: Definitions of the Urban Morphological Indicators (UMIs)

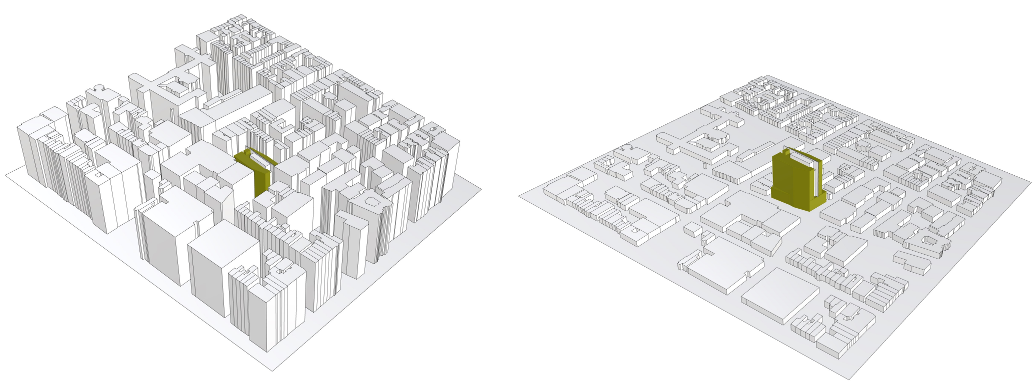
Category	**Urban Morphology Indicator**	**Definition**
Geometrical	Average Building Height (H)	It calculates the average height of the buildings within a block.
Urban Density	Floor Area Ratio (FAR)	Using the ratio of the gross floor area of buildings to their site area as a measure of compactness or urban density
Urban Density	Building Coverage Ratio (BCR)	The building area ratio divided by the site area.
Urban Density	Volume Area Ratio (V/A)	V/A is the ratio of the volume of the building to the urban site area.
Latitudinal	Sky View Factor (SVF)	SVF calculates the percentage of the surrounding hemisphere that is made up of sky at a specific location on a horizontal surface.

The height of buildings is considered an essential variable for investigating the impact of the surrounding buildings' shading effect. Therefore, three scenarios were introduced apart from the stand-alone condition. The first scenario (SC1) is the main building standing alone. Scenario number two (SC2) is the building with the actual urban context. The other alternative (SC3) is the case study building at its height surrounded by the existing buildings' footprints, expanded into 100 meters tall each. And finally, the last scenario is the main building among the context footprints extruded to only 10 meters, considered the low-rise scenario. Table 5.4 shows the characteristics of each scenario, and Figure 5.4 visualizes them. For creating the third and fourth scenarios, the footprints from the (OSM) data were used, and with the help of a Grasshopper algorithm, the geometries for these cases were generated.

Moreover, the abovementioned urban morphology indicators have been calculated for each scenario. Table 5.5 summarizes each parameter and its characteristics. The algorithm for automatically calculating the FAR, BCR, V/A, and SVF in Grasshopper is presented in Appendices C.1.



(a) (SC1) Stand-alone (b) (SC2) Actual Neighborhood



(c) (SC3) High-rise (d) (SC4) Low-rise

Figure 5.4: Visualization of different scenarios

Table 5.4: Different Scenarios

Number	Scenario	Number of buildings	Max. height of the buildings (m)	Min. height of the buildings (m)
SC1	stand-alone	1	77.67	77.67
SC2	main context	308	96.27	1.17
SC3	high-rise	308	100	77.67
SC4	low-rise	308	77.67	10

Table 5.5: Urban morphology indicator numbers for 4 scenarios

Parameter	SC1 Stand-alone	SC2 Main-context	SC3 High-rise	SC4 Low-rise
Number of buildings	1	308	308	308
FAR[1]	14%	389%	1335%	171%
BCR[2]	0.8%	40%	40%	40%
H_{bld}[3](m)	77.60	22.82	99.54	10.70
V/A[4]	0.42	9.25	39.19	4.25
SVF[5]	0.97	0.25	0.18	0.36

"[1]" Floor Area Ratio, "[2]" Building Coverage Ratio, "[3]" Average Building Height, "[4]" Volume Area Ratio, "[5]" Sky View Factor

Comparing the energy used for space cooling or heating when a building is part of a block network to the same building standing alone is the approach used to determine the shadowing impact from the surrounding environment. The results could be compared by a correction factor called "R," introduced by the literature [10]. This value is calculated as follows:

$$R = \frac{Energy\ of\ the\ building\ within\ the\ block}{Energy\ of\ the\ building\ stand-alone} \tag{5.3}$$

When there are no neighboring buildings, the "R" is one, and the energy changes depending on whether the "R" is less than or equal to one. "R" represents the correction factor for the building's space cooling and heating energy. The intensity of the shading corresponds to how far this number is from 1. Furthermore, the following calculation determines whether the energy demand is reduced or increased [10]. If the outcome is positive, it signifies that more energy will be used, and if the result is negative, it suggests that less energy will be used in that circumstance.

$$Reduced(increased)\ energy\ demand = (R - 1) \times 100\% \tag{5.4}$$

Figure 5.5 shows the heating EUI (kWh/m^2) for different scenarios. The columns are set from the least density to the highest to show the trend better. The stand-alone condition (SC1) has the least heating consumption, increasing as the surrounding buildings emerge. On the other hand, Figure 5.6 shows the opposite trend for the cooling EUI (kWh/m^2). Moreover, Table 5.6 summarizes the heating and cooling "R" values and the reduced or increased ratio of "R" in both summer and winter.

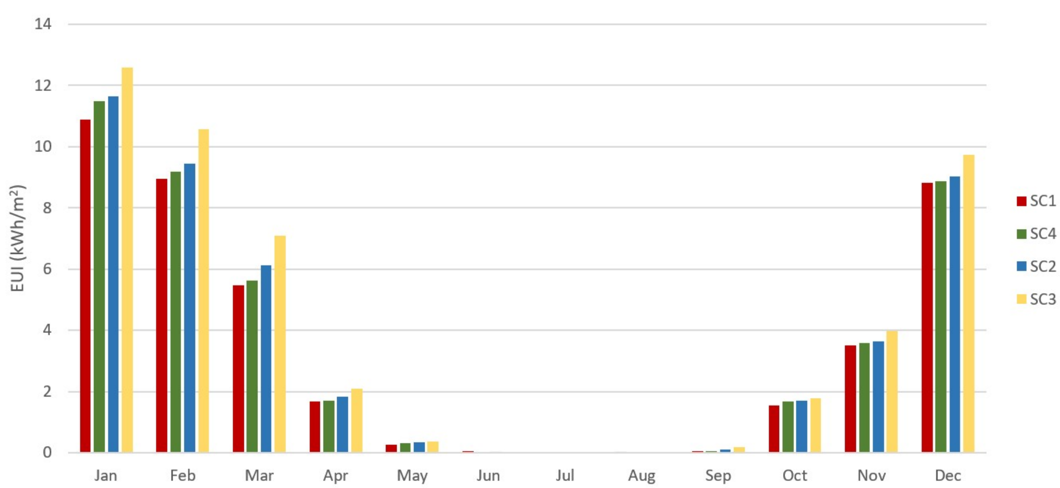


Figure 5.5: Heating EUI of the 4 scenarios

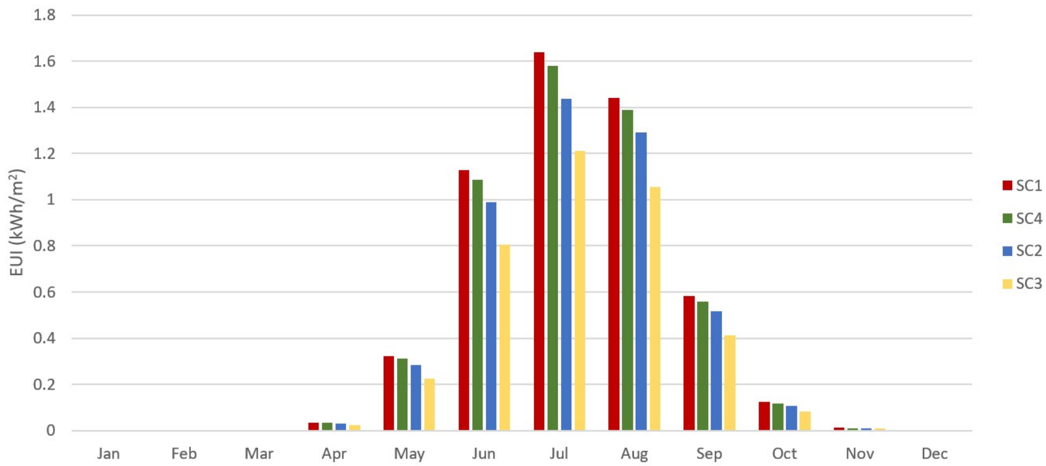


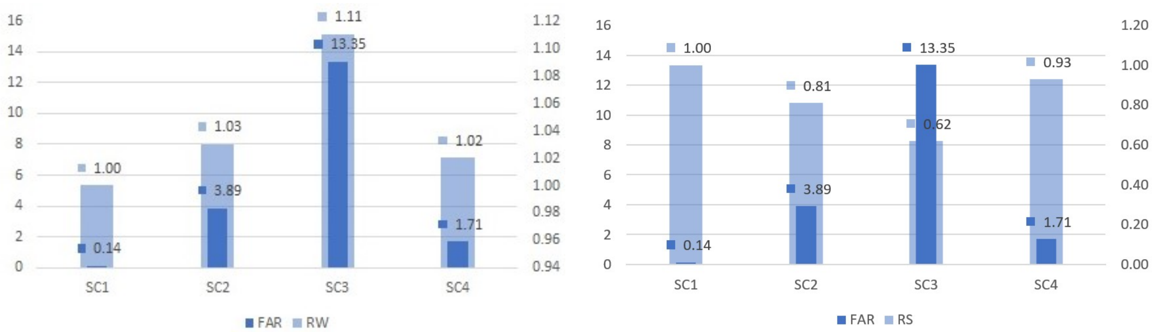
Figure 5.6: Cooling EUI of the 4 scenarios

Table 5.6: The numbers for "R" in summer and winter

Indicators	**SC1**	**SC2**	**SC3**	**SC4**
R_w	1	1.03	1.11	1.02
Increased energy ratio (winter)	0	4%	11%	2%
R_s	1	0.81	0.62	0.93
Reduced energy ratio (summer)	0	-19%	-37.48%	-6.23%

Based on the results, shading from neighboring buildings harms the targeted building and lowers energy consumption in the summer. However, energy consumption rises in the winter. It can be concluded that shading can have a positive effect in summer. Moreover, the reduced energy ratio in summer varies between 6.23% to 37.48%, meaning that the shadowing effect on space cooling energy readings is more pronounced than heating.

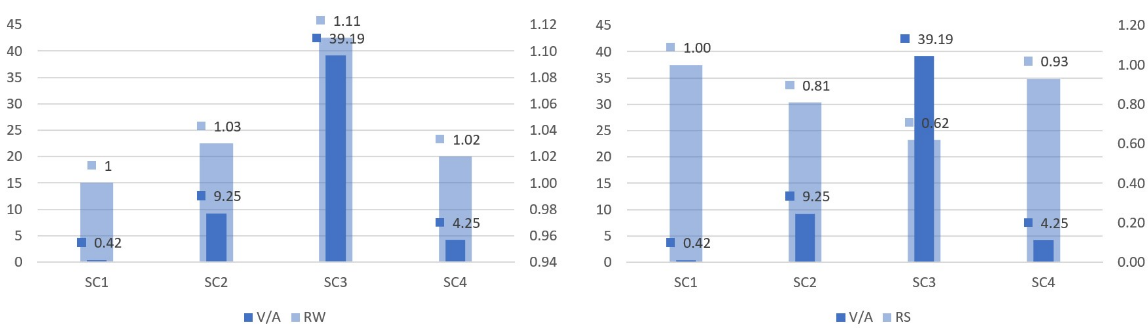
Additionally, the urban morphology indicators have been shown to influence the energy loads of a building in the metropolitan area. The graphs and trends of the relation between UMIs and R values are shown in the figures below. The Sky View Factor (SVF), for instance, has a reverse correlation with the height of the buildings or the FAR because of the blockage of the sunshades on the buildings, which results in a reduction in "R" during summer and its growth during winter. For example, creating dense blocks in hot climates reduces the SVF and lowers the received sun and cooling loads in the summer. However, the reverse could not necessarily be correct during winter in colder regions. Therefore, the impact of shading should be optimized and analyzed based on different parameters, and relative solutions should be implemented based on the region, envelope construction, and climatical matters.



(a) The relation between FAR and R_w

(b) The relation between FAR and R_s

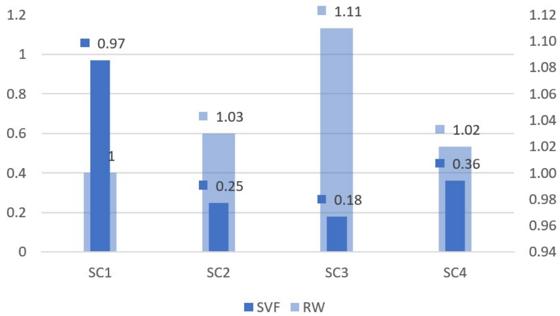
Figure 5.7: FAR and R in Winter5.7a and Summer5.7b



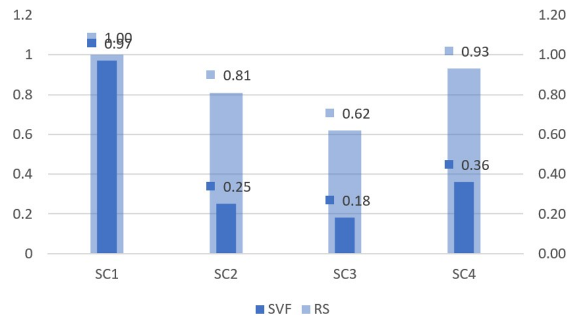
(a) The relation between V/A and R_w

(b) The relation between V/A and R_s

Figure 5.8: V/A and R in Winter5.8a and Summer5.8b



(a) The relation between SVF and R_w



(b) The relation between SVF and R_s

Figure 5.9: SVF and R in Winter5.9a and Summer5.9b

5.4 Impact of Window Types

As mentioned in the literature review, numerous studies have found that the building's façade, notably its outside windows, has significant energy-saving potential. The window primarily absorbs unwelcome heat increases through air penetration and sunshine radiation. In terms of heat gain, windows are the portion of the building that is most susceptible. Therefore, this objective evaluates the influence of implementing different window types on the case study building's heating and cooling values. The results are also compared by considering four different Window-to-Wall Ratios (WWR) and recognizing the optimized values for better energy performance.

There are specific characteristics related to the fenestrations in the buildings introduced by the National Building Code of Canada (NBC). Those metrics include the U-value, air leakage rate, and Solar Heat Gain Coefficient (SHGC). Their units and definitions are summarized in Table 5.7. The restrictions for implementing the mentioned metrics are assigned by NBC and are presented in Table 5.9, based on different zones in the country. Air leakage rates of operable windows and skylights that serve as environmental separators must be less than 0.5 L/(sm2). The National Building Code of Canada (NBC) divides the country into 6 zones based on the Heating Degree Days (HDD). As shown in Table 5.8, Montréal is considered among the areas with HDD values from 4000 to 4999, zone 6. Also, the National Energy Code for Buildings (NECB) establishes the maximum allowable door and fenestration areas for the business sector. With increasing HDD, the ratio of the glazed area to the total wall area changes from 0.4 to 0.2.

Table 5.7: Performance metrics in fenestrations

Performance metrics	**Unit**	**Description**
U-value	(W/m^2K)	The heat transfer per time per area and per degree of temperature difference
Solar Heat Gain Coefficient (SHGC)	-	The ratio of the solar heat gain entering the space through the fenestration
Air leakage	(L/sm^2)	The flow of air that passes through fenestration

Table 5.8: Climatic Design Data for Selected Locations in Canada

Location	**Elev., m**	**Design Temperature**				**DD below 18(° C)**	**Hourly wind pressure, kPa**	
		January		**July**			1/10	1/5
		2.5%(° C)	**1%(° C)**	**Dry(° C)**	**Wet(° C)**			
Montréal (CityHall)	20	-23	-26	30	23	4200	0.34	0.44

Table 5.9: The Required Thermal Characteristics of Fenestration and Doors

Components	**Thermal characteristics**	**HDD of building location in Celsius Degree Days**					
		zone 4: < 3000	**zone 5: 3000 to 3999**	**zone 6: 4000 to 4999**	**zone 7A: 5000 to 5999**	**zone 7B: 6000 to 6999**	**zone 8: ≥ 7000**
Fenestrations and doors	**Max. U-value** (W/m^2K)	1.84	1.84	1.61	1.61	1.44	1.44
	Min. Energy Rating	21	21	25	25	29	29

Many factors, including the type of framing material, number of glass layers, type and placement of low-emissivity (Low-E) coating, type and size of spacer between glass layers, and type of gas used to fill the glazing unit, are involved in the design of windows. These factors would affect their energy performance and compliance with the code's energy efficiency requirements. This study has selected and introduced different glazing configurations from the ASHRAE Handbook Fundamentals (2021) [91]. The last window type represents the best European windows extracted from Dermentzis et al. (2021) [98].

Moreover, four different WWRs (0.2, 0.4, 0.6, 0.8) have been selected for the case study. This ratio is assumed to be identical on all faces of the building. These configurations have been applied with and without the existence of surrounding buildings. Table 5.10 shows the performances of the selected windows. And, the results for the heating and cooling EUI $\left({}^{kWh}/{}_{m^2}\right)$ are presented in Table 5.11 and Table 5.12.

Table 5.10: Different window types

Window type	**Filled gas**	**U-value** $\left({}^{W}/{}_{m^2.K}\right)$	**SHGC**	**ID**
Single glazing	-	5.90	0.86	1S
Double glazing	Air	3.12	0.70	1D
	Argon	2.89	0.70	2D
Low-e double glazing	Air	2.85	0.60	3D
	Argon	2.15	0.60	4D
Triple glazing	Air	2.15	0.61	1T
	Argon	1.93	0.61	2T
Low-e triple glazing	Air	1.64	0.53	3T
	Argon	1.30	0.53	4T
Triple-glazed European window	Krypton	0.58	0.56	EU

Table 5.11: Heating EUI ($^{kWh}/_{m^2}$)

Winodw types	Model	WWR			
		20%	**40%**	**60%**	**80%**
1S	Alone	43.86	63.07	86.24	111.16
	In context	47.00	65.78	87.28	110.08
1D	Alone	35.37	43.85	56.14	70.55
	In context	38.37	46.82	57.90	70.44
2D	Alone	34.43	41.89	53.21	66.71
	In context	37.44	44.86	54.95	66.55
3D	Alone	35.36	42.50	52.94	65.31
	In context	38.12	45.59	55.23	66.24
4D	Alone	32.38	36.24	43.51	52.85
	In context	35.19	39.36	45.77	53.63
1T	Alone	32.27	36.13	43.47	52.91
	In context	35.11	39.24	45.68	53.59
2T	Alone	31.31	34.09	40.40	48.85
	In context	34.17	37.21	42.6	49.48
3T	Alone	30.99	32.32	36.66	42.95
	In context	33.63	35.49	39.25	44.36
4T	Alone	29.48	29.08	31.67	36.36
	In context	32.15	32.29	34.25	37.66
EU	Alone	25.92	21.95	21.20	22.93
	In context	28.73	25.28	23.64	23.60

Table 5.12: Cooling EUI ($^{kWh}/_{m^2}$)

Winodw types	Model	WWR			
		20%	40%	60%	80%
1S	Alone	11.13	14.87	18.71	22.41
	In context	9.68	11.98	14.42	16.85
1D	Alone	10.63	13.63	16.90	20.13
	In context	9.40	11.21	13.23	15.24
2D	Alone	10.68	13.72	17.04	20.31
	In context	9.44	11.28	13.32	15.36
3D	Alone	10.21	12.65	15.39	18.13
	In context	9.16	10.61	12.28	13.99
4D	Alone	10.38	12.95	15.85	18.75
	In context	9.31	10.83	12.60	14.41
1T	Alone	10.42	13.06	16.02	18.97
	In context	9.34	10.90	12.71	14.55
2T	Alone	10.49	13.18	16.19	19.22
	In context	9.39	10.99	12.84	14.72
3T	Alone	10.18	12.45	15.06	17.70
	In context	9.17	10.57	12.15	13.80
4T	Alone	10.30	12.67	15.39	18.16
	In context	9.27	10.73	12.40	14.13
EU	Alone	10.76	13.65	16.95	20.34
	In context	9.63	11.47	13.55	15.70

The results have been showing that there is a positive correlation between energy consumption and the window-to-wall ratio. In reverse, the energy consumption and the U-value are negatively correlated. Also, when introducing the context geometry to the model, it has been shown that the heating consumption increases and the contrary for the cooling consumption. The highest reading for heating is 80% WWR, single-glazed window (the highest U-value) in the stand-alone condition, which is the same for the cooling loads. At the same time, the lowest number in heating is dedicated to the 60% WWR, using the standard European window with the U-value of 0.58 $(^{W}/_{m^2K})$ standing alone. At the same time, the minimum energy reading from these window configurations during summer is linked with the low-e double-glazed glass filled with air with 20% of WWR and among the neighbors. In the following tables, the maximum values are represented in red, and the minimum numbers are shown in blue.

The following figures are created to understand better each design parameter's trends and influence on the heating and cooling loads. In Figure 5.10, stand-alone and group scenarios are compared in different WWRs for heating consumption. Moreover, a similar graph is represented for creating the other set of numbers during summer, as shown in Figure 5.11.

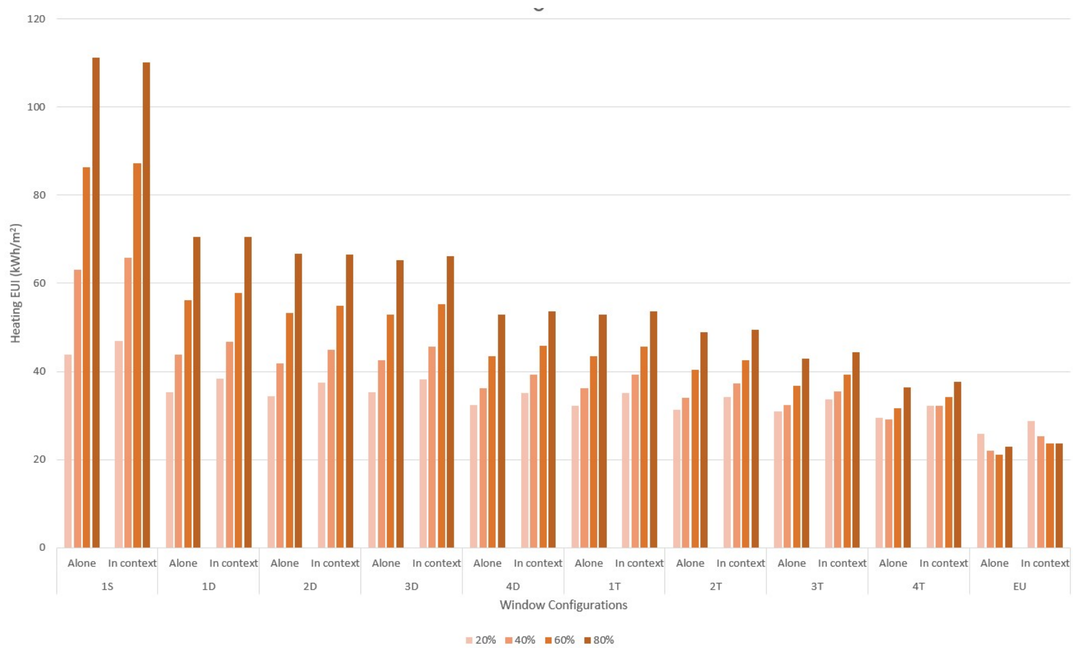


Figure 5.10: Heating EUI $\left(^{kWh}/_{m^2}\right)$ for different window configurations

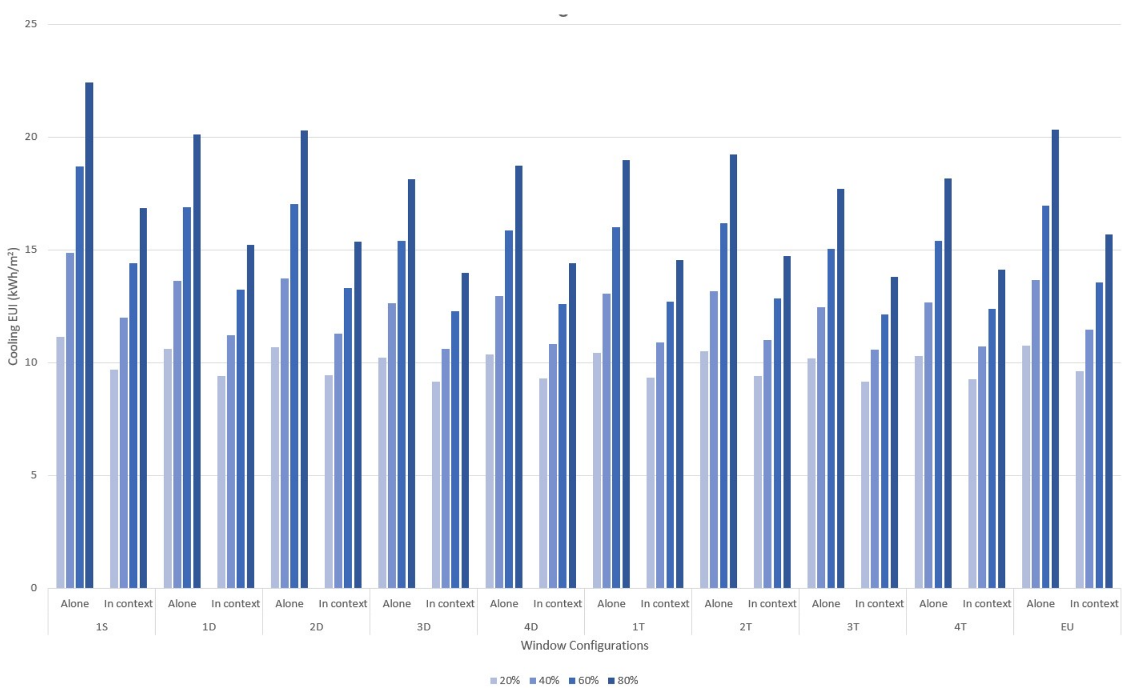


Figure 5.11: Cooling EUI $\left(^{kWh}/_{m^2}\right)$ for different window configurations

In urban energy simulations, different types of windows can significantly affect buildings' energy performance. Windows influence the amount of solar radiation penetrating the building and the heat lost through the windows. Single-glazed windows have poor thermal insulation and release significant heat from the building during cold weather. Consequently, there are heavier heating loads and more energy needs. While, Double and triple-glazed windows can help decrease heat loss from the building during cold weather, as well as the building's heating load. As shown in 5.11, with improving the glazing material, the heat loads are decreasing, both in the individual scenario and the urban model. The type of window used in cold climates is determined by several variables, including the building's orientation, the local climate, and the energy performance objectives. However, it is essential to consider the context buildings as the shading elements for modeling different window types for estimating their effect on building energy performance.

5.5 Comparisons and Discussions

Section 5.1 discusses the compatibility of using BIM in energy modeling and the simulated results. It is essential that we can benefit from the information within the building models. However, there is no standard translating procedure from the BIM environment to the BEM, and users can implement their methods based on their projects and needs. This chapter's findings indicate that the geometry, construction, materials, thermal zoning, and weather files could be extracted from BIM and used in the building energy modeling environment. At the same time, the occupancy schedules and HVAC systems were incompatible. Later in Section 5.2, the results from energy simulation of the case study buildings, among the others, were analyzed and compared to the ones from BIM. It has been shown that the results from UBEM are closer to the measured data of the last 5 years.

A more comprehensive investigation has been done on introducing the neighboring buildings in Section 5.3 with 4 different scenarios and building heights. Based on the results, shading from neighboring buildings harms the targeted building and lowers the energy consumption in the summer, while it rises in the winter. Shading has a positive effect during summer. The reduced energy ratio in summer varies between 6.23% to 37.45%, while the highest increased value for winter is 11%. The impact of shadowing on space cooling energy consumption is more pronounced than heating.

The urban morphology indicators have been shown to influence the energy loads of a building in the metropolitan area. The SVF, for instance, has a reverse relation with the height of the buildings due to the blockage of the sunshades on the buildings. Eventually, creating dense blocks reduces the SVF and cooling loads in summer, while the opposite is true during winter. SVF is essential to urban energy modeling because it influences the urban heat island effect, the quantity of solar radiation that hits the ground and buildings, and the urban microclimate. Moreover, The Floor Area Ratio (FAR) and Volume Area Ratio (V/A) are two of the density-related urban morphology indicators, and they have positive correlations with the R_W and negative correlations with R_s.

For the last objective of this study, a comparison between 10 different window types is made in Section 5.4. The window U-value, SHGC, and 4 different WWRs were analyzed in two scenarios of the individual buildings and the one in the neighborhood context. Windows with greater U-values have lower annual cooling loads and higher annual heating loads. Despite having less surface area than the buildings, windows account for the majority of heat gain in a building. This is because windows also have radiation gains in addition to conductive increases. Since the presence of the surrounding buildings influences the amount of received radiation by windows, the energy results vary depending on the neighbors' existence. The energy readings from different window types could be more accurate when modeled and simulated in the urban context. It has also been concluded that increasing the WWR makes the difference between the individual and UBEM scenarios more dramatic, meaning that with the 80% WWR, the difference between alone and in-context scenarios is higher compared to 20% of the window-to-wall ratio.

Overall, according to the results, the surrounding buildings' morphology and orientation change the shading effect. This change impacts the space cooling and heating energy of the main building. To determine the building energy demand for energy planning, it is essential to consider the circumstances of the targeted building's surroundings. It is impossible to disregard the effects of shadowing caused by surrounding elements. The amount of solar radiation entering the building must be minimized as much as possible in the summer, although the opposite is preferable during winter. The urban context serves as the foundation for the dynamic simulation of building energy consumption and determines the extent of the effect, therefore, it should not be neglected.

Chapter 6

Conclusion

Several objectives were studied in this thesis, including the differences between UBEM and BEM techniques, tools, and workflows. Additionally, the energy consumption of a single building and a group of buildings has been examined by calculating the heating and cooling consumption using physics-based engineering methods. The findings have been verified with the actual readings. Moreover, three different urban density scenarios were introduced to study the impact of nearby buildings' shade during summer and winter compared to the individual building. The effect of window types and WWR was also discussed in individual and group buildings for the final objective.

The outcomes indicated that the shade from surrounding buildings significantly impacts the precision of the targeted building's load calculations. In the summer, shading from adjacent buildings typically has a negative effect on the targeted building and lowers energy consumption, whereas energy consumption rises during the winter. The climatical conditions, block networks, and the urban layout could affect how the results alter. As a result, this conclusion could not be applied to all geographical areas and building types. However, the fact that increasing the heights of the surrounding environment results in an underestimation of energy requirements could be generalized, considering all other factors unchanged.

6.1 Summary and Contributions

Researching the energy behavior of high-rise buildings among their neighbors is now more critical due to the population shift from rural to urban areas. Given how crucially important building energy consumption is to a sustainable environment, a lot of work has been put towards precisely forecasting the building energy demand in various areas, including building envelope, internal gain, scheduling, and human behavior. Studying the performance of buildings in an urban setting is particularly crucial given the rapid urbanization rate and the increasing growth of urban buildings. It is essential to research the shading impact from surrounding buildings to determine the precise energy needs of a building since researchers tend to focus more on a building's energy performance within a network than on a structure that stands alone.

The primary contribution of this thesis includes the development of a method for measuring a building's energy performance that considers the morphology of its surrounding network of buildings. We first developed the energy models of our case study for both individual and urban energy simulations. We took advantage of different data formats and modeling platforms. BIM, for instance, could be beneficial in providing the as-built parameters for energy simulations. Implementing BIM could save time and effort in creating an energy model. Second, we introduced three scenarios with different surrounding buildings' heights. Then, we compared the heating and cooling consmuption of our case study building in each case. This confirmed that more shading from nearby structures positively influences the cooling consumption during summer, and on the contrary, it could increase the heating loads in winter. Aside from the height of the buildings, we investigated the impact of FAR, V/A, and SVF on the energy loads of our case study. Finally, as an essential element in urban buildings, we compared different window types in the context of an urban block.

Due to the population growth in urban areas, the importance of energy demand simulations on mid-rise and high-rise buildings is noticeable. Therefore, the height of the buildings is the key parameter of this research. The findings show that buildings can influence the energy dynamics of other buildings and that this effect changes depending on the climatological setting and season. Based on the results mentioned in Chapter 5, both in terms of primary energy and "R," this research has proved that when one or more of the parameters change, as in the case of an urban context, buildings can significantly impact the energy performance of their surrounding buildings. It is feasible to go beyond the limitations of conventional energy assessment techniques and offer innovative ideas to increase energy efficiency by considering the spatial interaction between the targeted building and nearby ones.

6.2 Impact and Significance

In a modern city, the government establishes its energy strategy to efficiently, safely, and effectively supply the community's energy demands. Various energy conservation strategies can reduce the environmental impact of energy production and use. As one of the biggest energy-consuming industries, buildings can significantly aid energy conservation. The results of this research will provide additional design considerations for urban planners, green building designers, and other experts in the AEC industry on the built environment. According to the local climate and geographic facts, the creative scheme design may re-evaluate the strategy of buildings and block networks. It can rebuild the urban form based on superior building energy characteristics.

It has been discussed that models could be more accurate by introducing the as-built thermal zoning or considering them among the actual neighborhood. Consequently, the outcomes from energy simulations are more accurate. However, there would be various constraints to that approach. The construction phase, the project timeline, the climatical condition of the site, the availability of the models, the surrounding environment, and so many other issues could vary from one project to another.

For instance, a BIM-created energy model offers various advantages because the information already contained in its aids in automating the process. However, the BIM to BEM conversion is a non-standard procedure that results in building energy models that differ from user to user and application. Eventually, it is up to the engineers to decide how they would proceed with energy evaluations and how they would benefit from the outputs.

6.3 Limitations

This study provides a variety of simulations in the field of energy efficiency on urban and building scales. However, several limitations have been found that can be further addressed. More importantly, this study has only considered one particular building type in a climate, meaning that the methodology is only implemented in a semi-continental environment with a warm, humid summer and cold winter. The tools, workflows, and data formats (epw, gbXML, DWG, etc.) all have different types of limitations regarding implementation, data exchange, level of detail, and compatibility.

Moreover, several impacts of the urban heat island effects are neglected due to the enormous computational cost. For instance, the impact of wind tunneling, the effect of longwave radiation exchange between buildings, the surrounding surfaces, and the human activity heat sources have been set aside in this study. In addition, in selecting the criteria for comparing different scenarios, only the shading influence of the surrounding buildings and their heights are considered. The facade reflections, the general UHI effects, and vegetation are set aside for this study. The buildings are assumed to be on the same level, and only the above-ground floors are considered in the simulations. Moreover, their geometries are simplified to ease the simulation procedure. Regarding the case study building, the same loads and schedules are assigned despite selecting rooms and spaces as thermal zones. Due to the limited availability of measured and collected data, the complexity of the building systems, and the model complications, the calibration procedure may have gone through some limitations. This is because we could not use the actual values for specific building inputs, such as building loads, and instead, we used the proposed standard values for them. Finally, BEM took precedence for the calibration procedure because the model would have fewer complications in implementing the changes.

6.4 Suggestions for Future Work

For future studies, the same approach could be implemented on different building types in different climates and urban blocks with various densities. Additionally, there could be other research criteria regarding the connection between the building and district-scale energy modelings, such as the microclimate effects, occupancy, vegetation, or pedestrian comfort. Even in the architectural aspects, morphology, design shapes, façade composition, and many other subjects are interested in urban energy modeling.

Also, other workflows and building simulation software tools, such as eQuest and IES-VE, could be compared for different case studies and building types. However, in the bigger picture, a modular, open-source urban modeling framework is required to simulate demand for cities in multiple places. Because most currently available modeling tools are not open source and have restrictions on a fully automated approach for predicting building energy consumption. The amount of solar radiation that reaches buildings in metropolitan locations is influenced by geographic factors like latitude, reflection, and shading carried on by nearby objects such as buildings. In particular, in cities with a high urban density, the effects of solar reflecting and shade might become more or less powerful when there is a greater density of buildings. A fully integrated BIM with the surrounding environment and emphasizing energy strategies and retrofit methods could facilitate sustainable design and development.

Appendix A

Data Preparation

A.1 OSM

This section provides the algorithms and supplementary visualizations of the data preparation procedure. As it was told in the body of the thesis, the OSM-extracted data was initially used to acquire the geometry and site elements. However, the lack of heights for the buildings changed the data collection process. The figure below A.1 shows the Elk component algorithm in Grasshopper, followed by the different data from open street map A.2.

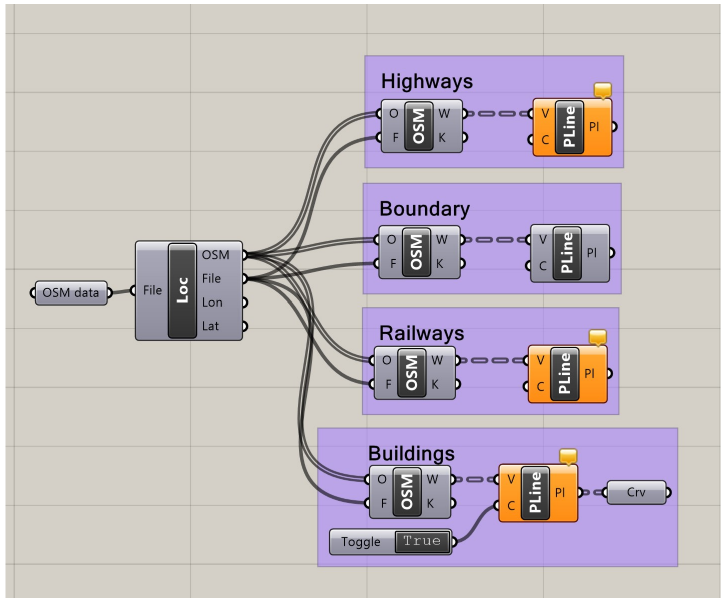


Figure A.1: Implementation of Elk in Grasshopper

Figure A.2: Visualized Data in Rhino Extracted from OSM

A.2 Sunlight Hour Analysis

The picture below shows the algorithm of Ladybug tools for calculating the total sunlight hours during a specific date and time.

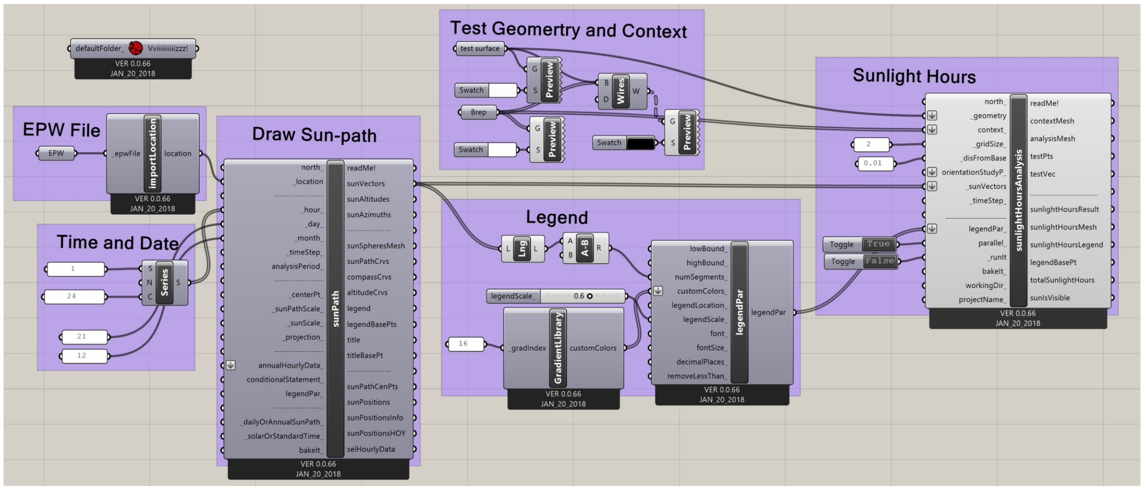


Figure A.3: Sunlight Hours Analysis in Ladybug

Appendix B

Weather Data

This section provides the Grasshopper scripts for calculating the weather-related diagrams on part 4.6. The first picture illustrates the creation of minimum and maximum temperatures in Montreal using Ladybug.

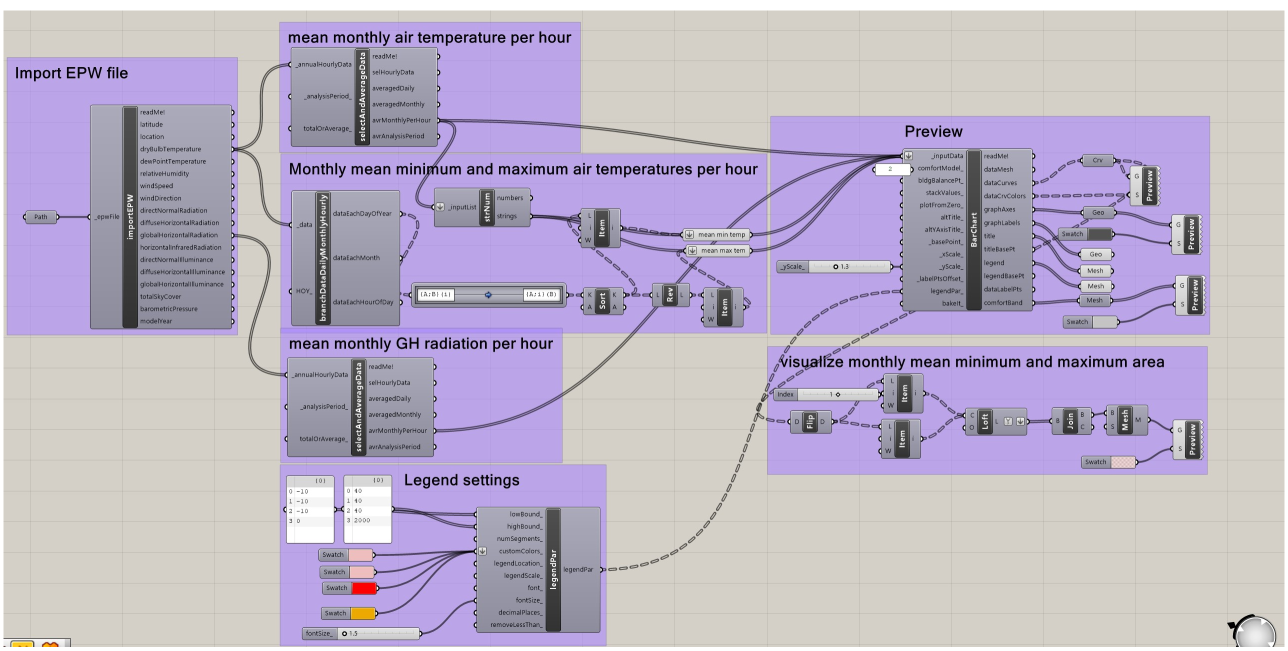


Figure B.1: Minimum and Maximum Temperature in Montreal

The following illustration presents the procedure of extracting the dry-bulb temperature and the relative humidity in an hourly resolution. Also, the yearly outdoor comfort, which was shown previously in 4.5, is extracted by considering a range from -3 (extreme cold) to +3 (extreme heat). With understanding the assumption that (-1,0, and +1) are only considered as comfortable outdoor temperatures, 34% of the time throughout a year, the weather is comfortable outside.

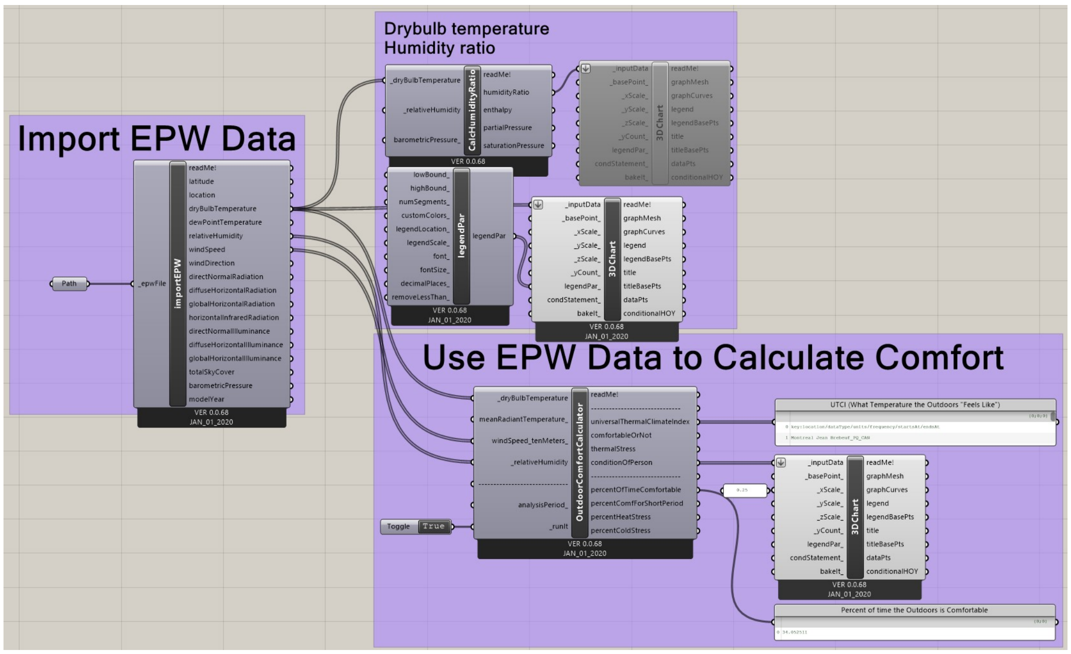


Figure B.2: Hourly dry bulb temperature, hourly relative humidity, and yearly outdoor comfort in Montreal

Appendix C

Simulation

This chapter of appendices presents the information and procedures for calculations and simulations. The algorithms for the Urban Morphology Indicators, the energy plus simulations process and inputs for both BEM and UBEM, and the extra outputs and results are described here.

C.1 Urban Morphology Indicators

In section 2.4, some urban morphology indicators are introduced, such as FAR, BCR, the average height of the buildings, V/A, and the Sky View Factor (SVF). The following Grasshopper algorithms are created for calculating these numbers.

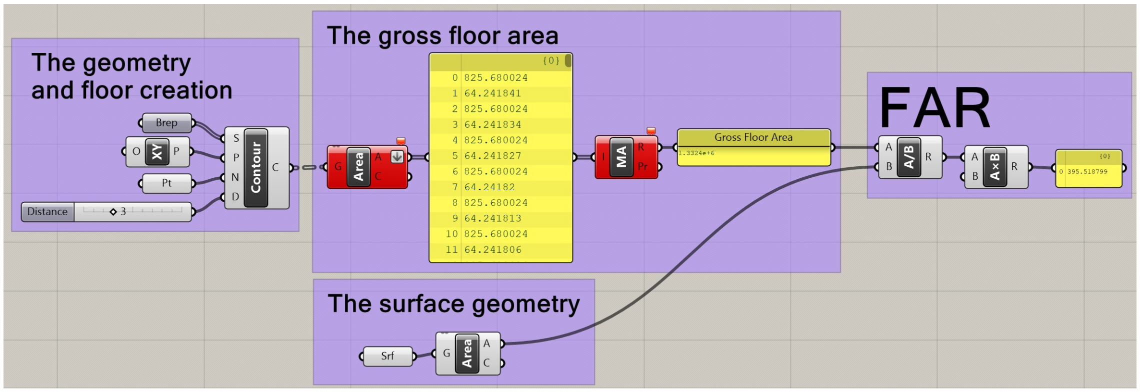


Figure C.1: Floor Area Ratio (FAR)

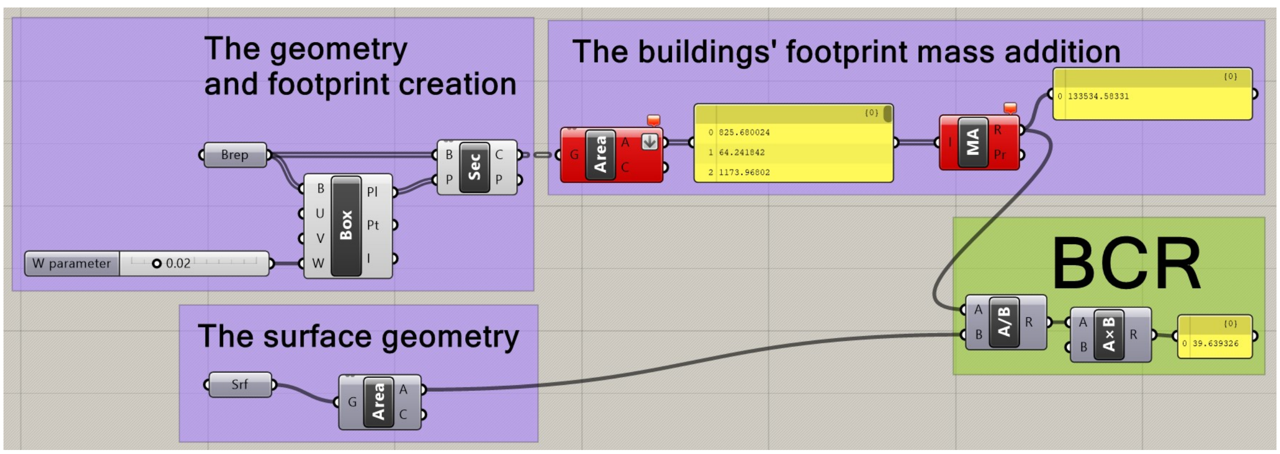


Figure C.2: Building Coverage Ratio (BCR)

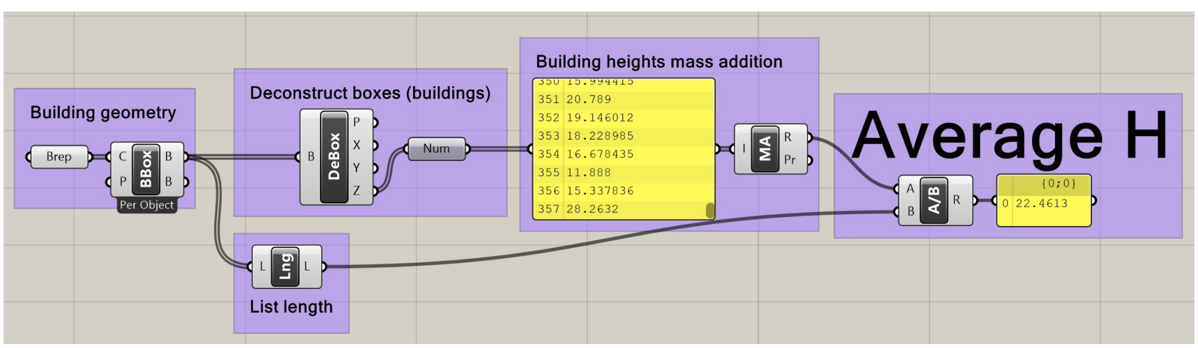


Figure C.3: The buildings' average height

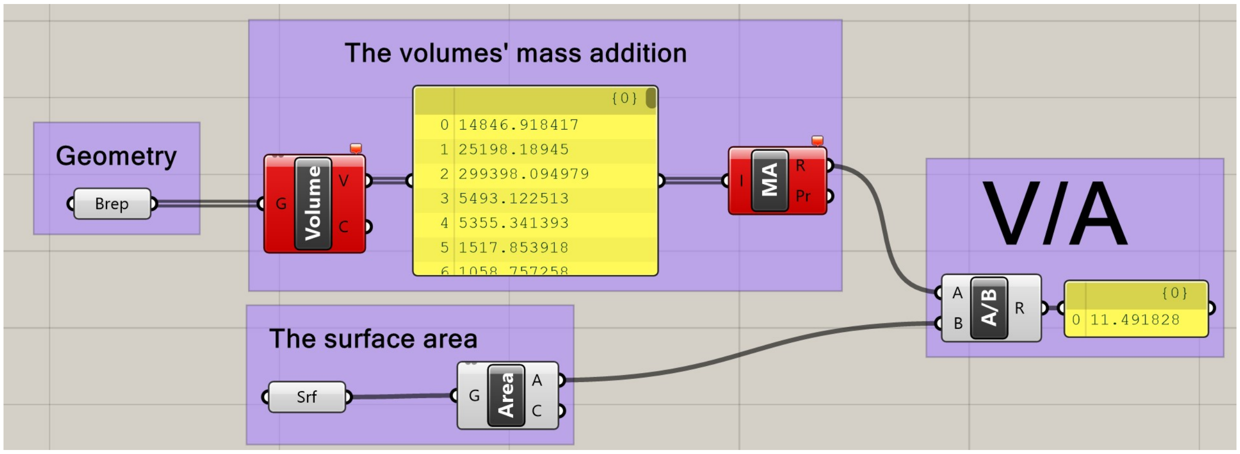


Figure C.4: The buildings' volume over area ratio

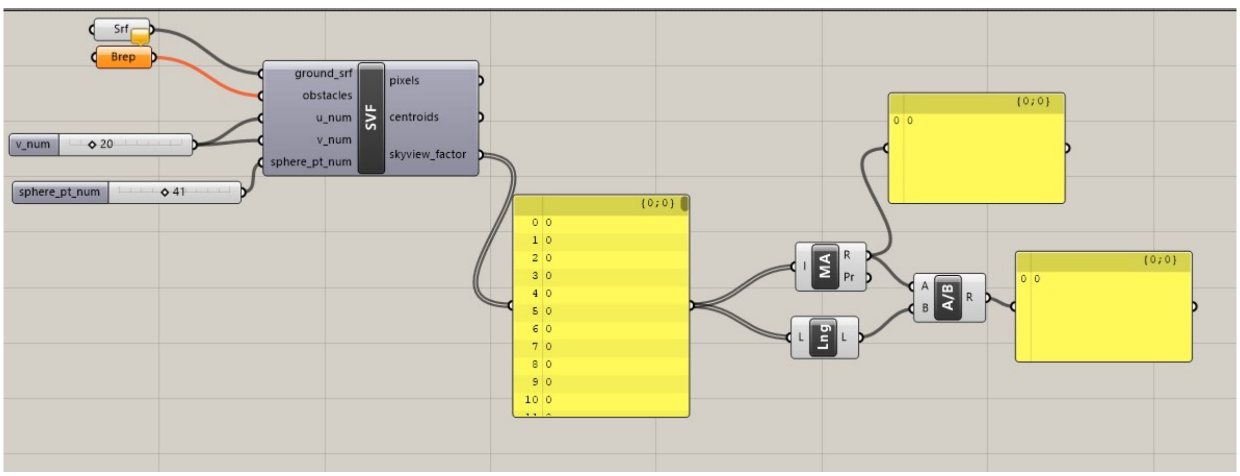


Figure C.5: Sky View Factor (SVF)

C.2 UBEM Simulation Workflow

The following figures describe the procedure for calculating the total EUI and electricity usage in Grasshopper, UrbanOpt. The first figure is the construction and load settings of the desired building C.6. After assigning the envelope and building loads, the geometries, WWR, and HVAC system are introduced to the model C.7. The final step is to assign the location, weather file, and simulation parameters, and to run the geoJSON file C.8.

The fixed and changing parameters used to do the optimization and calibration study on the created model are both introduced in the table. As it was mentioned previously in Chapter 4, the values are extracted from different sources. The main construction and some of the load values are from the as-built documents of JMSB. The other undefined inputs are extracted from the 2021 ASHRAE Handbook Fundemantals [91]. And finally, the schedules for the occupants are extracted from two related papers in this field [90, 89].

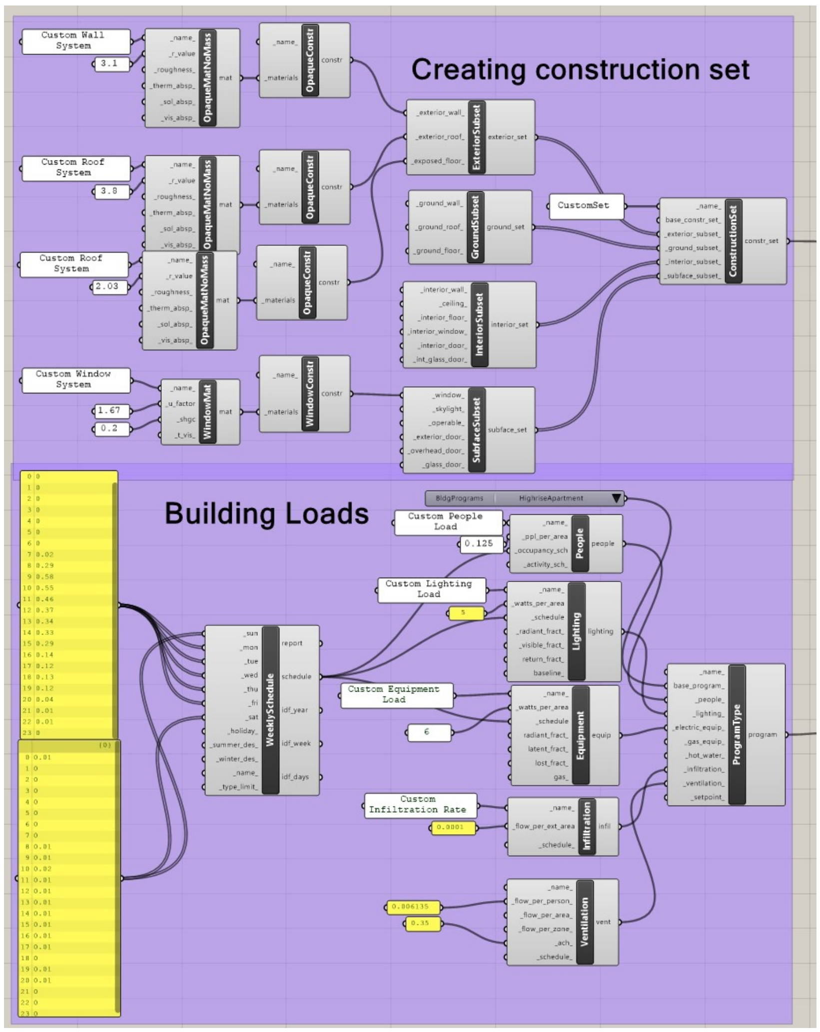


Figure C.6: The Construction and Load Settings in HoneyBee, Grasshopper

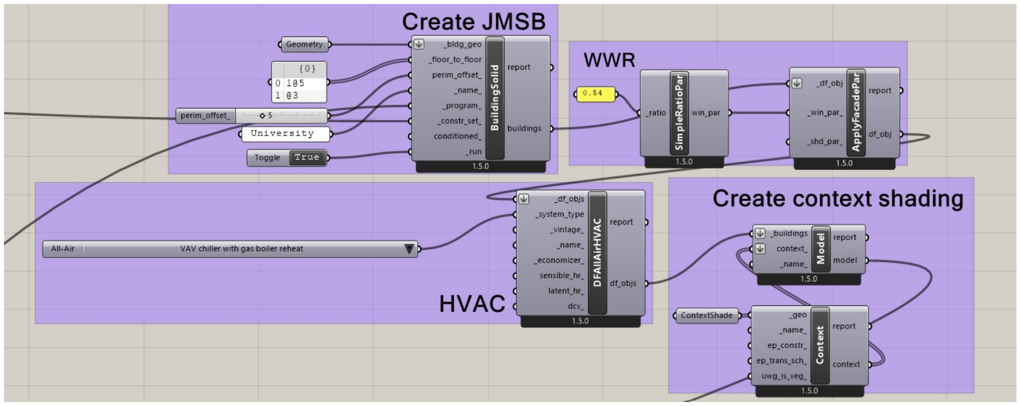


Figure C.7: The Geometry, WWR, and HVAC Assignment in HoneyBee, Grasshopper

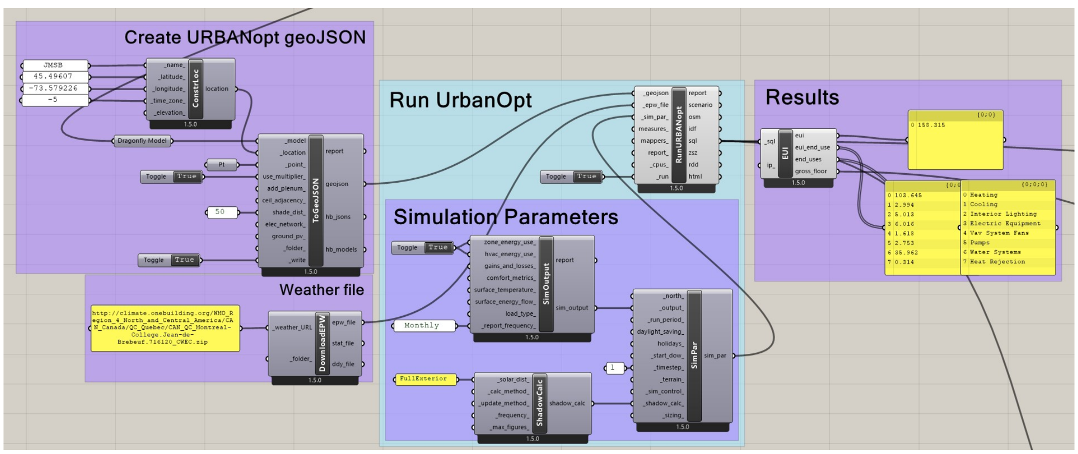


Figure C.8: The Location, Weather File, geoJASON RUN Components in UrbanOpt, Grasshopper

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