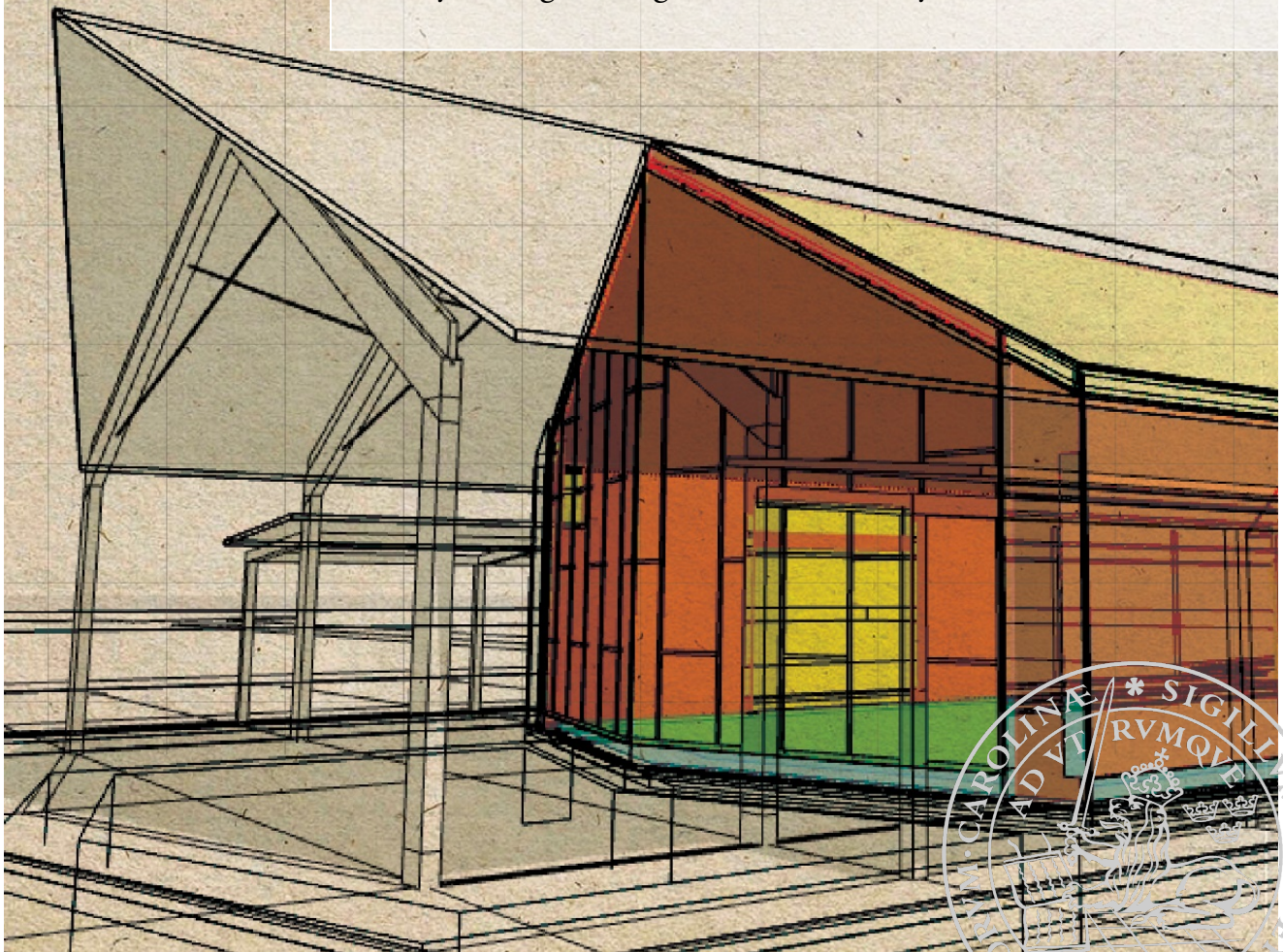


BIM to BEM

Development of integrated workflow from Archicad to
Energy Evaluation

Mariami Tkeshelashvili

Master thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University



Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

Master Programme in Energy-efficient and Environmental Building Design

This international programme provides knowledge, skills, and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behavior and needs, their health and comfort as well as the overall economy.

The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Keywords: Building Information Modelling (BIM), Building Energy Modelling (BEM), interoperability, performance based design, early design optimization.

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Abstract

Buildings are one of the main contributors to climate change as they consume a significant part of the total energy produced. The reduction of the energy consumption and carbon emissions of the buildings is vitally important for our environment. The building performance simulations (BPS) play an important role when it comes to energy-efficient building design. There are various BPS tools on the market today, and they are used for building design optimization at all stages of the design process. The most energy savings can be achieved during the preliminary design phase. Energy performance simulations can often be ignored during this phase for several reasons such as insufficient knowledge of simulation know-how, absence of detailed pieces of information about the loads and HVAC systems and interoperability challenges, which emerge during Building Information Modelling (BIM) to Building Energy Modeling (BEM) integration. Nowadays, interoperability between BIM and BPS tools is characterized by data clashes and losses during translation. In these circumstances, the given study analyzes current interoperability challenges by evaluating the shortcomings of the translation process using three typical BIM to BEM workflows. Workflows include one BIM and three different BPS tools and evaluations are based on three case studies. The results show that a promising solution to current BIM to BEM challenges can be the development of the BIM-integrated BEM tools, which today are often underrated due to their simplicity and limits.

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Abbreviations

BIM:	Building information modeling
BEM:	Building energy modeling
BPS:	Building performance simulation
EE:	Energy Evaluation
CT:	Cove.tool
CS:	Climate studio
GUI:	Graphical user interface
IFC:	Industry foundation class
gbXML:	Green building XML
TEUI:	Thermal energy use intensity
GFA:	Gross floor area
TFA:	Treated floor area
EEA:	External envelope area
TEDI:	Thermal energy demand intensity
EUI:	Energy use intensity
LPD:	Lighting power density
TST:	Total solar transmission
COP:	Coefficient of performance
SHGC:	Solar heat gain coefficient
ACH:	Air changes per hour
AEC:	Architecture Engineering Construction
CAD:	Computer-aided design
WWR:	Window-to-wall ratio
HVAC:	Heating, cooling and air conditioning
HDD:	Heating degree days

Definitions

Total solar transmittance

The percentage of incident solar radiation transmitted by an object includes the Direct Solar Transmission plus the part of the Solar Absorption reradiated inward. TST divided by 100 equals Solar Heat Gain Coefficient (SHGC) or g-value (Graphisoft, 2010).

Air changes per hour

The number of interior volume air changes that occur per hour and has units of ACH (Graphisoft, 2010).

Building volume

The volume of the conditioned air space of a building measured by its internal dimensions (Graphisoft, 2010).

Infiltration

Uncontrolled outside air movement into a building, typically through the cracks and nonvisible holes through the building envelope (Hopfe and McLeod, 2015).

Lighting power density

The maximum lighting power output per unit of floor area (Graphisoft, 2010).

U-value

U-value is the thermal transmittance, which is the rate of heat flow through matter. The U-value is dependent on the thermal properties of the window, wall, or component assembly and weather conditions. A smaller value indicates a lower rate of heat flow or better thermal performance. (Switala-Elmhurst and Udo-Inyang, 2014).

SHGC

Solar Heat Gain Coefficient is the fraction of solar radiation through a window to the incoming radiation on the window. g-values values range between 0 and 1 and a smaller value indicates less solar heat gain (Switala-Elmhurst and Udo-Inyang, 2014).

Infiltration

Infiltration or air leakage is the rate of air movement through a window or wall assembly. For windows, air leakage values typically range between 0.1 and 0.3 and the lower the value, the tighter the window (Switala-Elmhurst and Udo-Inyang, 2014).

HDD

Heating degree days (HDD) are a measure of how cold the temperature was on a given day or during a period of days (Graphisoft, 2010).

Dry Bulb Temperature

The dry-bulb temperature is the temperature of air measured by a thermometer freely exposed to the air, but shielded from radiation and moisture (“Dry-bulb temperature,” 2021).

WWR

The window to wall ratio is a fraction of the above-grade wall area covered with fenestration as a ratio of the total exterior wall area.

TEDI

Thermal energy demand intensity (TEDI) is calculated as transmission losses (conduction, convection, radiation, and air leakage) through the enclosure only. This metric is derived from the annual space heating and cooling energy demands, dividing them by the conditioned floor area of the building (Kesik and O'Brien, 2019).

EUI

EUI is expressed as energy per square foot or meter per year. It is calculated by dividing the total energy consumed by the building in one year by the total gross floor area of the building ("Energy Use Intensity (EUI)," n.d.).

Relative Humidity

The amount of water vapour present in air is expressed as a percentage of the amount needed for saturation at the same temperature.

Wind rose

A diagram showing the relative frequency of wind directions and speed at a place.

1 Introduction

1.1 Background

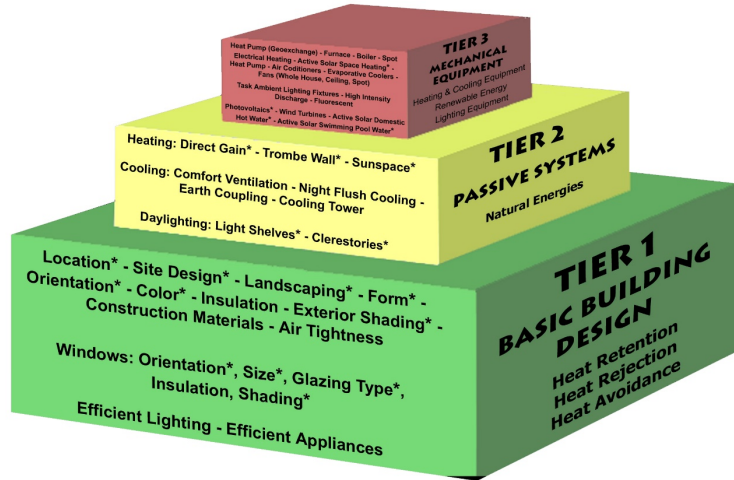
Globally, buildings are responsible for a significant part of energy consumption. The number varies by location, concretely in European Union buildings account for approximately 40 % of the total energy use (Energiläge, 2020), rate increases up to 48 % for the United States, with 36% for the operational energy and an additional 12% coming from the construction (Venkatraj et al., 2020). It has been several decades since scientists warned us that the planet and its natural systems have a specific limit of processing the waste. However, the rate of pollution is beyond this limit since fossil fuels are consumed at a pace beyond any previous point in history (Kendall, 1992).

As the age of cheap energy is coming to an end, the consequences of the accelerated climate change are forcing a radical rethinking of building construction techniques and the need for energy efficiency (Hopfe and McLeod, 2015). Numerous measures were taken to promote the reduction of energy consumption. The Kyoto protocol was one of the first initiatives towards the energy reduction process in 1997 (UNFCCC, 1997).

Despite increased awareness, the global energy demand continues to grow. It slowed down in 2019 due to slower economic growth and weather conditions (IEA, 2019), but the trend has changed due to the Covid-19 pandemic, which caused energy demand reduction by 6%, the largest in 70 years in percentage terms (IEA, 2020). The demand was decreased not because of the energy-efficient measures but rather due to lockdown restrictions. Unfortunately, as after previous crises, the rebound of the emissions can be larger than the reduction unless there are actions that promote cleaner and more resilient energy infrastructure (IEA, 2020).

The energy used to create an indoor comfort environment is mainly derived from non-renewable sources, which are carbon-based (coal, oil, and gas). The environmental problems that we face today are primarily caused by emitting large quantities of carbon dioxide (Alavyet al., 2021). Therefore energy reduction for the buildings is highly desirable.

Designing energy-efficient buildings can decrease their energy consumption up to 80% (Lechner, 2014). This can be more easily achieved by understanding the method of the three-tier design approach to sustainable design. The first tier works with basic building design techniques, the second tier with passive systems development, and the final tier with active systems such as mechanical equipment (Figure 1). The early design phase, mainly the first tier, is vitally important. It is characterized by the variability in the building parameters such as massing, the surface to volume ratio, orientation, etc. At this stage, 60% of reduction of the heating, cooling, and lighting can be achieved (Lechner, 2014). The decisions taken in this phase are the ones that most strongly affect building performance and are the most burdensome to adjust in a later stage.



THE 3 TIER APPROACH TO SUSTAINABLE HEATING, COOLING, AND LIGHTING OF BUILDINGS

* PART OF SOLAR RESPONSIVE DESIGN

Drawn by Barbara Ingreve at Auburn University

Figure 1. The three tier approach to the sustainability design of heating, cooling, and lighting (free poster available at www.heliodon.org).

The MacLeamy curve (Figure 2) shows that the further the design team is through the design process, the more complex and costly the changes become. The concept of “shifting the effort” can be understood as shifting the main working load towards the pre-design phase. The team has increased opportunity to make design decisions that have the highest effect on the functional capabilities and the cost of the design changes is the lowest (Gao et al., 2019).

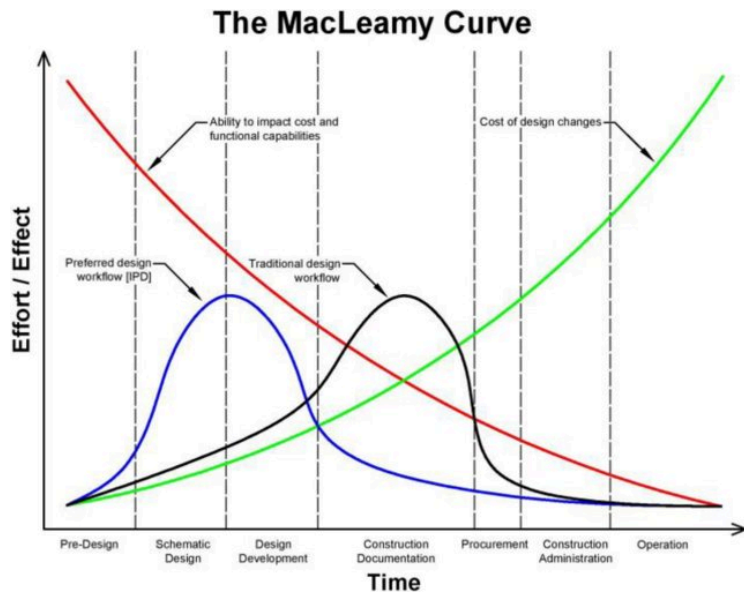


Figure 2. The MacLeamy curve (Available via license: CC BY-NC-ND 4.0).

The energy-efficient building design is a convoluted process, which involves a wide range of professionals with different backgrounds (Bracht et al., 2021). The trend of separating architecture and engineering is evident for much of the last century. Moreover, the energy part is mainly addressed at the third tier, which includes active systems. Usually, it is assumed that the engineering team can make any idea work at the mechanical systems level (AIA, 2012). On the other hand, architectural education is facing a skills gap – many architects do not obtain the skills they need to design energy-efficient buildings on graduation from schools of architecture (Thomson, 2020). Besides the fact that many architects lack simulation know-how, they do not have the time and resources to learn new tools (Paryudi, 2015). One of the reasons for the lack of motivation is that most Building Performance Simulation (BPS) tools are not architect friendly, which means that they are too complex and do not fit the working methods to which architects are used to. As a result, energy evaluation in pre-design is often avoided and the benefits of the early design optimization are reduced (Paryudi, 2015).

Another reason why the energy evaluation is being shifted towards the final design phase can be the lack of communication between different stakeholders during the early design phase. It is mainly caused by the low level of Building Information Modelling (BIM) use. BIM, shortly described as a software model containing information about the physical and functional properties of the facility, is mainly known for its ability of collaborative design (Rashed Alsharif, 2019). Thus, it is desirable to extract the full potential of BIM. Lack of joint effort can result in performing building's energy performance at the final stage of the design. Not because to motivate or examine design solutions that lead to energy efficiency, but rather for code compliance (Arayici et al., 2018).

There is a wide range of BPS tools worldwide. However, not all of them are suitable for the early design stage. The absence of accurate data in the first tier of the design process makes most BPS tools and workflows impracticable. Consequently, there is a need for the simulation tool, which can help architects to make early-stage decisions and provide a simple, flexible workflow that can result in reasonable energy assessment (Li, 2017).

1.2 Objectives

This study will assess the performance of Archicad's Energy Evaluation compared to other building performance simulation tools, identify associated challenges and limitations, and suggest modeling techniques and potential software features for better BIM to BEM workflows and integrations.

Moreover, the potential for immediate performance feedback referred to as “design optimization” will be determined. Which facilitates the achievement of energy-efficiency requirements at early-stage design and obtainment of a single model. Interoperability challenges will be further explored by proposing three different workflows based on three BPS tools in order to analyze the energy performance for three case studies.

1.3 Research questions

Within this study, the following questions were formulated:

- What type of interoperability challenges appears while converting BIM to BEM with different tools?
- How much time does it take to translate BIM to BEM and what is the complexity of the different tools?
- What are the pros and cons of the proposed BPS tools when compared to each other?
- What can be the possible solution to current interoperability challenges and which improvements can be made to further develop and raise the level of BIM to BEM integration?

1.4 Limitations

The study was accomplished with a holistic approach, considering different parameters that affect energy simulation evaluation and the whole building energy balance. The research includes topics related to architecture, building physics, passive and active systems (without getting deep into specific mechanical system details).

Due to limited time, the study will only focus on the energy part and investigate key indicators for early-stage design optimization such as energy use intensity (EUI), thermal energy demand intensity (TEDI) and the energy balance.

A validation of BEM simulation software to determine their accuracy will not be covered since BPS programs need to be validated against measured data, which is not applicable in a particular case.

On account of the limitations of the simulation software, no additional studies were conducted for moisture risks, thermal bridge assessment, carbon footprint, daylight and sewage.

2 Theoretical background

A literature review was conducted to identify studies addressing BIM to BEM integration during the design process. The electronic databases searched were mainly Science direct (“ScienceDirect.com,” 2021), Google Scholar (“Google Scholar,” 2021), and Research Gate (“ResearchGate,” 2021). Since BIM and BEM tools are developed rapidly and are updated frequently, these platforms were searched for full-text papers published in English for the last seven years, starting from 2014.

The following keywords were used for the search: BIM, BEM, building simulations, building performance simulation, interoperability, model integration, and early design evaluation.

After application of the keywords, articles were selected based on the title and abstract. The final selection was made by reading full texts to determine if they were relevant to the study objectives.

2.1 Definition of BIM

To fully understand all the benefits of the BIM to BEM integration, some of the key points of the BIM development will be reviewed in the following chapter.

Today, BIM can be defined as a process of creating an intelligent three-dimensional building model that enables stakeholders to manage and coordinate the whole life cycle of the building, including a plan, design, construction, operation, and maintenance (Autodesk, 2021). Since its first introduction, BIM has developed and matured into six directions: design, estimation, construction, building life cycle, performance, and technology (Latiffi et al., 2014).

An equally significant aspect of BIM is the levels of maturity which illustrates how this method progressed and formed throughout time (Figure 3). Level 0 includes computer-aided design (CAD) and can be described as a low level of collaboration since the design process is non-interoperable and information is exchanged via paper-based or electronic documents. Different stakeholders do not collaborate as everyone creates their own data. Even though industry professionals rarely use this level, it can still be applied. In other words, even BIM-oriented software can be used as a level zero if the exchange of information is paper-based and there is low cooperation (Biblus, 2019a). The key point in the next level of evolution is the introduction of 3D modeling.

Level 1 uses both 2D and 3D CAD information for visualizations and the generation of the necessary documentation. This level is a partial collaboration since information is shared electronically using a common data environment (CDE). CDE is a data-sharing platform, which can collect, store and organize data throughout the design process (Biblus, 2019b). However, this level is still referred to as a “lonely BIM” since different stakeholders rarely collaborate and usually, they work on their own, producing separate files.

As CAD software became more intelligent, users wanted to share the design and the data associated with it. As a result, more attention was given to the data rather than 3D visualizations. Some key points of level 2 include the introduction of time management and cost calculation. Libraries and object-based parametric modeling is introduced, which is one

of the main difference between BIM and traditional 3D modeling. In particular, objects are represented by parameters and the rules that determine shape and form together with some non-geometric data.

Objects are automatically updated according to user control. Sets of base building object classes are created, which predefine the wall, roof, or slab and how they interact. It was acknowledged that that multiple classes could share parameters. For example, the boundaries of the slab can be defined by the wall planes surrounding it. What’s most important, if the single object is moved, all the others change their location and appearance accordingly (Sacks et al., 2018). Apart from the technical improvements, a collaborative workflow is the main focus of the level 2 BIM. But, full integration does not necessarily mean that all the stakeholders are working within the same document. Instead, team members can develop separate CAD models while being part of the standard file type, such as industry foundation classes (IFC), which unites all the data produced throughout the design process.

Level 3 BIM is the final goal of the design and construction practice. It is often referred to as an” Open BIM” and includes full integration of the information in the cloud-based environment, which enables all the stakeholders to work on the same model simultaneously. Apart from the construction sequencing and cost calculations, with Level 3 BIM entire life cycle of the building can be assessed, resulting in a better business outcome. Integrated web services and multidisciplinary design eliminate the chances of conflicting information (UNITED-BIM, 2020).

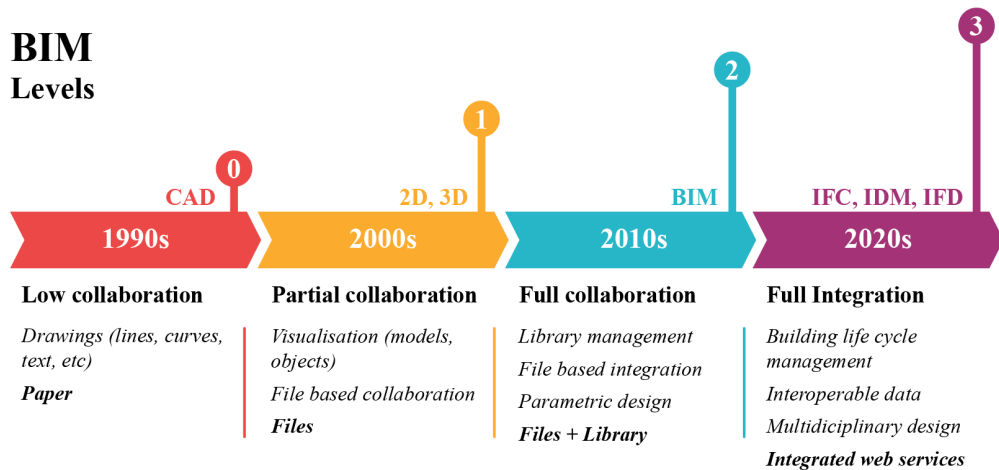


Figure 3. BIM development timeline.

Nowadays, most architectural projects are designed with BIM, one of the well-used instruments in architecture, engineering, and construction (AEC). With the help of BIM technology, a computer-generated model of the building can be constructed, enabling the coordination of the information for different disciplines that are needed to support the construction, fabrication, and mechanical, electrical, and plumbing (MEP) systems required to erect the building (Chen et al., 2018). Even though BIM enables optimization of design parameters such as location, orientation, glazing, and fabric properties from the preliminary design stage, an additional tool for building energy assessment is needed.

2.2 Definition of BEM

While BIM tools such as Archicad and Revit are used to create BIM models, separate tools for energy assessment are necessary. This is where BEM steps in. BEM can be described as an application of computer-based simulation software in order to perform a detailed energy assessment of the building and its systems (Farzaneh et al., 2019). Performed simulations are based on a mathematical model enacted by the software and provide an approximate representation of the structure. Additional data input is required for the creation of the complete building model. Input data, which is necessary to run detailed building performance analysis, include:

- Climate: typical weather data for a specific location;
- Site: Building location, orientation, context shading by site, trees, or surrounding buildings;
- Geometry: building shape and zone distribution;
- Envelope: envelope characteristics of materials, constructions, openings, thermal bridges, infiltration and shadings;
- Internal heat gains: generated by occupants, lighting and equipment;
- Schedules: occupant and operation schedules;
- Heating, ventilation and air conditioning (HVAC) system specifications (Rashed Alsharif, 2019), (Pezeshki et al., 2019), (Chaudhary et al., 2016).

The information about the climate is typically provided by importing a weather file. A weather file is an annual weather stream for specific climate zones containing text information regarding daily temperature measurements, relative humidity, radiation, wind, and precipitation. It represents an average year of 30 years (EnergyPlus, 2021).

Site, geometry, and envelope include input data that requires the most time. There is a high probability of human error due to the amount of information that needs to be inputted manually (E. Kamel and Memari, 2019).

Internal heat gains and schedules are predicted by numerous standards such as ASHRAE 55 (ASHRAE 55, 2010), ASHRAE 90.1 (ASHRAE 90.1, 2019), DIN18599 (DIN V 18599, 2011), etc. In most cases, simulation tools include templates that simplify and shorten the process of data input. Additional changes to the values can be made according to the specifications of the building. The energy model is different from the typical 3D models produced with BIM. It is possible to generate an energy model from an information model. The energy simulation process can be integrated within the design and can be more accurate and efficient. However, the integrity of the BIM-based energy modeling is not yet fully achieved (Elnabawi, 2020)

The complexity of HVAC input greatly depends on the simulation tool itself. Some of the tools have modes that enable the assessment of heating and cooling loads without any system details. However, it is necessary to define condition requirements for the zones, such as min and max indoor temperatures. Some tools only require details, such as the coefficient of performance (COP) and there are tools that additionally need specified HVAC system type.

When all the required data is provided, the software is ready to run the simulation. It means that the built-in engine will solve equations connected with thermodynamics and building science. The time required for the calculations can vary depending on the size of the building, level of detail and complexity of the analysis (Tupper et al., 2013). The building performance can be simulated in many different ways. Some of the most common types of simulation include climate analysis, thermal comfort, energy calculations, daylight assessments, etc. The output depends on the simulation type and tool. Usually, results are reported for annual performance and include heating and cooling demands, peak loads, daylight impacts, HVAC and renewable system performance, embodied and operational carbon emissions, resource consumption, energy costs and other performance-related variables (“Building performance simulation,” 2021).

BEM tools typically consist of two units: a graphical user interface (GUI) and a simulation engine (Figure 4). GUI can be described as a system of interactive visual elements facilitating

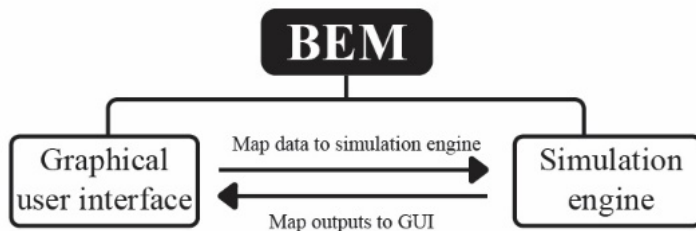


Figure 4. BEM simulation process.

the building energy modeling process by providing a graphical interface for users (Ehsan Kamel and Memari, 2019). The second component, the simulation engine, works behind and provides results based on input from GUI. In other words, there is a continuous process of mapping from GUI to simulation engine and usually, this is where the majority of the interoperability challenges occur. Currently, none of the simulation engines are capable of independently importing BIM file schemas such as international foundation class (IFC) and green building XML (gbXML) (Ehsan Kamel and Memari, 2019).

The mapping between GUI and simulation engine can also be described as a model integration process. There are three types of model integration: combined, central and distributed (Negendahl, 2015).

The combined method considers a software package that enables design and BPS simultaneously (Farzaneh et al., 2019). Combined model integration has several benefits: instant feedback regarding the building’s performance at any stage of the design, a high level of interoperability, and accuracy. Nonetheless, compared to other methods, combined model integration is somewhat limited.

Central model integration refers to a method where BIM to BEM translation happens with the help of the BIM file schemas such as IFC or gbXML. File schemas act as a medium between BIM and BEM containing the relevant input data. This is the most used approach nowadays. However, it might not be appropriate for all stages of building design, especially at the early stage when changes happen more frequently. When it comes to BIM to BEM translation, it

should be noted that there can be three types of compatibility: directly compatible, not compatible and indirectly compatible (Farzaneh et al., 2019).

Directly compatible translation refers to a process when BEM tool has a mapping interface that facilitates the direct translation of the file schema's data model to the internal data model of the simulation engine. For instance, Climate Studio can act as a mapping interface to connect BIM file schema to EnergyPlus simulation engine. The absence of a mapping interface means that process of translation is not compatible. And finally, translation is indirectly compatible when the middleware interface can be used instead of mapping to connect the simulation engine to the BIM file data (Farzaneh et al., 2019).

The distributed method may bear a resemblance to the most complicated workflow, but it has its advantages. Mainly, the middleware interface allows more control over the translation process, the possibility of geometry modification, deep integration and evaluation of complex forms. Grasshopper, which is the visual programming language, is one of the most used middleware interfaces.

2.3 State-of-art of BIM to BEM challenges and solutions

The evaluation of the articles for recent years (2016-2020) shows that BIM to BEM integration draws more and more interest among researchers and industry professionals.

The studies point out that full interoperability between BIM and BEM tools has not yet been achieved (Bracht et al., 2021; Chong et al., 2017). The absence of insufficient and valuable tools for architects that could lead to energy reductions by enabling the design team to evaluate more energy-saving measures during the early stage of the design process is also noticed (Asl et al., 2016; Jin et al., 2019; Kim et al., 2015). Usually, BPS is ignored at the early stage of design due to uncertainties, lack of information regarding specific details such as zones, loads, schedules, mechanical systems and computational time (Singh et al., 2020). The majority of the reviewed papers agree that the main problem with BIM to BEM integration is the limited capability of data exchange among different BIM and BEM software, making it hard to create a unique model containing all the types of information. Optimization of the interoperability process is error-prone and complicated due to the wide variety of BIM export file formats and energy engines available on the market. According to the reviewed papers, gbXML and IFC file format usage, i.e., the central model integration method for information sharing between BIM and BEM, is the most common workflow (Farzaneh et al., 2019). Although both schemas are comprehensive file formats, BIM authoring tools might still struggle to properly transfer required data to IFC and gbXML (Ehsan Kamel and Memari, 2019; Pezeshki et al., 2019). Another problem emerges when the BEM tool cannot correctly retrieve data provided with the BIM file. With the accurate BIM model, there are still missing information and recognition issues. Sometimes even the most advanced and complete tools fail to generate reliable BEM models which utilizes all required information from BIM file schemas (Gourlis and Kovacic, 2017).

Most of the studies are dedicated to the central method, and interoperability challenges are often solved by creating new middleware components (distributed model integration), often referred to as a corrective tool using Python programming language. It should be noted that this method might not be an efficient approach since this type of simulation can rarely be used

in the optimal design process due to complexity and frequent energy modeling. Also, it requires a high level of programming skills (Asl et al., 2016; Jabi, 2016; Kim et al., 2015; Sun and McArthur, 2016).

Even though the combined method of the model integration is an up-and-coming solution for the BIM to BEM interoperability challenges, only several studies focus on them (Farzaneh et al., 2019). A few studies investigating the BIM-based BEM tools suggest that this kind of workflow can be as accurate as advanced BPS tools. Moreover, the combined method can reduce the simulation's computational time and require fewer resources (Li, 2017; Sun and McArthur, 2016).

2.4 BPS tools used for case studies.

Based on the literature review, some main problems that emerge while performing BPS at the early design stage were identified to investigate them further in the case studies. These problems include:

- Inefficient translation of the data from BIM to BEM,
- Shortage of studies where combined model integration method is assessed,
- Calculation time and complexity,
- Relevancy to the early design stage.

BPS tools for the case studies were selected based on the above-listed criteria.

2.4.1 Energy Evaluation (EE)

Energy Evaluation is an add-on application for Archicad that enables architects to evaluate buildings within the BIM interface and provide fast feedback on specific design alternatives, efficiency and sustainability (Graphisoft, 2021). The outcome of the Energy Evaluation is based on building geometry, weather data for the particular location, operational profiles and mechanical systems. Energy evaluation provides templates for various operational profiles based on the DIN 18599 standard (DIN - Deutsches Institut für Normung e.V., 2018). Dynamic building energy evaluation is performed by passing data to StruSoft's Vip-Energy calculation engine (StruSoft, 2021). As a result, yearly energy consumption, carbon footprint (including only carbon dioxide emitted during building's operation) and monthly energy balance can be generated. The annual results are displayed on the automatically generated evaluation report (Appendix 1).

The Vip-Energy calculation engine integrated with Archicad depends on dynamic models. Dynamic models include deconstruction to the level where facts and behavior are known and each component group is analyzed separately ("VIP-Core Dynamic Simulation Engine," 2014). The data is calculated for every hour. The Vip-energy calculation engine is validated with ANSI/ASHRAE standard 140-2007, the standard test method for evaluating BPS tools (ASHRAE140-2007, 2010). The VIP-Energy's calculation method is based on DIN 18599 standard for energy performance of the buildings (DIN - Deutsches Institut für Normung e.V., 2018)

When it comes to the model integration method, Archicad and Energy Evaluation can be referred to as a combined system since BEM is produced directly from BIM and design/energy simulation processes are carried out simultaneously. Most of the data from the BIM model is utilized by Energy Evaluation.

2.4.2 Cove.tool (CT)

Cove.tool is a web app, an automated building performance platform that allows architects and engineers to perform energy evaluation (Cove.tool, 2021). Cove.tool is connected to the Archicad with a plugin that automatically translates BIM to BEM. After proper classification of the different building elements, geometry is uploaded to the web page. Whenever changes are made to the BIM model, the geometry needs to be uploaded manually. The Cove.tool's outcome is based on the geometry of the uploaded model, climate data, operational schedules and specifications of the mechanical systems. At the moment, the application only extracts the geometry and does not draw any information about the assembly from the BIM model. All of the other values regarding thermal envelope are populated using the selected energy code for the project location. The established regulations determine the minimum values for a given building. At the moment, available building codes are valid for U.S. and Canada. The templates of the operational profiles are based on ASHRAE standards. They are assigned automatically depending on the selected building type. Currently, CT has eight variations of the buildings, including both residential and commercial classes. CT only allows single-zone assessment, runs annual simulations and delivers results regarding daylight, energy and carbon footprint. An automatic report can be generated based on the outcome. Apart from the energy calculations, CT offers design optimization and is integrated with American Institute of Architects 2030 commitment (AIA, 2021), a national effort to reduce building-related impacts on the environment (Cove.tool, 2021).

The simulation engine is based on Argonne ISO 13790 (Argonne National Laboratory, 2008), which gives calculation methods for assessing the annual energy use for space heating and cooling of a building. The calculation method includes assessment of the heat transfer by transmission and ventilation, the contribution of internal and solar heat gains towards buildings heat balance, annual energy needs for heating and cooling and yearly energy use.

Since building geometry is exported from the BIM modeler, the model integration using CT can be classified as a central method. CT acts as a mapping interface to facilitate data translation.

2.4.3 Climate studio (CS)

Climate studio is environmental performance analysis software for the AEC industry developed by Solemma LLC. It is a plugin for the Rhinoceros and it is integrated with Grasshopper as well. The connection between Archicad and CS is possible through the Grasshopper live link plugin for Archicad (*Climate Studio*, 2021). Live connection plugin enables Archicad components to be imported in Grasshopper and projected in Rhino viewport. It should be noted that live link plugin is mainly used for design purposes and not for energy simulations since currently it is impossible to automatically create BEM model through the live connection from the Archicad. CS can run multizone thermal simulations based on the

buildings geometry, weather conditions, operational schedules, and mechanical system specifications. CS provides a vast amount of building material libraries and schedules based on ASHRAE standards, almost for all types of buildings. CS can generate results regarding buildings' energy performance, daylight and carbon footprint. At present, the creation of a report based on the results generated in Grasshopper is not possible. CS attributes fully parametric energy modeling via Grasshopper and enables automatic AIA 2030 reporting (AIA, 2021; *Climate Studio*, 2021).

CS calculation method is based on EnergyPlus simulation engine. Like the Vip engine, EnergyPlus supports heat balance-based solutions, including radiant and convective effects on the building.

Archicad-Grasshopper-CS workflow can be referred to as a distributed method since Grasshopper is the middleware tool that connects the BIM file with the simulation engine. In this case, CS acts as a GUI.

3 Method

The research was divided into five main stages. Figure 5 exhibits a detailed overview of each step. In the first stage of the study, a literature review was carried out, with the primary purpose to reflect the current knowledge and challenges within the AEC industry when it comes to BIM to BEM integration. Based on the assessed literature, some of the main problems were listed and relevant BPS tools were selected.

In the second stage, all the necessary data for the BPS was collected. Specifically, BIM models for three case studies included information about the building geometry, orientation and envelope specifications. Weather files were downloaded from EnergyPlus databases (EnergyPlus, 2021). Toronto weather file was used for all of the case studies. For comparison, weather file was assessed in Excel and min, max and average values of the key climate indicators (Dry bulb temperature, relative humidity and wind speed) were calculated manually. Additionally weather files from cities (Victoria, Yellowknife, Ottawa, Quebec, Toronto and Whitehorse) located in different climate zones (“Comparing the Energy Codes,” 2020) were used for additional climate analysis such as Heating Degree Days (HDD) calculations. Custom schedules were made according to building types and usage. Loads for detailed internal heat gain calculations and HVAC system specifications for more rational energy use intensity (EUI) results were taken from the relevant standards and energy codes.

During the third stage, numerical and analyses were carried out. BIM files for each of the case studies was evaluated with three BPS tool. Some preferable conditions included:

- BPS tools could transform BIM to BEM automatically
- Remodeling of the building should be avoided as much as possible.

Subsequently, at the fourth stage, simulation results could be obtained. Apart from the energy outcome, climate and geometry analysis can be assessed. Climate as the variability of different weather data over a predefined period can play an essential role in the adaptation of passive strategies. Understanding the connection between the climate conditions and thermal comfort requirements can lead to climate responsive design, which can reduce the usage of the active

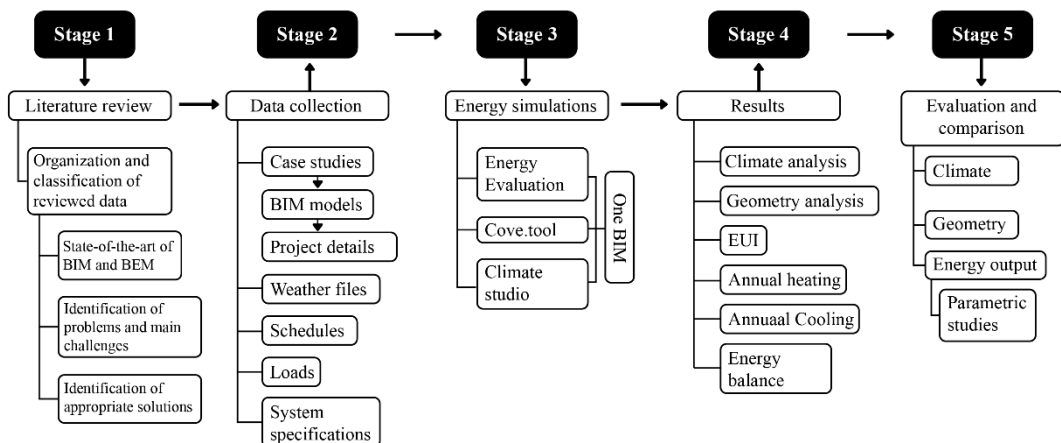


Figure 5. Workflow of the study.

mechanical systems and rely more on passive strategies (AIA, 2012). Therefore it could be essential to evaluate how different BPS tools read weather data.

Obtained results were further analyzed at the fifth stage. Comparative analyses evaluate different BEM software outcomes and explain the possible reasons behind the differences between the same indicators.

3.1 BPS tools workflow

Three different workflows were used for the case studies. The starting point for all of them is the one BIM model produced in Archicad (Figure 6).

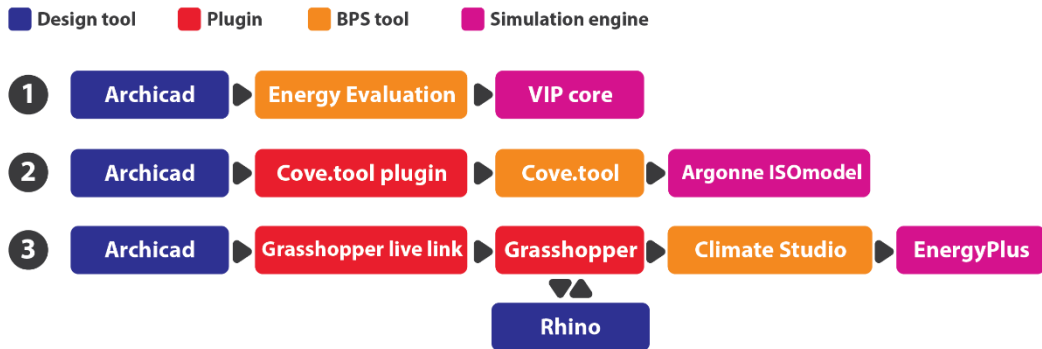


Figure 6. BPS workflows used for the case studies.

The first workflow includes energy assessment via Energy Evaluation. General information regarding building location, orientation and climate conditions need to be provided to simulate building with Energy Evaluation. If BIM model already includes information regarding these matters, EE automatically uses it and no additional input is required. As a next step, the building needs to be divided into relevant zones. Zones are spatial units of the building which later are assigned to specific thermal blocks of EE. Thermal blocks are simply a group of zones that share an operational profile and mechanical systems. Zones should be placed with the inner edge method and it should cover all the spaces which need to be evaluated by EE. Zones created with the inner edge method include area (m²) between the internal edges of the walls (Graphisoft help center, 2014). After all the zones are assigned to relevant thermal blocks, BEM model can be created instantly. Some of the final steps include the allocation of the infiltration, operation profiles and mechanical systems. Infiltration (ACH) needs to be assigned to each building assembly, such as a wall, roof, floor, windows and doors separately. All the loads determined in the operational profiles were reduced to zero to evaluate passive design impacts. HVAC systems were set to “Not yet specified” mode, a demand calculation mode proposed by EE, which means that systems fulfill all heating and cooling demands as they arrive during hourly simulation throughout the entire reference year (Graphisoft, 2010).

The second workflow includes energy assessment via Cove.tool. BIM geometry is exported by CT plugin, which is an add-on for Archicad. According to their type and classification, the plugin can automatically create a new 3D view where all the building elements are displayed in different colors. CT only requires basic building elements such as floors, internal and external walls, windows and shadings, to generate BEM model. After all the assemblies are

classified correctly, geometry can be exported and linked to the CT web page. Additionally, it creates a quick graph in Archicad's interface showing approximate EUI loads. CT requires information regarding the building's location. The weather file is assigned automatically and orientation information is taken from the exported BIM model. Other values regarding thermal envelope, operational schedules, loads, infiltration and HVAC systems are populated automatically based on the selected building type and code. All the loads were reduced to zero and the coefficient of the performance (COP) for heating and cooling was reduced to one to evaluate passive design systems. The Integrated Part Load Value (IPLV), a performance characteristic used to describe the performance of a chiller capable of capacity modulation, was set to "no chiller."

The third workflow demonstrates the energy simulations performed with Climate Studio. The geometry, particularly the 3D representation of the zones, is connected to the Grasshopper through the live link, the add-on for the Archicad. The geometry can be displayed in the Rhino viewport. After some modifications, zone geometry can be connected to the CS. If the changes are done in BIM model, geometry in the CT can be updated automatically since there is a live connection between the add-on and Archicad. As additional information, CS requires the building's location, infiltration, operational profiles, loads and HVAC system specifications. The live link connection is mainly used for design purposes and not for energy modeling. Therefore, it could be possible that this workflow won't work for complex geometries. Even though it is undesirable, an alternative workflow where the geometry will be created in Rhino, can be offered. Similarly to CS, loads and COP for HVAC systems were reduced to zero and one respectively for passive systems assessment.

Even though the range of the results provided by selected BPS tools can be extensive, only the shared outcomes for all of them can be compared.

3.2 Case studies

Three case studies were selected to evaluate the performance of the BPS tools. The first is the simple shoebox, second and third ones are public and residential buildings, respectively. Energy simulation can be a complex process, which is influenced by multiple factors. BPS tools have different methods; hence they read, analyze and interpret data differently. Consequently, narrowing influencing factors as much as possible for the starting point could bring to light indicators whose impact could be not noticeable among the vast amount of data that BPS tools can provide. Based on these assumptions, the shoebox was selected as a starting point due to its simple geometry and sensitivity analysis based on the significant variables for the early design stage; the first tier of the three-tier design approach was carried out (Figure 1). Sensitivity analysis could reveal how BPS tools assess the changes between different variables such as infiltration rate, orientation, window to wall ratio (WWR), thermal envelope and glazing properties, shading strategies, occupancies and loads. For simplification, mechanical ventilation was excluded from the shoebox simulations.

Second (POSH the wedding venue) and third (Muskoka residence) case studies are typical buildings with complex geometry and their BIM models include more data than a simple shoebox. Therefore, it could be interesting to assess how BPS tools based on different model integration methods handle BIM to BEM translation.

Simply running BPS without any HVAC and loads can capture the enclosure's thermal efficiency and thermal mass effects also account for the solar and transmission factors. The form and fabric of the envelope remain constant, whereas loads and HVAC systems vary with occupancy (Kesik and O'Brien, 2019). Moreover, high heat recovery efficiency can be compromised against the thermal envelope. From the perspective of the passive performance, it could not be desirable to enroll measures that allow active systems to compromise it (Kesik and O'Brien, 2019). Thereby, all of the case studies were tested for their passive performance as a starting point. As a next step, BIM models were simulated with all the inputs that were disregarded before.

3.2.1 Shoebox

A simple shoebox with two south-oriented windows was modeled in Archicad for the first case study (Figure 7).

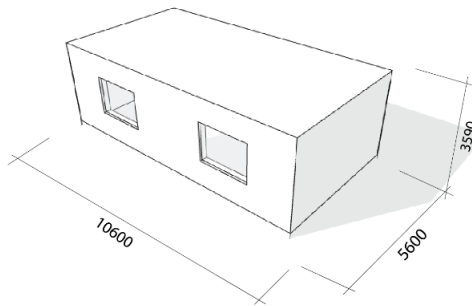


Figure 7. Shoebox geometry.

3.2.1.1 Envelope details

The envelope materials were selected based on the other two case studies (Table 1).

Table 1. Shoebox envelope details

Wall		Roof		Ground floor	
Thick / mm	Material type	Thick / mm	Material type	Thick / mm	Material type
<i>Outside</i>					
19	Siding wood	22	Galvalume Roof	102	Concrete
13	Air Space	19	Air space	250	Polyurethane
89	Roxul Batts	3	Air barrier	203	Gravel
3	Air barrier	13	Plywood	-	-
13	Plywood	140	Mineral Batt	-	-
140	Roxul Batts	140	Roxul Batts	-	-
13	Plywood	13	Plywood	-	-
3	Vapour barrier	3	Vapour barrier	-	-
16	Vapour barrier	38	Structural deck		
<i>Inside</i>					

3.2.1.2 Loads

The shoebox was assessed as a residential building and it was assumed that it can be fully occupied from 06:00 to 09:00 and from 17:00 to 24:00. The same schedule was assigned to equipment and lighting loads. From 24:00 to 06:00 it is assumed that people are sleeping therefore there is no lighting and equipment load.

Thermal transmittance of the envelope components, glazing specifications, leakage, internal heat gains and other assumptions made to run the simulation can be seen from (Table 4).

Table 2. Loads for the shoebox

Case study 1 -Shoebox			Source
U values / W/m ² K	Roof	0.19	<i>BIM</i>
	Wall	0.13	<i>BIM</i>
	Window	0.6	<i>BIM</i>
	Ground floor slab	0.13	<i>BIM</i>
TST / %	Window	52	<i>BIM</i>
Air leakage at 50 Pa	Roof	0.1	<i>BIM</i>
	Wall	0.1	<i>BIM</i>
	Window	0.9	<i>BIM</i>
	Door	0.9	<i>BIM</i>
	Slab	0.1	<i>BIM</i>
Ventilation	Airflow per person / L/s/person	-	
	Airflow per area / L/s/m ²	-	
Total infiltration	Air changes per hour / ACH at 50 Pa	0.1	<i>Custom</i>
Temperature setpoints	Heating / °C	20	<i>ASHRAE 140</i>
	Cooling / °C	26	<i>ASHRAE 140</i>
Temperature setbacks	Heating / °C	-	
	Cooling / °C	-	
Internal heat gains	Human heat gain / W per capita	108	<i>ASHRAE 55</i>
	LPD / W/m ²	0.5	<i>DIN 18599</i>
	Equipment / W/m ²	1	<i>DIN 18599</i>
	Occupancy count / m ² per capita	25	<i>Custom</i>

3.2.2 POSH – Wedding venue

POSH is an 1140 m² one-story wedding pavilion and accessory uses in the region of Ontario, Canada Figure 8. It is classified as a commercial A2 assembly occupancy (“The Ontario Building Code | Classification of Buildings,” 2018). From the South and East, it is surrounded by the forest.

The maximum height of the POSH is approximately 10 m. The wedding venue has high glazed facades towards South, West and North. West curtain walls glazing is shaded with a large overhang (~ 8.7 m). Glazed sliding doors located on the south and north facades are shaded with relatively smaller overhang (~ 3.74 m).



Figure 8. POSH - Wedding Venue, render by Enzyme Architecture.

The Wedding venue unites several spaces (Figure 9). The majority of the floor area is dedicated to the reception and ceremony spaces (~ 980 m²). The rest of the site includes a small vestibule and cloakroom, storage, WC and the bar. For simplification, the whole building was assessed as a one-zone and was treated as a reception and ceremony space.

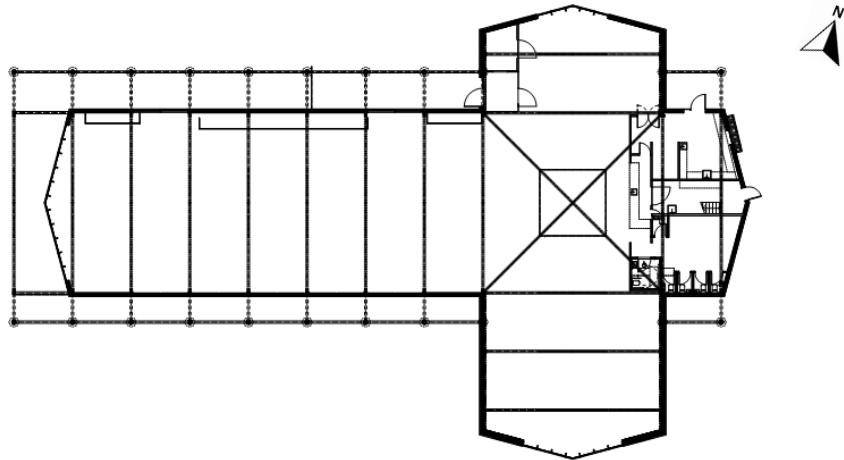


Figure 9. POSH-Wedding Venue floor plan.

3.2.2.1 Envelope details

Table 3 provides detailed information regarding the materials of the thermal envelope.

Table 3. POSH - Thermal envelope details

Wall [type 1]		Wall [type 2]		Roof	
mm	Material type	mm	Material type	mm	Material type
<i>Outside</i>					
19.1	Wood Siding	88.9	Brick	25.4	Seam Metal Roof
19.1	Air space	25.4	Air space	6.4	Cap sheet membrane
152	Rockwool	76.2	Rockwool	6.4	Base sheet membrane
6.4	Air barrier	6.4	Air barrier	12.7	Plywood
6.4	Vapour barrier	19.1	Plywood	228.6	Rockwool
19.1	Plywood	140	Roxul Batts	76.2	Polyisocyanurate
88.9	Mineral Fibre Batts	6.4	Vapour barrier	6.4	Vapour barrier
15.9	Gypsum Board	15.9	Gypsum board	12.7	Plywood
				38.1	Structural deck
<i>Inside</i>					
Floor slab					
mm	Material type				
102	Structural concrete				
76.2	Polyurethane				
203	Gravel				

3.2.2.2 Loads

The building is mainly occupied on Friday, Saturday, and Sunday, the whole year-round. The ceremony usually starts at 11:00 and continues until 24:00. When it comes to occupancy, two scenarios are possible - 126 and 300 people, respectively. The simulations are carried out for 300 people as it is considered the worst-case scenario with the highest heat gain possibilities.

Thermal transmittance of the envelope components, glazing specifications, leakage, internal heat gains and other assumptions made to run the simulation can be seen from Table 4.

Table 4. POSH- Specifications and loads

Case study 1 - POSH Wedding Venue			Source
U values / W/m ² K	Roof	0.09	BIM
	Wall	0.11	BIM
	Window	0.6	Supplier
	Door	0.7	Supplier
	Intermediate floor slab	3.6	BIM
	Ground floor slab	0.12	BIM
TST / %	Window	52	Supplier
	Door	52	Supplier
Air leakage at 50 Pa	Roof	0.1	BIM
	Wall	0.1	BIM
	Window	0.9	BIM
	Door	0.9	BIM
	Slab	0.1	BIM
Ventilation	Airflow per person / L/s/person	3.8	ASHRAE 62.1
	Airflow per area / L/s/m ²	0.9	ASHRAE 62.1
Total infiltration	Air changes per hour / ACH at 50 PA	1	Custom
Temperature setpoints	Heating / °C	20	ASHRAE 90.1
	Cooling / °C	26	ASHRAE 90.1
Temperature setbacks	Heating / °C	15	Custom
	Cooling / °C	-	Custom
Internal heat gains	Human heat gain / W per capita	126	ASHRAE 55
	LPD / W/m ²	0.5	DIN 18599
	Equipment / W/m ²	1	DIN 18599
	Occupancy count / m ² per capita	45	Custom
Hot water load	l/day per capita	10	Custom

3.2.3 Muskoka – Residential

Muskoka is a 186 m², off-grid, Net-Zero residence in stick-frame construction located in the region of Ontario, Canada. The north side is protected by a high hill, which can act as a wind barrier. The Southwest facade is the most glazed among the others, while the north facade has the lowest number of openings. Southwest facing openings are shaded with the roof and



Figure 11. Muskoka residence, render by Thomson Architecture.

balcony overhangs. The plan drawings of the residence are shown in Figure 10. For simplification, rooms were grouped according to the floors and were assessed as one zone per floor.

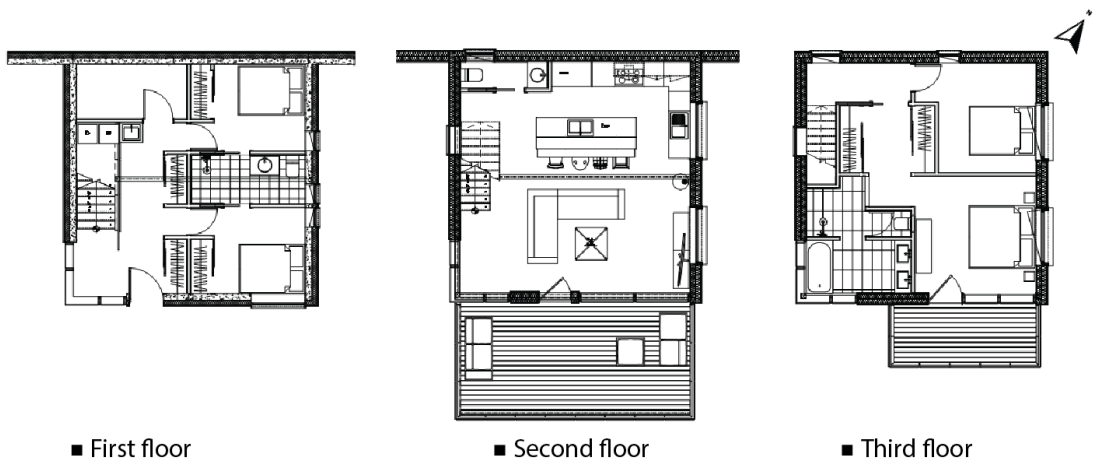


Figure 10. Muskoka residence floor plans.

3.2.3.1 Envelope details

Table 5 provides information about the envelope components of the Muskoka residence.

Table 5. Muskoka residence envelope specifications.

Wall		Roof		Ground floor	
mm	Material type	mm	Material type	mm	Material type
<i>Outside</i>					
22	Galvalume Cladding	22	Galvalume Roof	102	Structural concrete
13	Air Space	19	Air space	254	Polyurethane
152	Continuous Mineral Batt	3	Air barrier	203	Gravel
3	Air barrier	13	Plywood	-	-
13	Plywood	89	Continuous Mineral Batt	-	-
140	Mineral Fibre Batts	241	Mineral Fibre Batts	-	-
3	Vapour barrier	3	Vapour barrier	-	-
19	Plywood	13	Plywood	-	-
<i>Inside</i>					

3.2.3.2 Loads

Thermal transmittance of the envelope components, glazing specifications, leakage, internal heat gains and other assumptions made to run the simulation can be seen from Table 6.

Table 6. Muskoka envelope specifications and loads.

Case study 2 - Muskoka residence			Source
U values / W/m ² K	Roof	0.09	BIM
	Wall	0.11	BIM
	Window	0.6	Supplier
	Door	0.7	Supplier
	Intermediate floor slab	3.6	BIM
	Ground floor slab	0.12	BIM
Thermal resistance / m ² K/W	R _{si}	0.12	DIN 18599
	R _{se}	0.03	DIN 18599
TST / %	Window	52	Supplier
	Door	52	Supplier
Air leakage at 50 Pa	Roof	0.1	BIM
	Wall	0.1	BIM
	Window	0.9	BIM
	Door	0.9	BIM
	Slab	0.1	BIM
Ventilation	Airflow / L/s	33	Custom
Total infiltration	Air changes per hour / ACH at 50 PA	0.6	Custom
Temperature setpoints / °C	Heating	20	ASHRAE 140
	Cooling	26	ASHRAE 140
Temperature setbacks / °C	Heating	-	
	Cooling	-	
Internal heat gains	Human heat gain / W per capita	140	DIN 18599
	LPD / W/m ²	0.5	DIN 18599
	Equipment / W/m ²	1	DIN 18599
	Occupancy count / m ² per capita	45	Custom
Hot water load	l/day per capita	60	Custom

4 Results

In this chapter the results of the different performance simulations are presented regarding climate analysis, geometry and energy assessment from the three different BPS tools.

4.1 Climate analysis

Climate analysis is a significant part of energy simulation. BPS tools generate several representative diagrams based on the provided weather files. Weather files contain information about dry and wet bulb temperatures, relative humidity, wind speed and direction, solar radiation, etc., for a typical year. Therefore, it is essential that the BPS tool reads the weather file correctly and displays relevant measures.

Figure 12 demonstrates the dry bulb temperature for Toronto, Ontario for three different software: Energy Evaluation (EE), Cove.tool (CT) and ClimateStudio (CS). Additionally, max, min and average values were calculated manually from the weather (EPW) file.

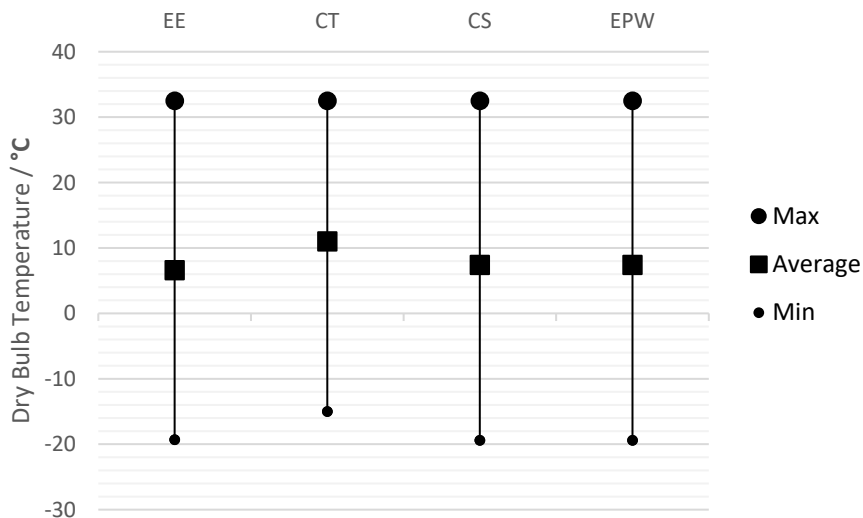


Figure 12. Min, max and average dry bulb temperatures.

The highest temperature value is identical for all of the tools. In contrast, a notable difference can be noted when it comes to minimum values. While the EE and CS outputs are similar, CT provides a higher value that later can be reflected in the building's heating demand. Consequently, average value of the dry bulb temperature of the CT is higher than others. Dry bulb temperature plays a significant role in making up the primary comfort conditions. Moreover, it acts as a basis for various other climate measures.

Another key measure that is used to predict the thermal comfort of the occupants is relative humidity. Figure 13 illustrates max, average, and min values for relative humidity. Unlike the dry bulb temperatures, all of the min and max values are identical for all three tools. There is a slight difference when it comes to the average value. In heating-dominated climates such as Toronto, relative humidity and dry bulb temperatures are critical factors that determine EUI.

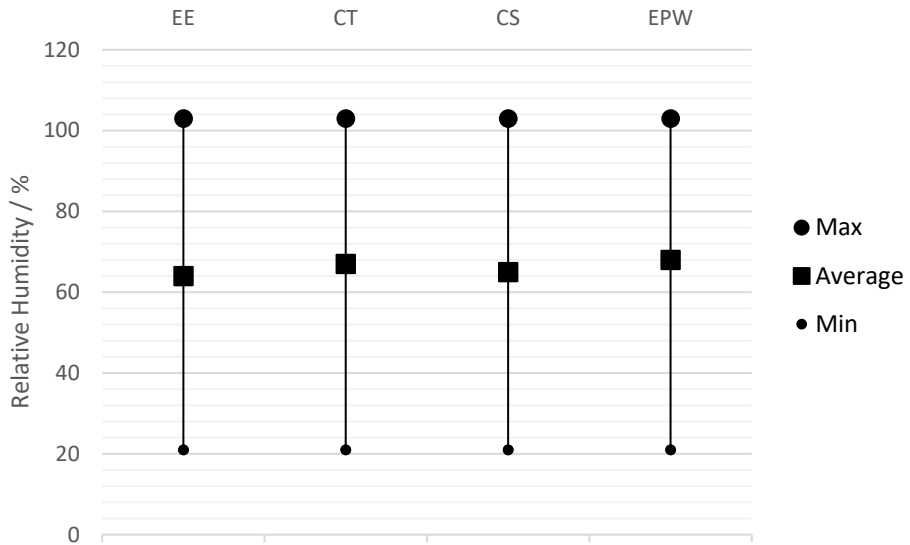


Figure 13. Min, max and average relative humidity.

While the results for the relative humidity and dry bulb temperatures differ only slightly, values for the wind conditions are not on the same level. The wind rose assessment is fascinating since it identifies the direction and the speed of the prevailing winds. The wind rose diagrams can be used to determine the most efficient passive ventilation strategies. Moreover, it is an important part when it comes to infiltration calculations. Figure 14 evidences the difference in max and average values of the wind speed frequency. The

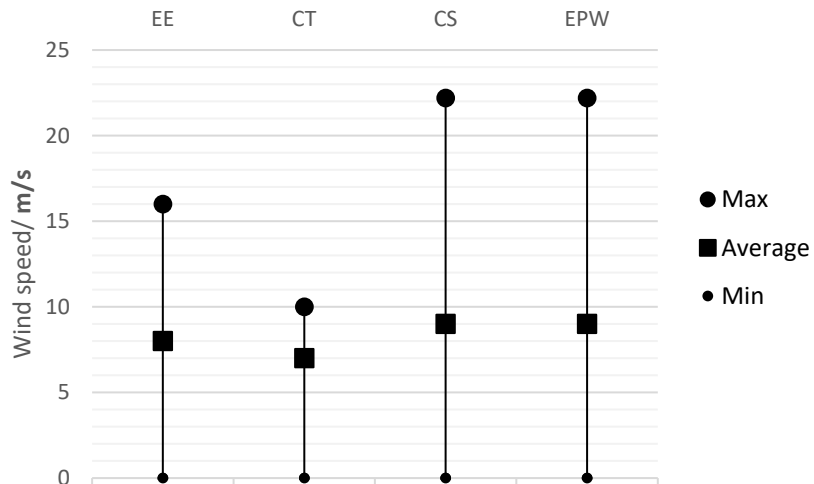


Figure 14. Min, max and average wind speed.

difference is relatively high, and it can impact the energy balance of the building. Since max values are different, averages are on different levels as well. This impact can even be higher since not only speed, but the wind direction is also unlike for EE and CS. According to the wind rose diagram generated by EE, which can be seen in Figure 16, more frequent and high-

speed winds are expected from the west. When it comes to CS, in addition to the west, north, and northwest orientations are highlighted, which can be seen from Figure 15. The comparison with CT is not applicable since it only provides monthly rather than yearly output for wind rose. The diagrams can be seen in the report generated by the CT in Appendix 2.

When it comes to total radiation, the results from the BPS tools are identical. Apart from these

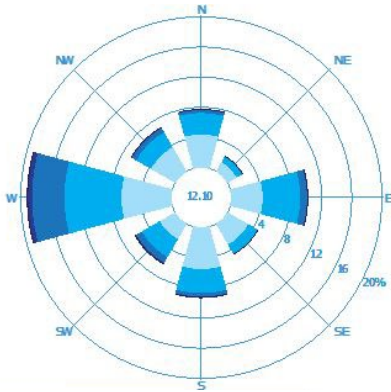


Figure 16. Wind rose diagram (EE).

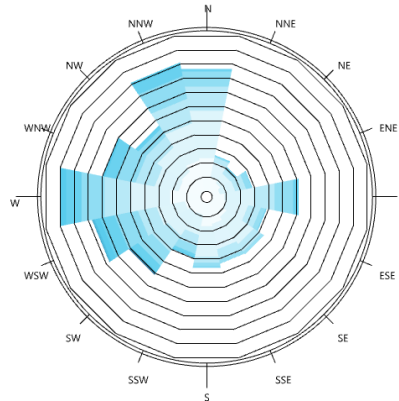


Figure 15. Wind rose diagram (CS).

key indicators, selected BEM tools provide some more climate analysis. Nevertheless, this analysis is not the same type. Therefore they will not be compared. Additional outputs can be seen in Appendix 2.

Additionally, to standard climate analysis, EE also calculates Heating Degree Days (HDD) and Cooling Degree Days (CDD) and displays them in the generated report. Since they are directly proportional to the heating and cooling requirements of the specific location, degree days are significant indicators. It was noticed that, EE calculates higher values for the HDD.

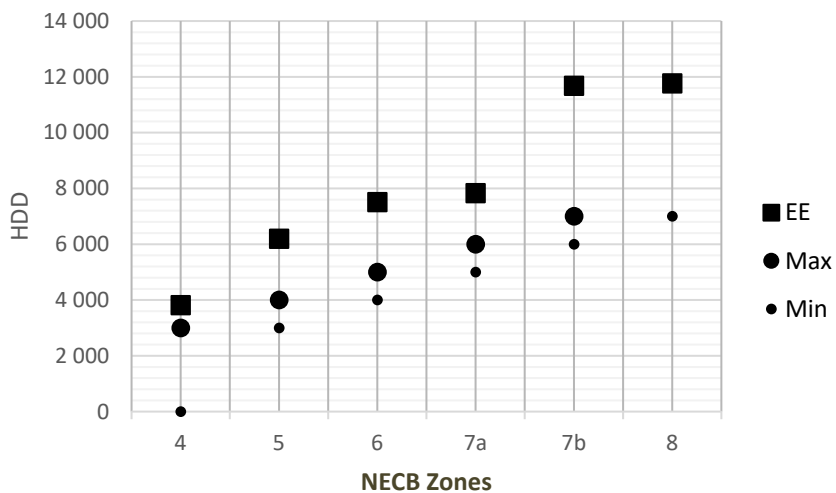


Figure 17. HDD values for various NECB climate zones.

Additional simulations were run to check HDD values for different locations from different

zones defined by the National Energy Code of Canada for Buildings (NECB) and ASHRAE (“Comparing the Energy Codes,” 2020). Since the main focus is on the heating-dominated climate, only HDD values were assessed. As shown in Figure 17 and Figure 18, HDD values for EE are always 20-30 % higher than the standard. Several feedbacks reported the same issue, and it seems to be a bug. However, this can be one reason behind the difference between EE and other tools when it comes to energy, especially TEDI calculations.

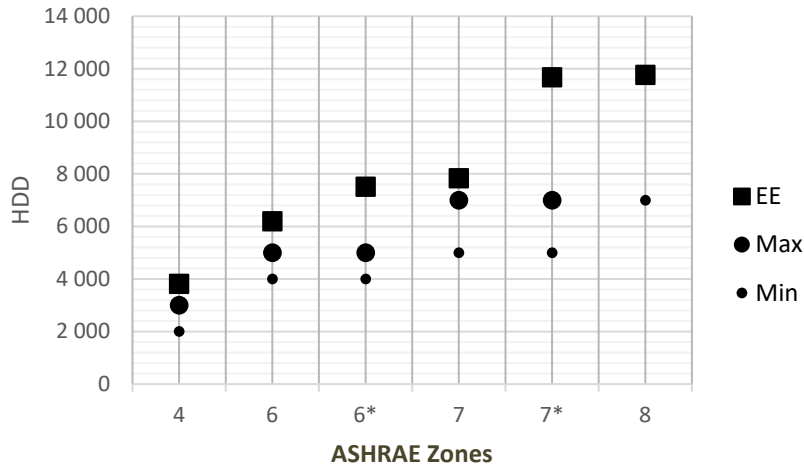


Figure 18. HDD values for various ASHRAE climate zones.

4.2 Geometry

Geometry is another crucial factor in the energy simulation process. At the same time, it can be the trickiest and time-consuming part since this is where most of the interoperability challenges take place. Smooth translation from BIM to BEM geometry is essential at the preliminary design phase when changes happen very often, and efficient workflow can save a lot of time.

When it comes to geometry and the data related to it, EE captures most of the data provided by the BIM model. Characteristics of the constructions such as thicknesses of the various layers, thermal properties, their connections are automatically exported. Landscaping and site design is also reflected. Since Energy Evaluation uses every component of the building, it is vitally important that all the building materials are well-defined include all the necessary information such as conductivity, heat capacity, and density. Energy Evaluation automatically calculates U values of the different assemblies. However, it does not account for the thermal bridging of the framing members. Therefore, transmission through the wooden studs is not included in the outcome of the simulation.

CT utilizes a relatively more minor portion of the information of what BIM can offer. Mainly, it only reads the geometry and orientation of the building. CT plugin for Archicad automatically classifies the building components such as floors, interior, and exterior walls, openings, roofs, and shading devices. Classification is more accurate when components are classified correctly in BIM model itself. Therefore, the quality of the BIM model plays a significant role here, similarly to EE. It should be noted that during the case studies, CT used

to classify floors as shading devices automatically. Since this incident happened with three different BIM models, it can be a bug or shortcoming of the plugin.

The CT Archicad plugin is a relatively new software solution, and this issue can be already fixed in the next update. The application does not draw any information about the assembly from the Archicad model. All of these values are populated using the selected energy code for the project location. Consequently, all the information about the thermal properties is lost in the Cove.tool. This estimation can be fine for the preliminary design. However, it's always better to include precise values to get more accurate results. In some cases, the difference can be relatively significant. For example, Table 7 shows the estimated values for different envelope elements during the shoebox study.

Table 7. Estimated U values by CT

Envelope elements		EE	CT	CS
U value / W/m ² K	Average	0.17	-	-
	Floor	0.13	0.2	0.13
	Wall	0.13	0.28	0.13
	Openings	0.63	1.93	0.6
	Roof	0.19	0.18	0.19

When it comes to CS, 3D zones from Archicad were directly connected with the GH script with the Archicad zone component. The main advantage of this workflow is the live connection between GH and Archicad. If the changes are made to the geometry in Archicad, it will be automatically reflected in GH. Similarly to CT, it is only possible to connect information about the geometry. It is impossible to draw any information about the thermal assembly properties, and this information needs to be entered manually.

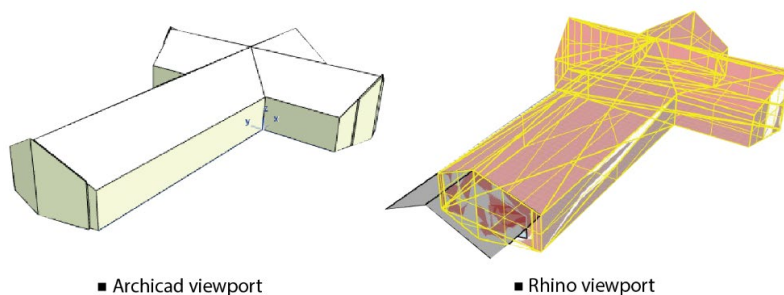


Figure 19. Complex geometry converted with Grasshopper live link.

This workflow only captures simple geometries such as a shoebox. The same components did not work for the other two case studies, which had much more complex geometries. Figure 19 shows that geometry, consisting of simple planar surfaces, was not imported in the same manner in Grasshopper. Instead, surfaces were divided into smaller polygons, which made it

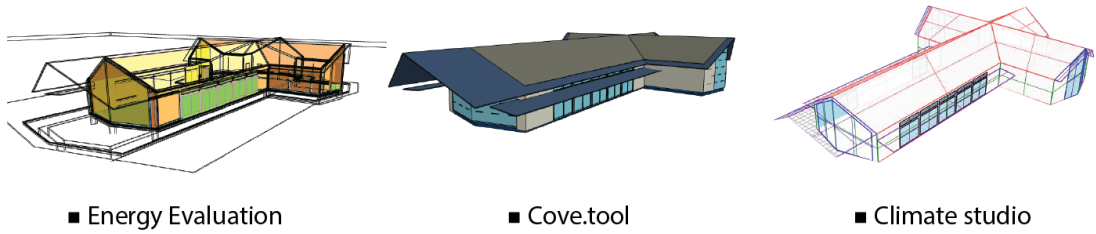


Figure 20. POSH energy models with various BEM..

impossible for Climate Studio to correctly assess building envelope parts. As a result, the other two cases were modeled manually from scratch in the Rhino and later connected to the climate studio script. Figure 20 and Figure 21 show how geometry looks in different tools. At first, it may seem that shading is not taken into account by EE since it is not shown on the energy model. Even though shadings are not classified in the EE's structures, such as other building elements, they still affect the results since EE takes into account every solid surface that can act as shading. It can be a tree, column, or even elevations of the landscape itself.

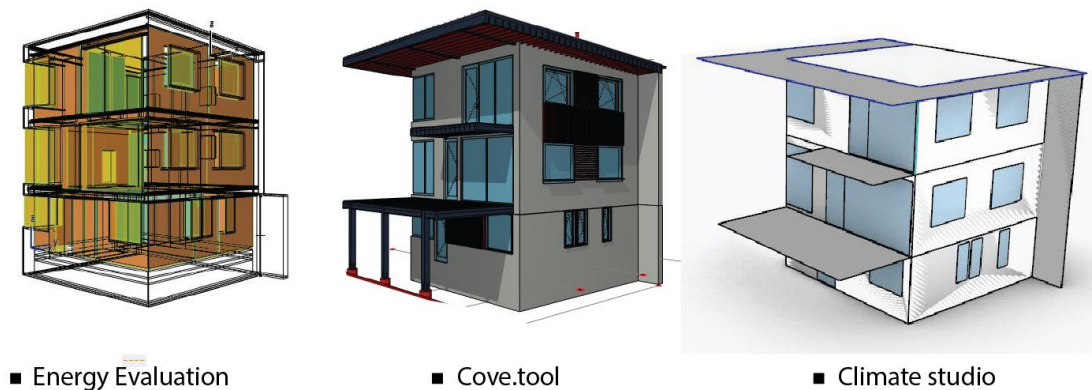


Figure 21. Muskoka energy models with various BEM.

Even though the base of the simulations is the same BIM model, tools still calculate geometry differently. Table 8 shows summary statistics for some of the key geometry calculations for the shoebox model. These values were taken from the GUI and reports generated by EE. Since EE simulations are based on the zones created in Archicad and the same zones were connected throughout the live link to the Grasshopper, the geometry data is almost identical.

EE does not display the height of the building in the generated report. When it comes to the Cove tool, the value is much higher than measured by hand. It must be noted that the height value was the same for the other two case studies. It can be an error or a bug. Nevertheless, it should not impact simulation results since when it comes to the external envelope area, the Cove.tool's value is lower than manually measured. The height of the manually calculated value is higher than the GH value since it also takes into account roof thickness.

For gross floor area calculations, EE uses the perimeter of the zones together with the plan area of the bounding exterior walls. The slight difference between manually calculated area and EE value can be due to window insets.

Unlike the gross floor area, the Cove.tool does not automatically show value for the treated floor area. It needs to be inserted manually, together with other thermal envelope input details. It might be caused by the fact that CT cannot export information about building assemblies and their thicknesses.

External envelope area is lower for both EE and CT compared to manually measured one. This can be explained by the fact that EE interprets external envelope area as the sum of all surfaces facing the exterior, however from the interior dimension of the zones, instead of exterior. When it comes to CT, the difference is caused by the fact that it does not take into account the roof thickness. These differences can later impact the building's energy balance since more heat can be escaped through the higher envelope area.

The difference between the values of the ventilated volume can be explained by the elements such as window geometries, which can be subtracted by EE when calculating total interior volumes.

Even though the same window geometry was used for all BEM tools, WWR ratios are still reported differently. EE does not calculate glazing ratio based on the window to wall ratio but as a percentage of above-grade envelope surfaces, including roofs and slabs exposed to exterior air and exterior walls. CT reports the highest value since it calculates the glazing ratio as a percentage of the particular wall on which the opening is located.

Table 8. Shoebox geometry data

Geometry	Manual	EE	Cove	GH
Height above ground / m	3.59	-	6	3
Gross Floor Area / m ²	59.62	59.24	59.6	-
Treated Floor Area / m ²	50	50	-	50
Internal Envelope Area / m ²	140	-		140
External Envelope Area / m ²	176.20	140	157.6	-
Ventilated Volume / m ³	150	145	-	150
WWR / %	5.15	3	15.6	-

4.3 Energy

In the following chapters energy results for the three case studies will be presented.

4.3.1 Shoebox

Figure 22 illustrates the annual energy use intensity. It only consists of heating and cooling demands since all the other factors, such as internal heat gains, loads and HVAC system effects were excluded to assess the passive performance of the building envelope. CT shows the highest heating demand, while EE calculates the highest cooling demand. Cooling and heating demands depend on the monthly energy balance. Unfortunately, at the moment CT does not show data regarding energy balance.

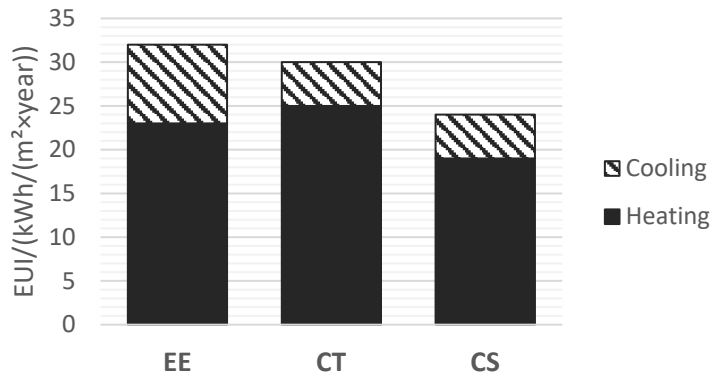


Figure 22. Shoebox base case energy results.

EE and CS generate a bar chart which is a graphical display of the amount of energy the building emits and absorbs from the environment and its own internal heat sources. Figure 23 sums up the information regarding gains and losses provided by EE and CT. Gains are lower than the losses for both cases which is a reasonable when it comes to heating

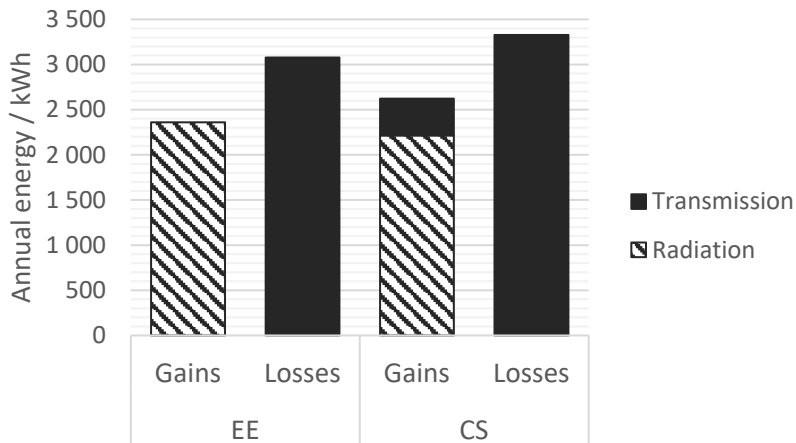


Figure 23. Shoebox base case energy balance.

dominated climates. Consequently, heating demand is higher than the cooling. When no additional loads are introduced, solar radiation and transmission are the only energy balance factors. Radiation, specifically solar heat gains can be expressed as a increase in temperature of the space or object due to solar radiation. The amount of the solar gain depends on the amount of radiation and the properties of the material of short wave radiation absorption, reflectance and longwave radiant interchange (Graphisoft, 2010). Transmission can be expressed as the flow of the thermal energy from hotter to cooler mass. Thermal currents are induced inside a building material if there is a temperature difference between its two sides. Conduction through the building element and convection to the air are significant energy balance factors (EnergyPlus, 2014).

It should be noted that when it comes to the absorbed energy, EE reports the gains received from the sun, while additionally CS calculates gains due to transmission. Particularly, this are opaque surfaces' inside faces total conduction heat gains. In general, gains and losses are higher for CS. There can be various reasons behind this difference, one of them can be values of the thermal resistance (R_{si} , R_{se}) and their calculation algorithms. In addition, these differences can be influenced by the climate or geometry evaluation. Different simulation engine and non-identical calculation methods can be another key factor.

Different infiltration values from lowest to highest were simulated to test how BPS tools evaluate airtightness. Analysis shows that CT responds to increased airtightness values more sharply than EE. (Figure 24). This can be explained by the fact that both infiltration input and calculation methods are different for these tools. In EE, the infiltration model is pressure-driven. To put it in more simple words, it is not constant. EE does not allow inputting a gross airtightness value. Instead, infiltration is defined automatically based on the manually inputted values for every instance of the structures and openings.

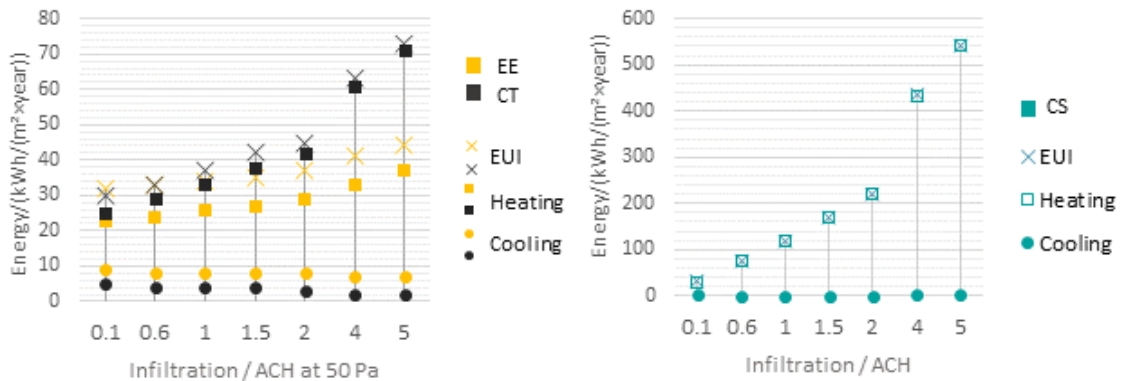


Figure 24. EE, CT and CS energy output based on different infiltration rates.

On the other hand, CT requires a gross weight. It should be noted that by default, the pressure value is set to 4 Pa in CT. Additional calculations are necessary to convert the pressure and match it with EE, which requires an airtightness value at 50 Pa.

CS shows much higher values for the same airtightness than EE and CT. Even though the difference between results is high, some similarities can still be noticed for all BPS tools.

Specifically, after the infiltration rate reaches 2 ACH, heating and EUI start to increase rapidly. One of the main reasons for this difference can be the calculation methods.

EE calculations are based on DIN 18599 (DIN V 18599, 2011). CT calculates airtightness according to EN 15242 (EN 15242, 2007). CS uses "ZoneInfiltration:DesignFlowRate" model for infiltration calculations. Specifically, this model uses a user-defined design floor rate that can be impacted by temperature differences and wind speed (Owen, 2009). As shown in the wind rose diagram (Figure 15), CS has the highest max value for the wind speed frequency, and in contrast with EE, according to CS, strong winds are expected from the western and northern orientations as well. Another reason can be the different values for pressure difference. The user interface of the CS does not provide any additional information regarding pressure difference. The lowest value, 0.1 ACH was selected for the further analysis, since the results for all three tools were closest at this point compared to others.

Changing the orientation of the shoebox affects its energy indicators significantly (Figure 25). The building was rotated step by step by 90° counterclockwise. Despite the fact that EE and CS follow a similar trend for heating demand. On the other hand, CS and CT follow a similar trend for cooling demand. The highest heating and lowest cooling demand are reported for the northern orientation, which is reasonable since a low amount of solar radiation characterizes the north orientation. When it comes to cooling loads, EE peaks at the western orientation, while CT and CS have a similar trend and report the highest value at the east. The lowest EUI is reported for the south, while the other orientations more or less stay on the same level.

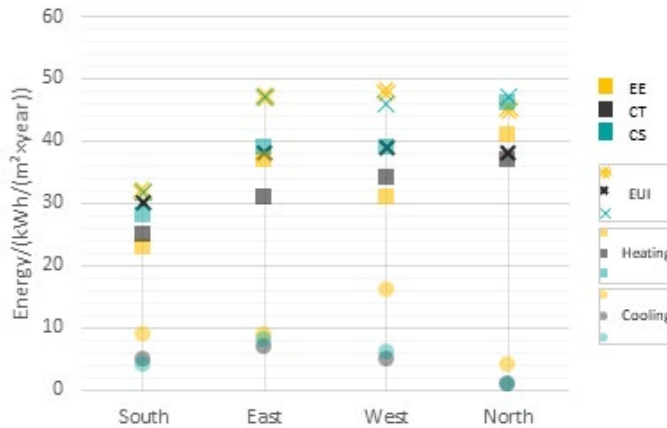


Figure 25. Annual heating and cooling loads for different orientation.

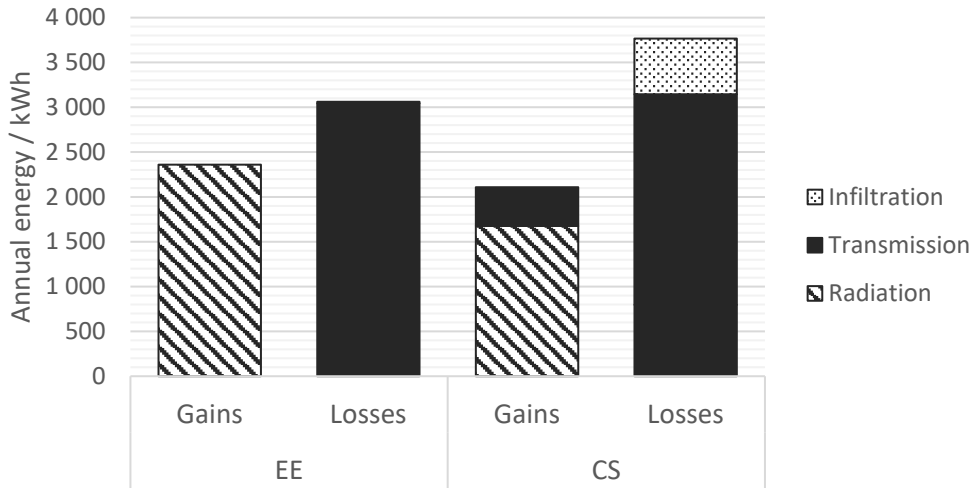


Figure 26. Energy balance for west orientation.

The difference between TEDI and EUI values generated by BPS tools was the most noticeable for the western orientation. Therefore energy balance data was assessed for deeper analysis (Figure 26). The high cooling load for EE can be explained by the fact that it reports more radiation gains than CS. It is worth mentioning that despite the lowest infiltration value, 0.1 ACH, which was selected to proceed with further studies, the difference between heat losses due to infiltration is still significant between EE and CS.

Solar responsive design strategies are an important part of the design process. Window size and the orientation are one of the key variables when it comes to the passive solar gains. Figure 27 shows the analysis of different window size and their orientation. In general the trends for heating cooling and EUI are similar for all three tools. Particularly, bigger window area results in decreased heating and increased cooling loads. Cooling loads are the highest for the EE in all of the cases. It is particularly noticeable at S 80 %. This can be due to high solar heat gains calculated by the simulation engine. When it comes to heating, CS reports the highest demand for almost all of the cases, especially at N 80 %.

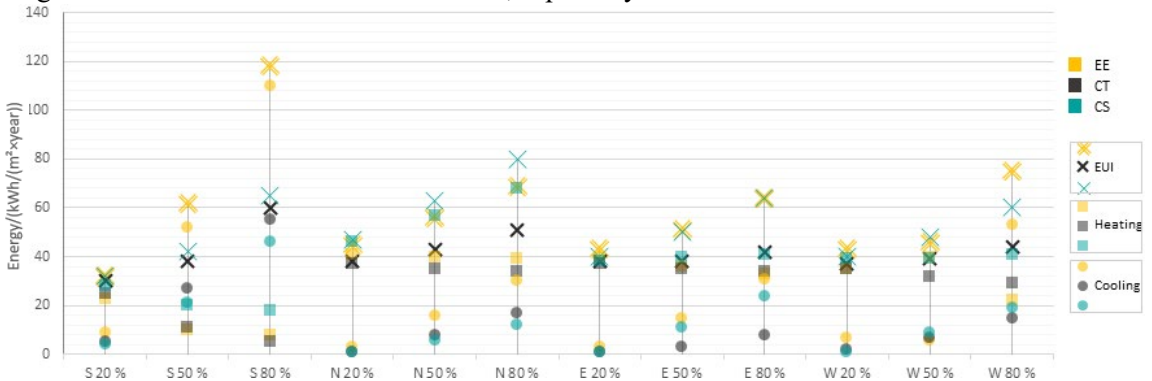


Figure 27. Annual energy use intensity based on window orientation and size in relation with area of external walls.

Even though the areas of the west and east facades are smaller compared to south and north, outputs are similar. East and west orientations are not favorable for the windows due to low-altitude angle of the sun in the morning and afternoon. Maximizing the area of north windows cannot be a good solution for heating dominated climates, since north windows receive only diffuse radiation from the sky and heat gains are not as high as from the south facing windows. Larger glazing areas collect more solar energy, however losses are higher for them as well. South orientation gives possibility to minimize the heating loads by increasing window area, but it negatively affects cooling as well. Therefore it is very important to find a balance between window size and orientation, maximize and minimize solar gains according to heating and cooling seasons by creating appropriate shading systems.

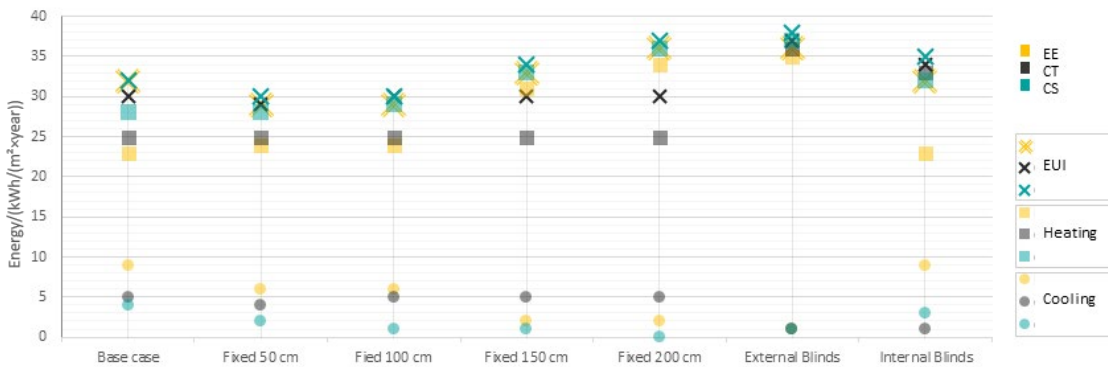


Figure 28. Annual energy use intensity based on different types of shadings.

Shading strategies not only reduce cooling loads but can also be an important design detail. Figure 28 illustrates how different shading strategies can affect annual energy use. EE and CS results appear to be similar until internal blinds are assigned. In CT and CS, internal blinds are assigned automatically, but EE does not have this feature. Therefore internal blinds were placed manually. CT could not see this geometry change since reported results were similar to the base case, where no shading was assigned. Contrastingly, it can be seen that CT cannot effectively read manually created fixed shading. Even though the component was classified and uploaded correctly, it seems like fixed shading does not impact EUI.

Figure 29 portrays how different tools respond when the solar heat gain coefficient of the openings is altered. Unlike other cases, here, all of the tools have a roughly similar pattern.

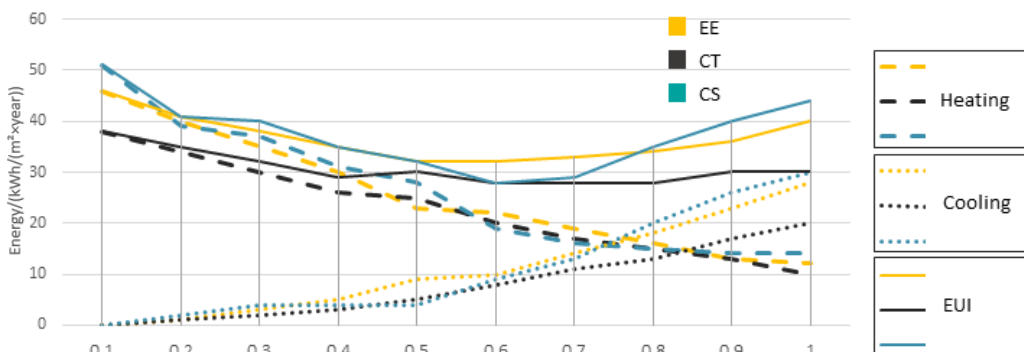


Figure 29. Annual energy use intensity based on different SHGC values.

The difference in the results can be explained by different calculation methods from the simulation engine.

Another important variable in the early design stage is the heat transmittance characteristics, which are mainly impacted by the thickness of the insulation in the thermal envelope. Unlike other cases, simulation results for wall and roof variations follow the same trend for all three BPS tool (Figure 30, Figure 31 and Figure 32).

The results for the floor insulation levels are a little bit different. This can be due to different soil heat transfer coefficients, which cannot be controlled in CT. Thicker insulation resulted in less energy consumption for all of the envelope details. However, after some point curve flattens and the difference between savings is so small, it can be negligible.

Detailed information about the internal heat gains is not always available at the preliminary stage of the design. However, defining the approximate schedule and checking how generated

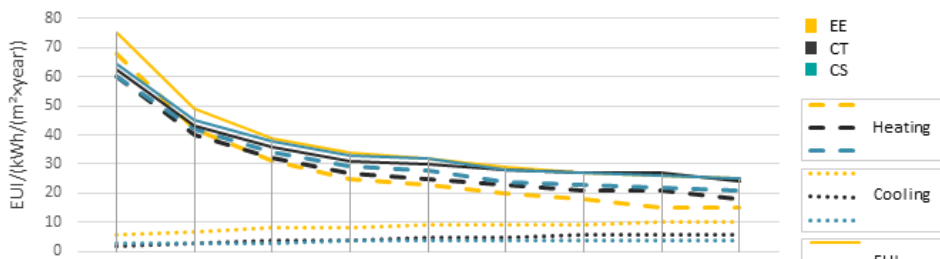


Figure 30. Annual energy use intensity based on different wall insulation thicknesses.

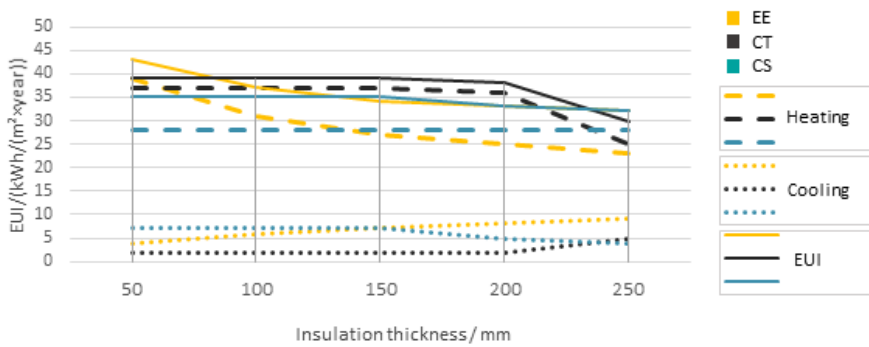


Figure 31. Annual energy use intensity based on different floor insulation levels.

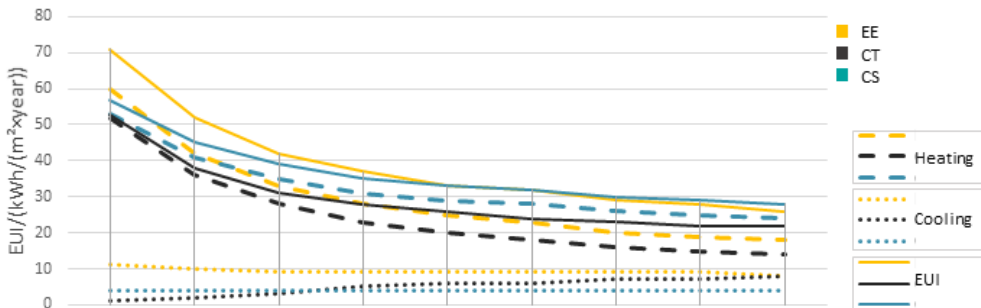


Figure 32. Annual energy use intensity based on different roof insulation levels.

heat affects a building's loads is possible. Figure 33 displays three occupancy scenarios. If the occupancy is more than half, EUI for EE and CT increase while the CS curve comes down. Even though the same schedules and metabolic rates were applied to all of the tools, the behavior of the heating and cooling loads are still different.

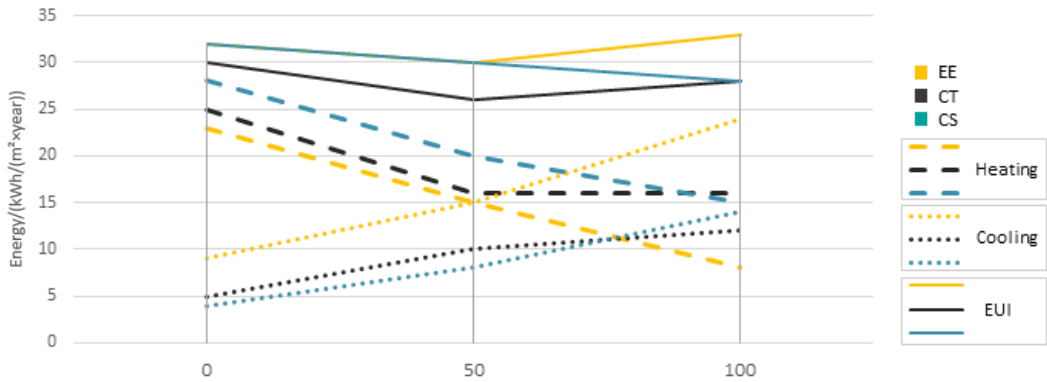


Figure 33. Annual energy use intensity for different occupancy levels.

Based on Figure 34, the one of the reasons for the difference between EE and CS results can be the infiltration. If not, such a big difference in infiltration simulation results would be closer to each other. Columns for the human heat gains are similar.

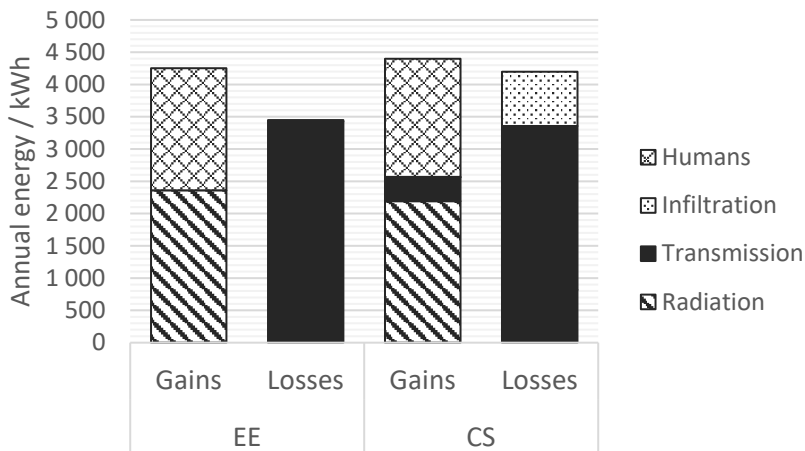


Figure 34. Energy balance when shoebox is fully occupied.

Figure 35 shows the results from the increased lighting and equipment loads. The tendency is the same as it was with human-generated heat; as the load increases, EUI increases as well. The inclination is the highest for the EE and lowest for the CS since the cooling load for CS is smaller due to high infiltration losses that balance heat gains.

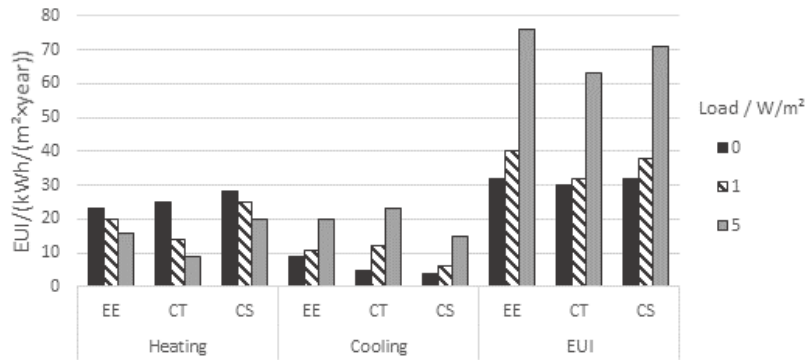


Figure 35. Annual energy use intensity based on different equipment and lighting loads.

4.3.2 POSH – The wedding venue

The navigation between the different results is getting more complicated when more complex geometry is introduced. If the results for the shoebox were moderately close to each other, the situation is significantly different for POSH. When all the loads and active systems are excluded and there is no infiltration heat loss, CT yields at the highest EUI value caused by substantial cooling load, as shown in Figure 36. This can be because in CT, heating and cooling loads cannot be run if active systems are not selected. After the system is selected from the default list, typical COP values are assigned automatically, higher than one,

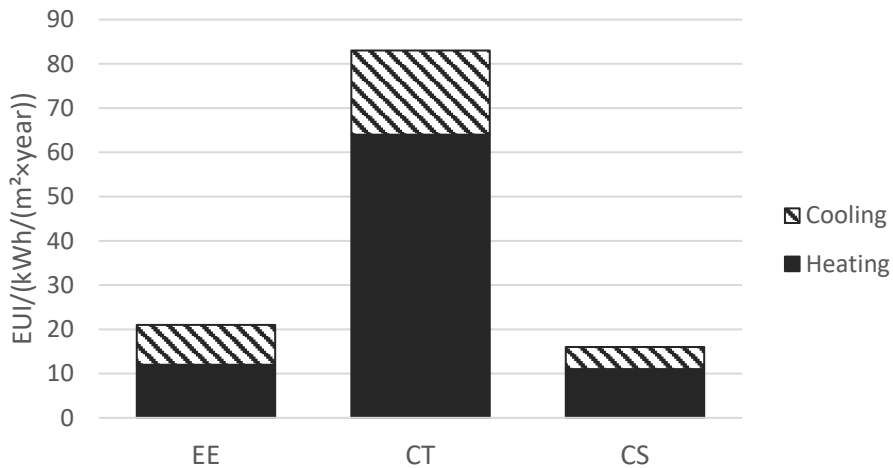


Figure 36. Passive system effects on EUI for POSH.

especially for the cooling load. Therefore, when the default value is decreased loads increase drastically. This tendency was not notable for the shoebox case since the cooling load was already small due to smaller geometry.

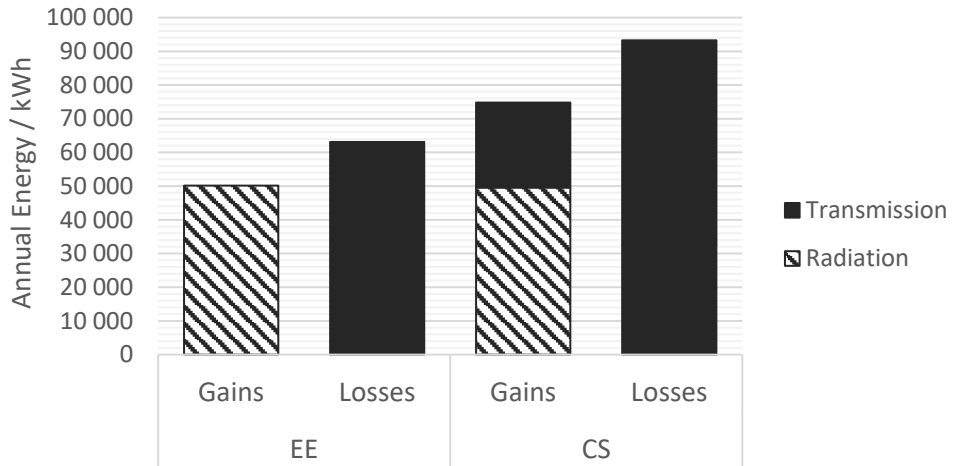


Figure 37. Annual energy, when no loads, infiltration and active systems are assigned.

The somewhat smaller dissimilarity between EE and CS can be explained by energy balance (Figure 37). The gains due to radiation and losses due to transmission are almost similar for both, EE and CS.

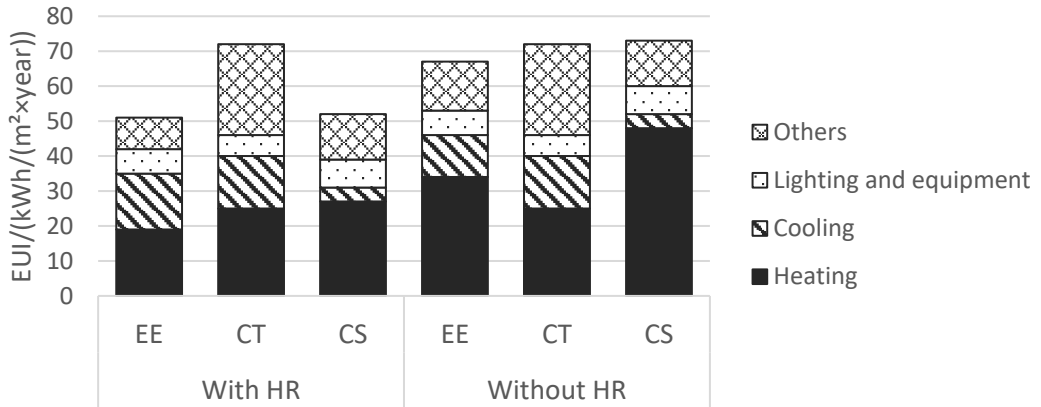


Figure 38. Annual energy use intensity with and without heat recovery system.

Figure 38 displays EUI results after all the loads, schedules, infiltration, and HVAC systems were applied for two cases, one with a heat recovery system and another without. The main reason behind this decision was that unlike CT and CS the efficiency of the heat recovery system cannot be indicated in EE. To make results more comparable, another simulation with the same input but without heat recovery was carried out. Even though it is not possible to validate results with measured data, it can be noted that the results are within the range of the 2030 targets, based on Ontario data (Thomson, 2020). EUI goes high according to EE and CS as the heat recovery system is removed since no heat is recovered.

On the other hand, the EUI value for CT stays on the same level, which does not seem reasonable. It should be noted that even though EE and CT have non-identical values for heating and cooling, in the end, they end up with EUI, which is almost on the same level. Figure 39 and Figure 40 demonstrate the energy balance behind the above-described cases. The same tendency is continued here as CS calculates more gains and losses than EE. With heat recovery, the main difference is infiltration. On the other hand, when heat is not recovered, losses due to mechanical ventilation are more significant for EE.

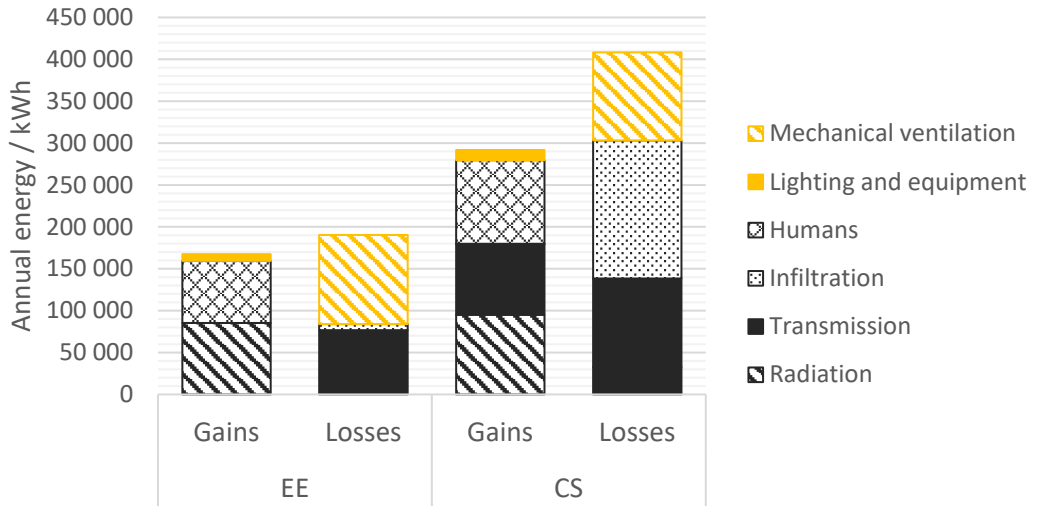


Figure 39. Annual energy balance for POSH with heat recovery system

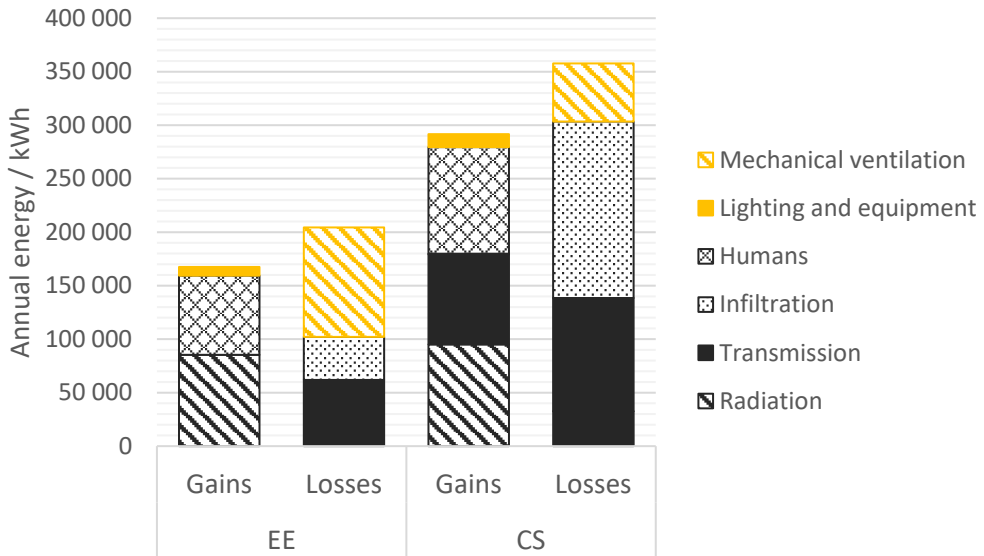


Figure 40. Annual energy balance for POSH when no heat recovery system is assigned.

4.3.3 Muskoka

The results of the energy performance simulations of Muskoka (Figure 41) follow the same tendency as it was noted for the POSH case study. Therefore it can be assumed that CT cannot display reasonable value until active systems are not appropriately defined. This information is not always available at the preliminary design stage, therefore based on the results from two case studies, it can be assumed that CT might not be a relevant solution for passive design

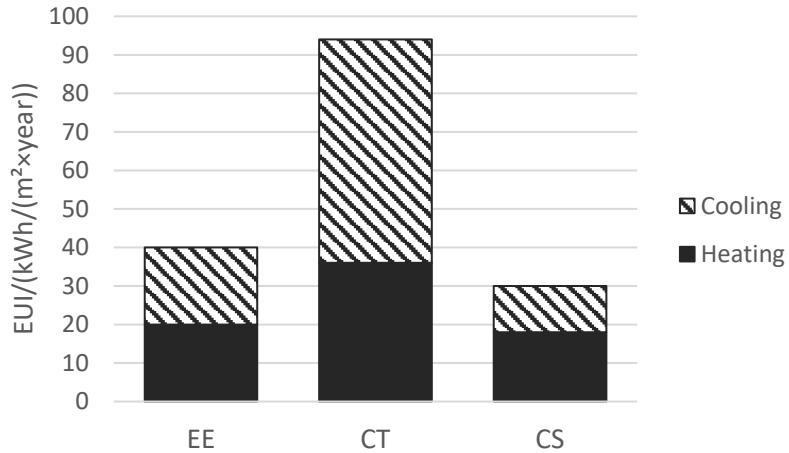


Figure 41. Passive system effects on EU for Muskoka.

evaluation. On the other hand, EE and CS still manage to deliver reasonable values even if no systems are assigned. Moreover, they generate energy balance data, shown in Figure 42, which can be effectively used in the early design phase to motivate passive design solutions such as orientation, shading, surface-to-volume ratio, etc.

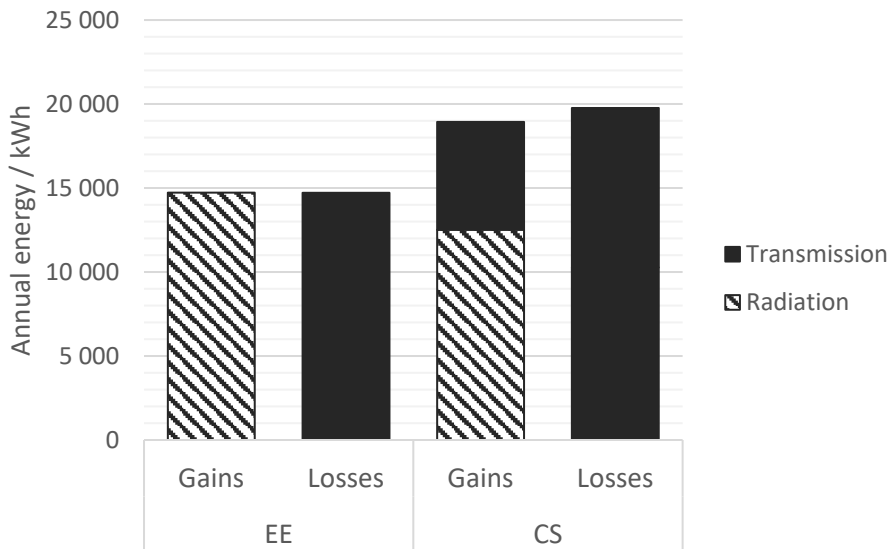


Figure 42. Annual energy, when no loads, infiltration and active systems are assigned.

Figure 43 again highlights the shortcoming of the CT, when similarly to POSH results, EUI values are not affected by the heat recovery system.

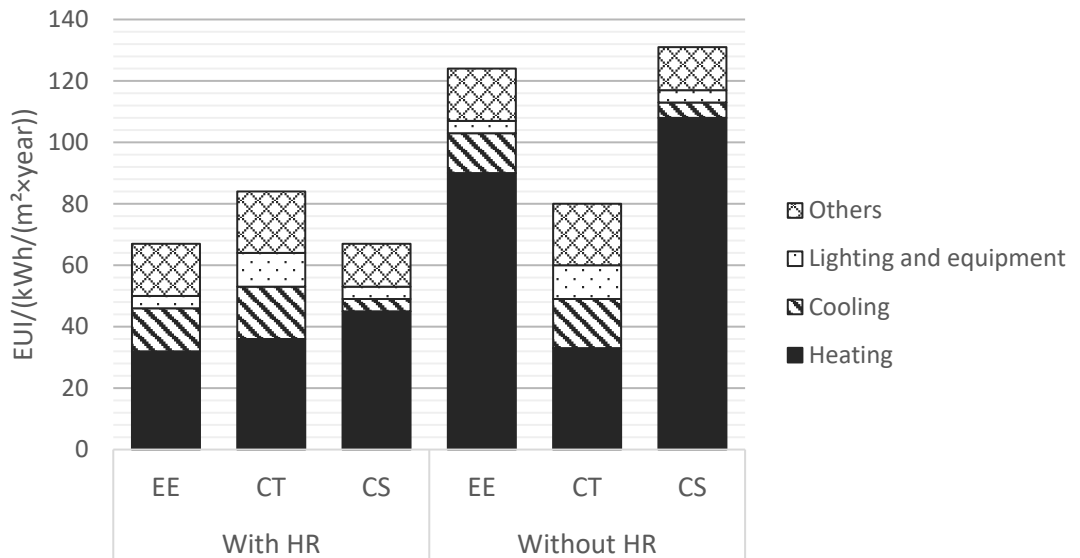


Figure 43. Annual energy use intensity with and without heat recovery system.

Figure 44 and Figure 45 demonstrate annual energy balance for Muskoka with and without heat recovery. It can be seen that in this case heat losses due to infiltration is relatively smaller. This is because the infiltration value for CS was selected based on the EE outcome. As a result, one ACH in EE was closer to 0.1 ACH in CS. However, if we only take EUI into

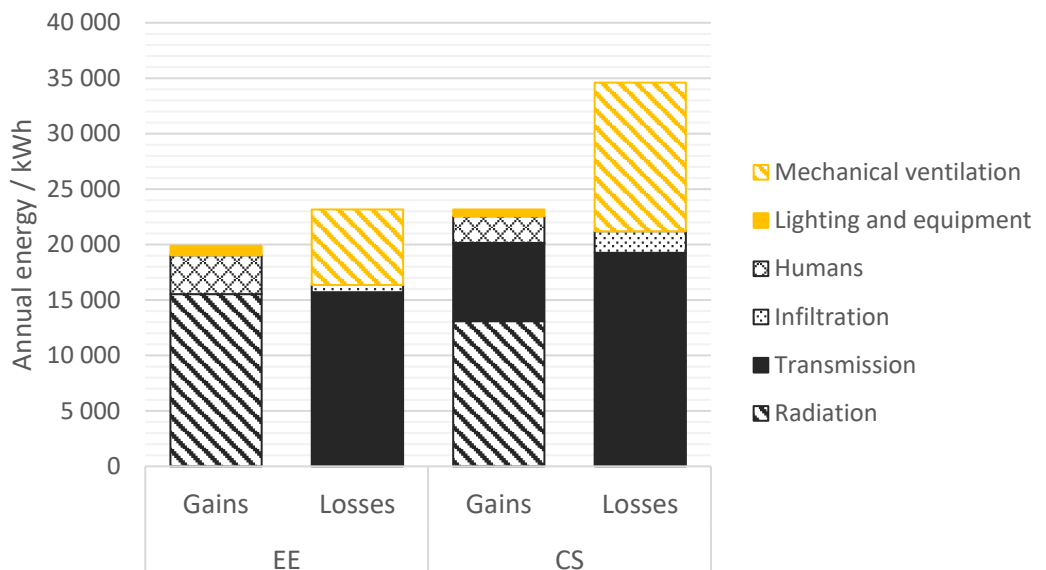


Figure 44. Annual energy balance for Muskoka with heat recovery system

account, results for EE and CS are close for both Muskoka and Posh, even if the infiltration is different.

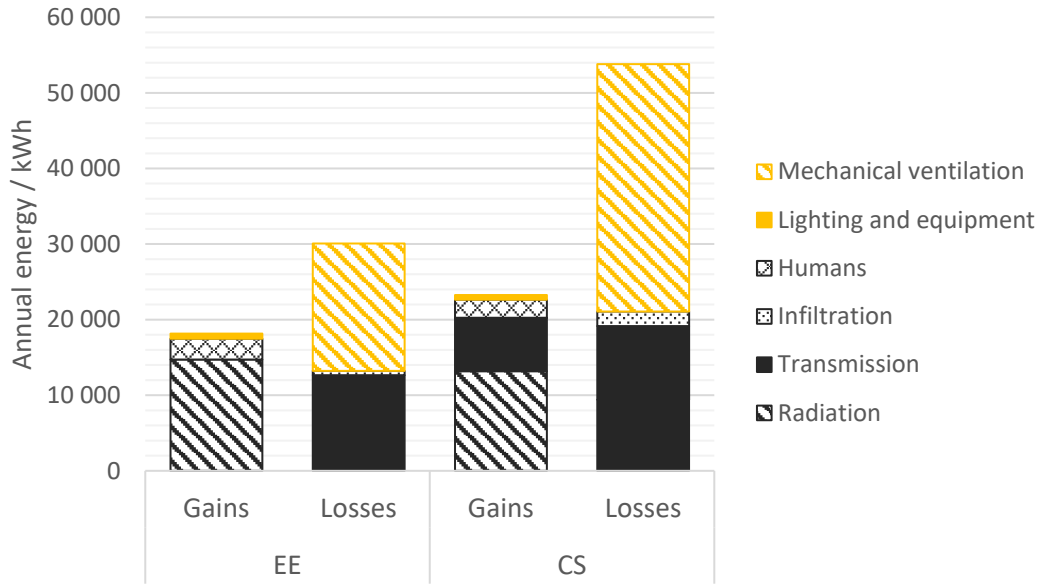


Figure 45. Annual energy balance for Muskoka when no heat recovery system is assigned.

5 Discussion

During the sensitivity analysis of the BPS tools, some principles and relationships between various parameters were revealed. Despite many different results, some generalizations can be listed.

Based on the results, there can be three primary sources for the differences between produced results. These sources are on the program level – the calculation method the simulation engine is based on, on the location level – climate file evaluation, on the building level – BIM file assessment. Despite the fact that the basis of the simulation was one weather file, there still was some difference between generated key climate indicators such as dry bulb temperatures and wind speed/directions. These differences explain dissimilarities between heat balance, particularly losses due to transmissions and infiltrations.

With respect to the BIM file, potential problems emerge when BPS tools analyze the geometry. Even if the same BIM model was used, BEM tools read the information differently. There can be differences in areas, heights, volumes, WWR, etc. Even though many different results were produced, some general patterns are visible. During the sensitivity analysis of the shoebox, EE reported the highest cooling loads for most of the cases. At the same time, CT stayed in the middle and CS ended up with the lowest values. On the other hand, CS reported the highest values for heating load, while CT stayed in the middle again and EE had the lowest values (Figure 25- Figure 32). This can be explained by the fact that CS accounts for more losses due to infiltration and radiation when it comes to energy balance than EE. Therefore heating energy required to balance emitted energy is higher.

During the evaluation of the two case studies (POSH and Muskoka), where all specific details regarding loads, occupancies, infiltration and HVAC systems were provided, EE and CS reported almost similar EUI results. At the same time, CT showed higher values (Figure 39, Figure 44).

During the passive design impacts assessment, CT always shows higher results than others. This difference is more noticeable with more complex geometries than a shoebox (Figure 22, Figure 36 and Figure 41). It is hard to exclude active system effects on the building with CT completely. One must assign a specific system with automatically defined COP values to get reasonable heating and cooling loads. After COPs are reduced to one, TEDI increases dramatically, especially cooling load. The information regarding HVAC systems and their characteristics is hardly available at the preliminary design stage. The fact that the performance of the active systems mainly defines EUI can lead to a diminishing of passive measure impacts. On the other hand, EE and CS allow TEDI calculations while systems are not assigned or are not specified. This could be a comfortable workflow for architects who do not have complementary knowledge in mechanical systems.

EE captures the most information provided by the model in the matter of BIM data utilization compared to other two BPS tools that only extract the geometry. As a result, EE requires the least time and resources to translate BIM to BEM automatically and run energy simulations.

The workflow with Grasshopper live link failed to connect complex geometry and extract all the information that BIM can provide. However, this type of workflow can be up-and-coming

since it is very flexible in input and output variations. It could be interesting to evaluate connection possibilities between EE and Grasshopper with live link in the future. Nowadays, this type of workflow is not possible.

However, Energy Evaluation has its requirements for running adequate simulations. The quality and the level of the BIM model need to be high. All the components need to be appropriately classified, and building details need to be modeled with high accuracy. Building assemblies should include all relevant data regarding thermal properties.

The main advantage of the EE, as a combined model integration method, compared to other BPS tools is the utilization of the majority of the information that BIM model can provide. This workflow is very time efficient and flexible at the early design stage when changes are happening more often than in other phases. EE does not require advanced knowledge in active systems to effectively calculate reasonable heating and cooling demands. It automatically displays results graphically and has a short running time regardless of model complexity.

When it comes to disadvantages, it can be noted that information extracted from the EE is somewhat limited compared to other tools such as CS. For instance, it does not display information about peak loads which can be an essential indicator of the building energy efficiency. The input of the data is also limited. For example, it is impossible to define heat recovery efficiency, assess thermal bridges, or simulate renewable energies.

Several improvements can be made for further development of the Energy Evaluation. First of all, the issue of HDD and CDD needs to be fixed. Based on the results, it seems like it does not have any impact on heating loads. If it had, loads would be much higher for EE, which is not the case according to the performed studies. Moreover, it would be better if it allowed more user control, including defining some important parameters such as heat recovery efficiency. In order to catch up with other BPS tools, additional analysis such as embodied carbon and water, daylight and renewable energies should be added. In order to simplify the simulation process for the architects, a more user-friendly GUI can be introduced, with more guides and explanations across each input boxes.

As the other studies reported, most interoperability challenges happen due to data loss while BPS tools assess the BIM model. The combined model integration method utilizes the most data related to the BIM, but it is somewhat more limited than central or distributed methods. Despite these limitations, the results show that EE reasonably calculated most of the key variables of the early design phase. It showed almost the same accuracy as the combined model integration method, such as ClimateStudio.

It is hard to talk about the validation of the results without having measured data. However, EUI provided for POSH and Muskoka to comply with Ontario's 2030 targets for reference buildings. Therefore it can be assumed that results are reliable.

6 Conclusion

This study evaluated three different BPS tools based on the three case studies, starting from the simple shoebox and more complex public and residential BIM models.

The interoperability challenges and problems, such as inefficient data translation, impacts of different calculation methods, input and output limitations, were reflected during the case studies.

Parametric analysis of the shoebox showed that even the reported values for the TEDI and EUI were different for each BPS tool, they still followed the same trend. These differences were mainly caused due to different calculation methods and assumptions regarding the building's energy balance. The biggest difference was reported during infiltration studies.

The assessment of the passive design revealed that not all the tools could calculate reasonable values without defining HVAC system characteristics, which usually is not known at the early stage of the design.

The EUI results reported for the POSH wedding assembly and Muskoka residence were almost identical. Even though BPS tools calculated losses and gains differently, they have balanced heating and cooling systems accordingly.

In conclusion, all of the evaluated workflows showed a different level of interoperability and their energy output was different from each other even though all the inputs were similar. The differences in the outcomes were reported during all stages of the evaluation, including climate and geometry assessment and energy calculations. In reality, each BPS tool has its simulation engine and is based on different calculation methods. Therefore, results varied from one platform to another. Within the one BPS tool, the impact of design alternatives can be approximately tracked by result variations. Still, the number of the building itself cannot be precise and should not be used as a reference to building energy performance in operation.

Based on the overall performance, BIM to BEM translation efficiency, simulation time, flexibility and simplicity, Energy Evaluation can be identified as the most appropriate BPS tool for the early-stage design evaluations compared to the other two workflows. As a combined method of model integration, EE has its limits, which can be seen in both simulation input and output. However, these limitations can be acceptable in the early stage of design. It might not meet the requirements for the final stages when more accurate information is needed for HVAC system sizing.

As revealed from the literature review, few studies are conducted with a combined method for BIM to BEM integration. As shown from the results, the combined model integration method can be as reliable as others. Therefore, more studies are necessary to popularize and develop this kind of workflow, which would help architects perform quick energy simulations by themselves at any stage of the design process.

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Appendix 1

Report generate by Energy Evaluation

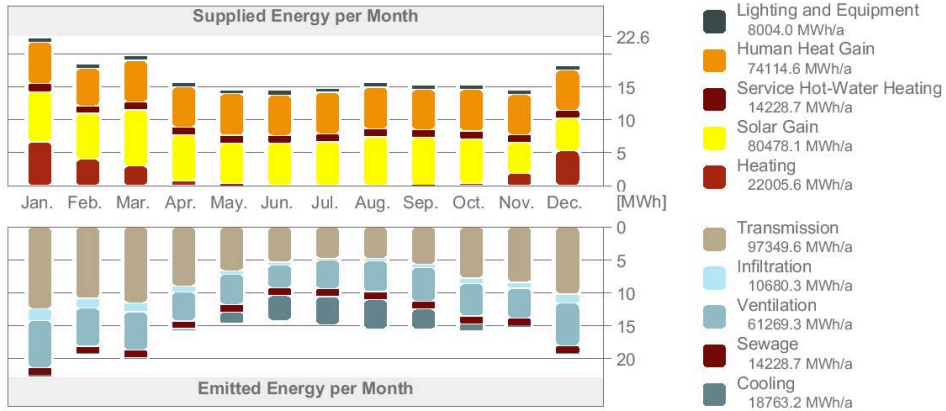
Ontario Building Code | Performance Path Evaluation SB12 (3.7)

2012 Three Feathers Terrace | (HDD error, EEA solved)

Key Values

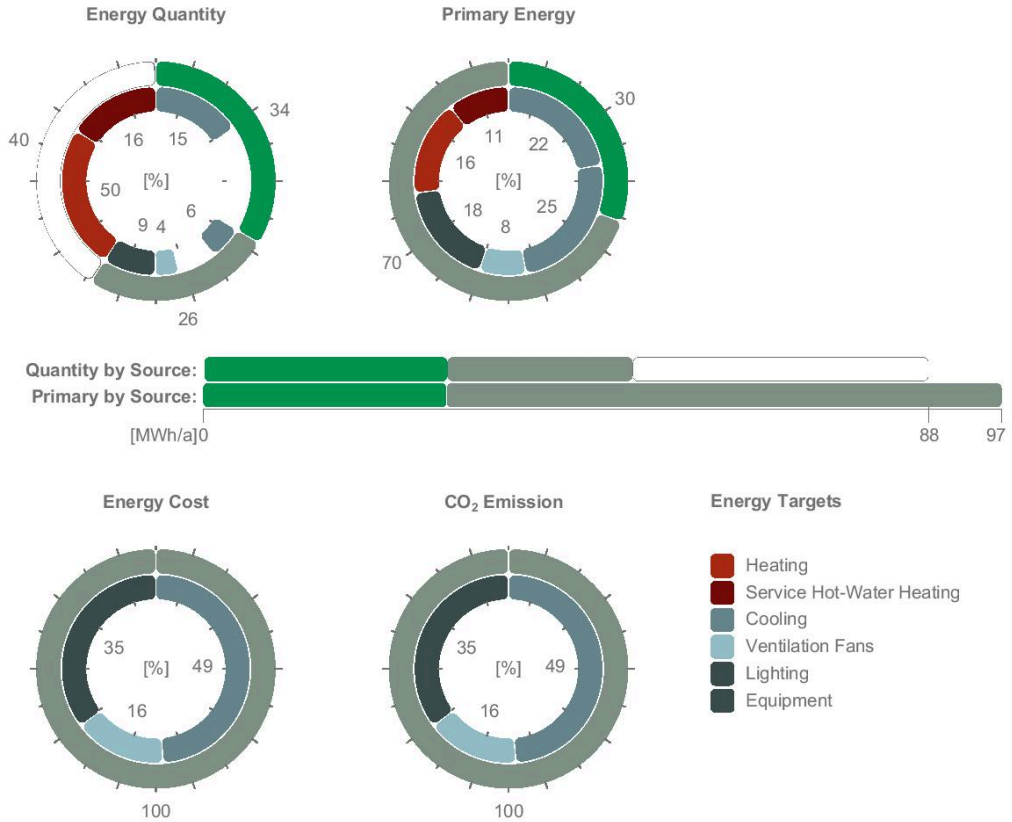
General Project Data		Heat Transfer Coefficients		U value	[W/m²K]
Project Name:	Three Feathers Terrace	Building Shell Average:	0.25		
City Location:		Floors:	0.38 - 0.38		
Latitude:	43° 39' 0" N	External:	0.11 - 0.24		
Longitude:	79° 30' 0" W	Underground:	--		
Altitude:	512.00 m	Openings:	0.81 - 0.97		
Climate Data Source:	CAN_ON_Tor...EC (1).epw	Specific Annual Values			
Evaluation Date:	06-May-21 18:38	Net Heating Energy:	19.30	kWh/m²a	
Building Geometry Data		Net Cooling Energy:	16.46	kWh/m²a	
Gross Floor Area:	1180.49 m²	Total Net Energy:	35.76	kWh/m²a	
Treated Floor Area:	1140.18 m²	Energy Consumption:	58.42	kWh/m²a	
External Envelope Area:	2350.80 m²	Fuel Consumption:	51.66	kWh/m²a	
Ventilated Volume:	8540.0566 m³	Primary Energy:	85.77	kWh/m²a	
Glazing Ratio:	15 %	Fuel Cost:	2.98	CAD/m²a	
Building Shell Performance Data		CO ₂ Emission:	0.24	kg/m²a	
Infiltration at 50Pa:	0.62 ACH	Degree Days			
		Heating (HDD):	6195.25		
		Cooling (CDD):	934.45		

Project Energy Balance



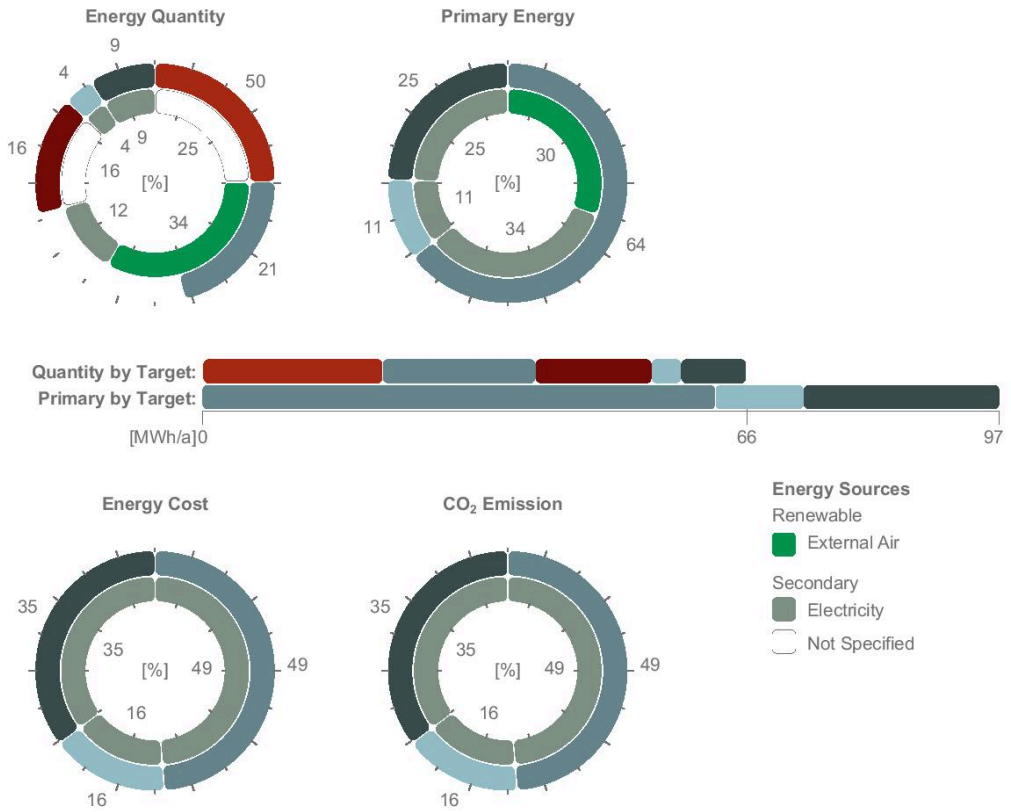
Energy Consumption by Sources

Source Type	Energy				CO ₂ Emission
	Source Name	Quantity	Primary	Cost	
		MWh/a	MWh/a	CAD/a	kg/a
Renewable	External Air	29	29	NA	0
Secondary	Electricity	22	67	3399	269
	Not Specified	36	--	--	--
Total:		88	97	3399	269



Energy Consumption by Targets

Target Name	Energy				CO ₂ Emission kg/a
	Quantity MWh/a	Primary MWh/a	Cost CAD/a		
Heating	22	0	0	0	0
Cooling	18	62	1657		131
Service Hot-Water	14	0	0		0
Ventilation Fans	3	10	541		42
Lighting & Appliances	8	24	1200		95
Total:	66	97	3399		269



Thermal Blocks

Thermal Block	Zones Assigned	Operation Profile	Gross Floor Area m ²	Volume m ³
001 One Zone	1	Restaurant	1180.49	8540.0566
Total:	1		1180.49	8540.0566

Environmental Impact

Source Type	Source Name	Primary Energy MWh/a	CO ₂ emission kg/a
Renewable	External Air	29	0
Secondary	Electricity	67	269
Total:		96	269

Appendix 2

Report generated by Cove.tool

5/6/2021
ANALYSIS SUMMARY

Report

Location
1263 3 Line, Lefroy, ON L0L 1W0, Canada

3

Walk Score®
Car-Dependent

26

Bike Score®
Somewhat Bikeable

Building Type



Wedding assembly

81

Overall Energy

The current model is done using **NECB 2011** energy code assumptions. The current design is **better** than the national average and can be significantly improved by higher performance of envelope, HVAC and more. The building load is driven by **Heating and Hot Water**.

<https://app.cove.tool.com/project/21040/report?baseline=true>

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5/6/2021
BENCHMARKS

WHERE DO WE NEED TO BE?

Report

Energy

847

National Average

169

2030 Target

Energy
EUI is expressed as energy per square meter per year. It is calculated by dividing the total energy consumed by the building in one year (measured in kWh) by the total floor area of the building. The most common unit for EUI is kWh/m²/year.

55%

Daylight

Spatial Daylight Autonomy (sDA) describes the percentage of floor area that receives at least 300 lux for at least 50% of the annual occupied hours.

10%

Glare

Annual Solar Exposure (ASE) refers to the percentage of space that receives too much direct sunlight (1000 Lux or more for at least 250 occupied hours per year), which can cause glare or increased cooling loads.

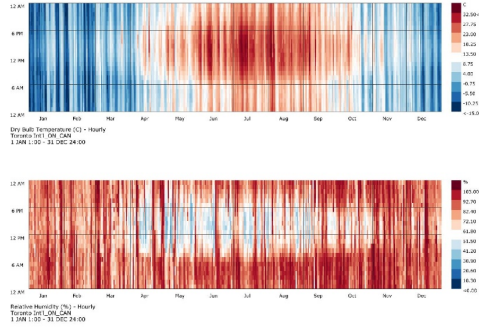
<https://app.cove.tool.com/project/21040/report?baseline=true>

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5/6/2021

Report

CLIMATE ANALYSIS
RELATIVE TEMPERATURE & HUMIDITY



This graph shows the outdoor comfort in **hmsif** using the yearly range of temperatures and humidities.

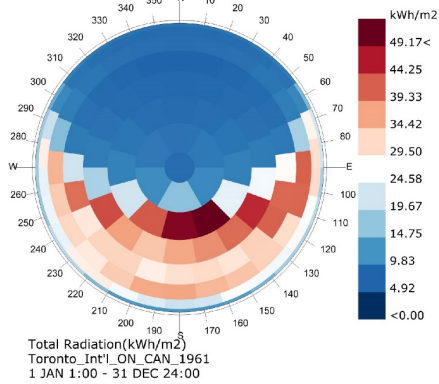
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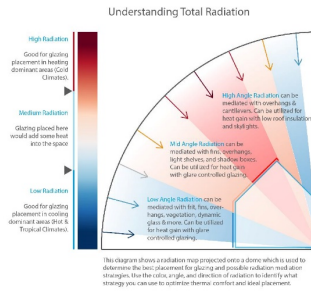
5/6/2021

Report

CLIMATE ANALYSIS
RADIATION BY SKY SEGMENT



This graph maps the radiation onto a sky dome to show the intensity of the direction and intensity of solar radiation on a yearly basis around the cardinal points in **hmsif**.



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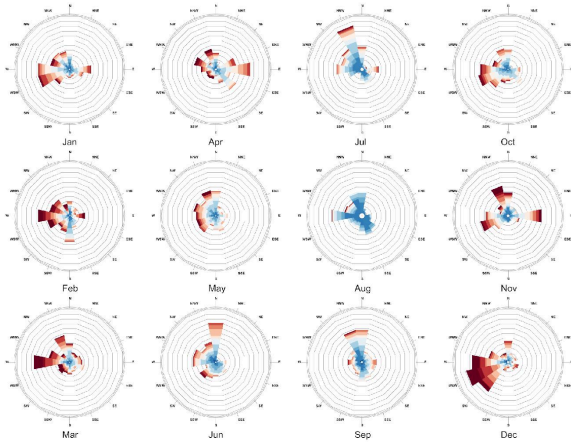
8/12

5/6/2021

Report

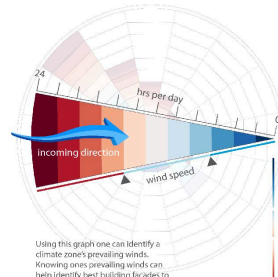
CLIMATE ANALYSIS

WIND



The diagrams show the wind direction and intensity coming to the site. The number of hours are reflected by the size of the rose, and the intensity is expressed in colors as shown in the legend.

Understanding the Wind Diagram



Using this graph one can identify a climate zone's prevailing winds. Knowing ones prevailing winds can help identify best building facades to use for passive ventilation strategies such as operable window placement.

- Low Wind Speeds**
Ventilation placed along the directions of 'low wind speeds' or winds of minor reach will not be effective in cooling dominant areas (Hot/Tropical Climates)
- Mild Wind Speeds**
- High Wind Speeds**
High wind with the furthest reach is the prevailing wind for that climate area. This is the best area/ direction for ventilation strategy.

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<https://app.covetool.com/project/211046/report/baseline>true>

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LUND UNIVERSITY

Dept of Architecture and Built Environment: Division of Energy and Building Design
Dept of Building and Environmental Technology: Divisions of Building Physics and Building Services