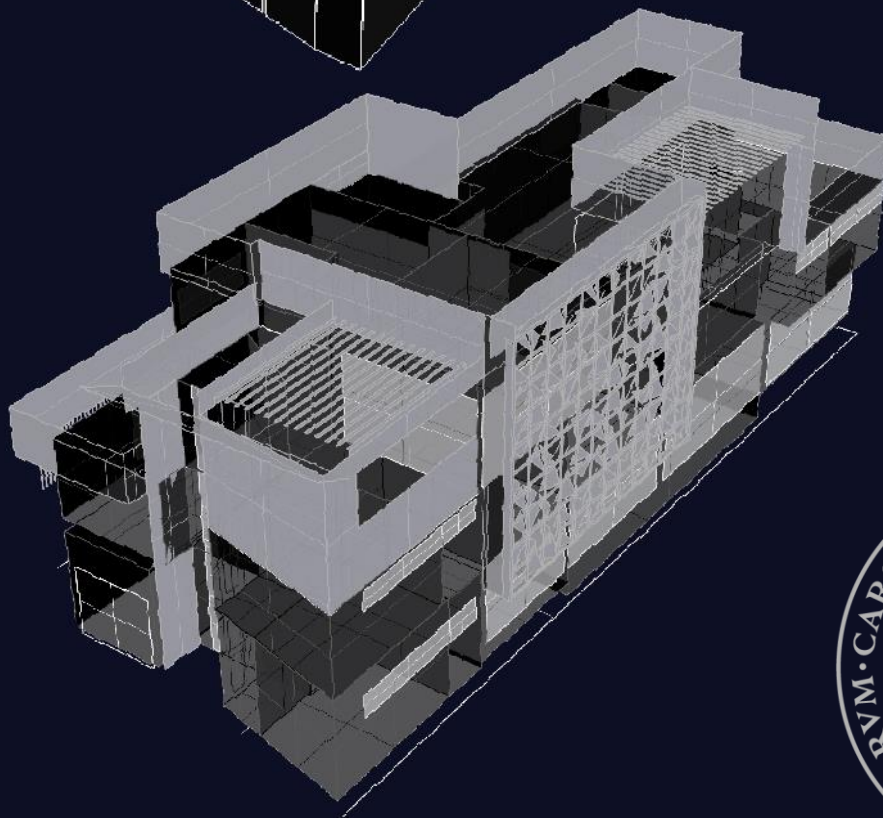
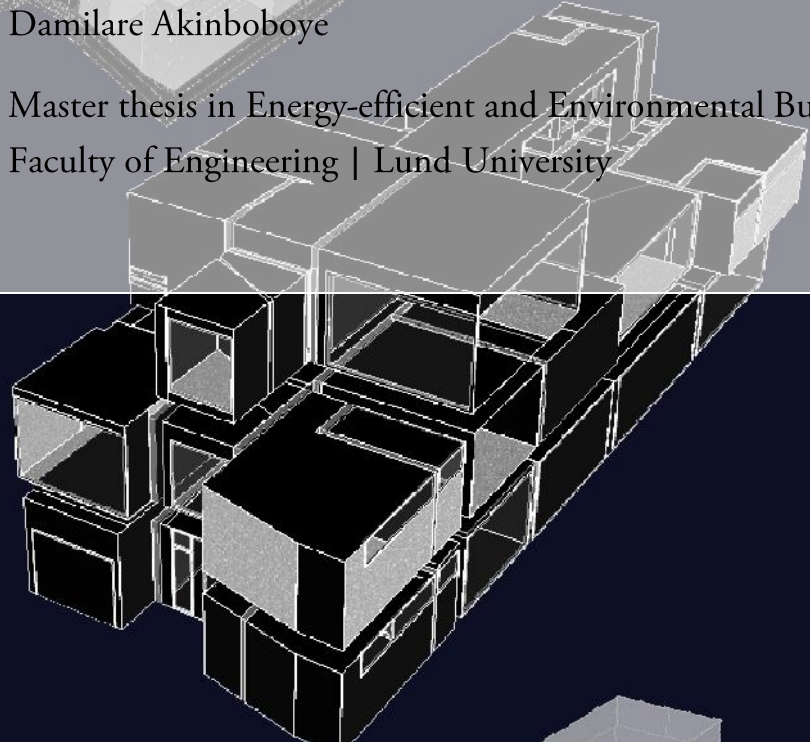


A Comparison of Building Energy Performance Simulation Tools in BIM and non-BIM environments

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Master thesis in Energy-efficient and Environmental Buildings
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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' behaviour 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), Building Energy Simulation (BES), Interoperability, BPS tools.

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Abstract

The detailed use of Building Performance Simulation (BPS) tools to estimate the energy use and encourage energy savings solutions is vital in mitigating the energy use for buildings and the production of this energy. Furthermore, the design of energy-efficient and environmentally friendly buildings involves a collaborative effort among professionals in the Architecture, Engineering, and Construction (AEC) industry. The introduction of Building Information Modelling (BIM) tools provides the assessment of the performance of different design solutions possible with timely feedback during each design phase and over the life cycle of the building. However, there have been some limitations in its use for building performance simulations in BIM environments such as the translation of building specific data from the objects of 3D geometries to BEM, the less customizable inputs of the HVAC systems, and the insufficient knowledge of the operation of the HVAC systems. Consequently, the major issue of BIM and BEM interoperability (in BIM environments) has resulted in data clashes and data loss of the functional and physical specifications of the building as represented by the 3D building objects.

Using a systematic analysis, this study analyzed the inputs that are relevant to the three selected BPS tools in one BIM environment and two non-BIM environments, after which a case study located in a cooling-dominated climate was assessed to examine the combination of the customizable inputs for each BPS tools.

The study found that using the BPS tool in a BIM environment resulted in some promising results based on the comparison with the other BPS tools. However, the possibility of integrating BIM with one of the BPS tools using the IFC data scheme and its wide range of customizable inputs for HVAC systems showed that its use in the EDP and other stages would reduce the time for remodelling and inputting the relevant building data to provide timely feedback for its use in estimating energy efficiency in buildings.

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Abbreviations

AHU – Air Handling Unit

ACH – Air Changes per Hour

AEC – Architecture, Engineering, Construction

ANSI – American National Standards Institute

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

BEM – Building Energy Modelling

BES – Building Energy Simulation

BESTEST – Building Energy Simulation Test

BIM – Building Information Modelling

BPS – Building Performance Simulation

CAD – Computer-Aided Design

EDP – Early Design Phase

EER – Energy Efficiency Ratio

ES – Energy Simulation

EPW – EnergyPlus Weather

ESBO – Early-Stage Building Optimization

EUI – Energy Use Intensity

GBS – Green Building Studio

gbXML – Green Building eXtensible Markup Language

HVAC – Heating, Cooling, and Air Conditioning

IDA ICE – IDA Indoor Climate Energy

IFC – Industry Foundation Classes

NREL – National Renewable Energy Laboratory

SHGC – Solar Heat Gain Coefficient

TMY – Typical Meteorological Year

VAV – Variable Air Volume

VRV - Variable Refrigerant Volume

1 Introduction

1.1 Background

Climate change is seen as one of the most critical environmental issues of our time. It is fueled by the release of greenhouse gases such as carbon dioxide produced in the generation of energy for use in buildings. Energy use in buildings has risen dramatically over the past few decades, largely because of population growth, economic growth, and increased standards of living (Kelso, 2012). In 2017, the housing and services sector accounted for 39% of end-use energy use in Sweden (Swedish Energy Agency, 2021). The Swedish government has set ambitious sustainability targets, such as going fossil-free by 2045 and relying entirely on renewable energy (Swedish Climate Policy Council, 2022). Energy-efficient buildings can achieve this target. There is an increasing need for buildings that are both energy-efficient and environmentally friendly (Yan et al., 2013). However, improving energy efficiency requires several approaches and technologies to be integrated into a combination of systems (Hestnes et al., 2003). Nevertheless, a holistic and integrated approach to building design is crucial to improving energy utilization and minimizing energy use in buildings so that conflicting requirements and variances do not arise in architectural designs (Hestnes et al., 2003). Building energy modelling (BEM) technology is one of the most efficient ways to ensure energy efficiency in buildings as it helps evaluate alternative designs, compare, and select systems and subsystems, allocate annual energy budgets, achieve energy standards, and optimize economics throughout the building design process (Al-Homoud, 2001).

The application of Building Information Modelling (BIM) in new buildings has proven to improve the construction process and facility management over the life cycle of the buildings (Gholami et al., 2015). According to Ahn et al., 2014, the importance of BIM has been beneficial for sharing information and facilitating easy interoperability with software tools used in the Architecture, Engineering, and Construction (AEC) industry. One of the most crucial aspects in constructing sustainable building retrofits is determining its building energy performance (Habibi, 2017). The Building Performance Simulation (BPS) software programs that generate optimal measures for retrofitting buildings to identify energy saving potential are essential in reducing the energy use of the existing dwellings (NREL, 2011). However, the energy simulation findings derived from earlier studies comparing BPS systems integrated with BIM to state-of-the-art BPS programs have a limited level of reliability. NREL (2011) established a series of test scenarios to test the accuracy of building energy audit software and calibration techniques to analyze and enhance the accuracy of energy performance analysis accuracy in retrofit residential buildings. Nonetheless, BEM has not yet been fully integrated and synchronized with the digital planning and design process, as it does not yet benefit from the continuous information flow that the digital modelling provides (Gao, Koch, and Wu, 2019).

1.2 Aims and Objectives

With the introduction of BIM, the need for better coordination and integration between all stakeholders in the AEC industry has increased dramatically. Integrating BIM and BEM at all phases of the building design process is vital for ensuring better building design decisions, most importantly during the early phases of the design process.

The aim of this study is to investigate the performance of Revit's Energy analysis tool compared to other BPS tools, which will allow for its use in the design process. This will maximize the benefits of using BIM in all design stages and reduce the time consumed in remodelling and setting Building Energy Simulation (BES) inputs of BPS tools in non-BIM environments.

It aims to investigate the comparison of three BPS tools, one in the BIM environment and two in the non-BIM environments, and to evaluate the simulation results of the different BPS tools to evaluate their accuracy, detail level, output quality, and speed.

This thesis also attempts to attain an efficient and accurate translation of data between BIM (Revit) and BEM tools using the Revit API and EnergyPlus as the simulation engine.

1.3 Research questions

The following research questions have been designed to further understand the research:

- How to improve the confidence and reliability of using a BPS tool in a BIM Environment compared with BPS tools in non-BIM environments.
- How the BIM tools translate models for energy simulation calculations.
- How well and fast do the BPS tools translate the models and the calculation time and its relation to the complexities of the models.
- Applicability to the conceptual stage of a building design to accommodate changes in the design.
- Comparison of the accuracy of the BPS tools based on different calculation methods.

1.4 Structure of the thesis

This report is structured in five chapters as shown in Figure 1. First, there is an introduction to explain the importance of energy efficiency in buildings and the use of BEM technology by the construction industry. Furthermore, this section describes the aims and objectives of this study, as well as the questions and the structure of the study.

The second chapter covers the theoretical background study that explains:

- BIM in detail based on Level of Development (LOD) and how it can be applied during various phases of the design project,
- How BIM and BEM can be integrated, the different design stages BIM and BEM are used,
- The approaches adopted in this research to bridge the interoperability gap between BIM and BEM,
- and Different data extraction processes and data format types used in translating data from BIM to BEM, as well as the challenges experienced in BIM's integration with BEM, and the BPS tools were chosen for evaluation in this study.

The third chapter entails the data collection for all evaluated case studies. This chapter presents in detail the methodology for the energy simulations carried out in the BIM and non-BIM environments. The fourth chapter describes the results obtained from analyzing the energy simulation results of the examined BPS tools. Finally, the fifth chapter discusses the findings from the research study, and the sixth chapter discusses the general conclusions, limitations, and any further research needed in the future.

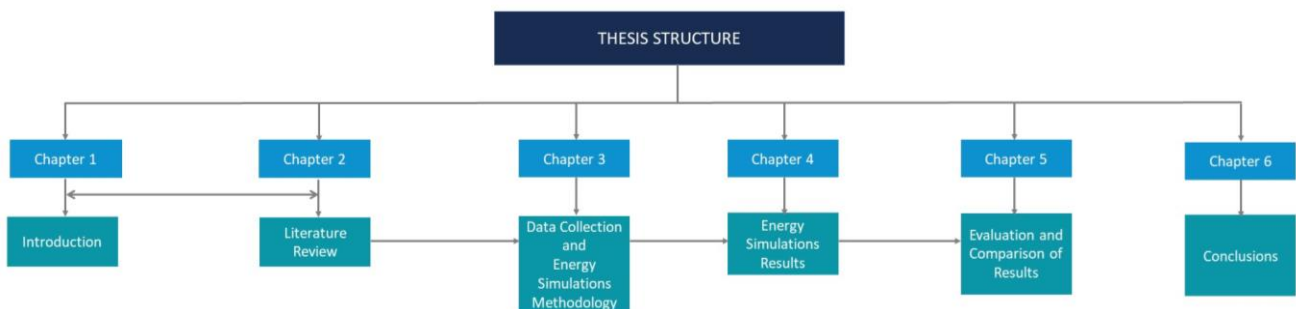


Figure 1: Thesis Structure and workflow.

2 Literature Review

An extensive literature review was carried out in this section to identify the applications of BIM and BEM in the building design process, the interoperability of BIM and BEM, as well as issues found in integrating BIM and BEM. Full-text papers published in ScienceDirect, ResearchGate, and other relevant databases were studied to identify salient points relevant to the subject of study. The following keywords were used for the search: BIM, BEM, building energy performance, interoperability, and BPS.

2.1 BIM

BIM provides information about a building in an object-oriented, intelligent, and parametric form, creating an interface that can be adapted to the needs of users (Gao et al., 2019). The U.S. national BIM standard (NBIMS-US) defines BIM as “the act of creating an electronic model of a facility for visualization, engineering analysis, conflict analysis, code criteria checking, cost engineering, as-built product, budgeting, and many other purposes” (NBIMS-US, 2013). BIM is also defined by Smith and Tardif (2008) as “a mechanism to transfer from data into information to gain the knowledge that allows us to act with wisdom”. BIM focuses on the concept of a single digital model representing the entire ontology of a building to design, simulate, and construct it (Lack & Butler, 2019). BIM also refers to a 3D object-oriented parametric digital representation of the physical and functional characteristics of a facility (Belsky, Sacks, Brilakis, 2013).

2.2 Level of Development (LOD)

The LOD concept is introduced in BIM to enable actors in the AEC industry to specify and articulate with a high level of content clarity as well as reliability of the 3D models at various stages (AIA, 2013). According to Succar (2009), it is vital for the implementation of BIM stages to be well-defined in relation to the LOD by organizations and teams in the AEC industry. The combination of object-based modelling, model-based collaboration, and network-based integration should have been considered and effectively applied to achieve a high level of content clarity and reliability (Succar, 2009).

LOD is a measure of how thoroughly the specification and geometry of the element and its associated information have been conceived (Latiffi et al., 2015). There are five levels of development in BIM, namely LOD 100, LOD 200, LOD 300, LOD 350, LOD 400, LOD 500, LOD 600. These LODs are at all levels of development during the design phase.

Figure 2 presents the different levels of development in BIM and what it entails.

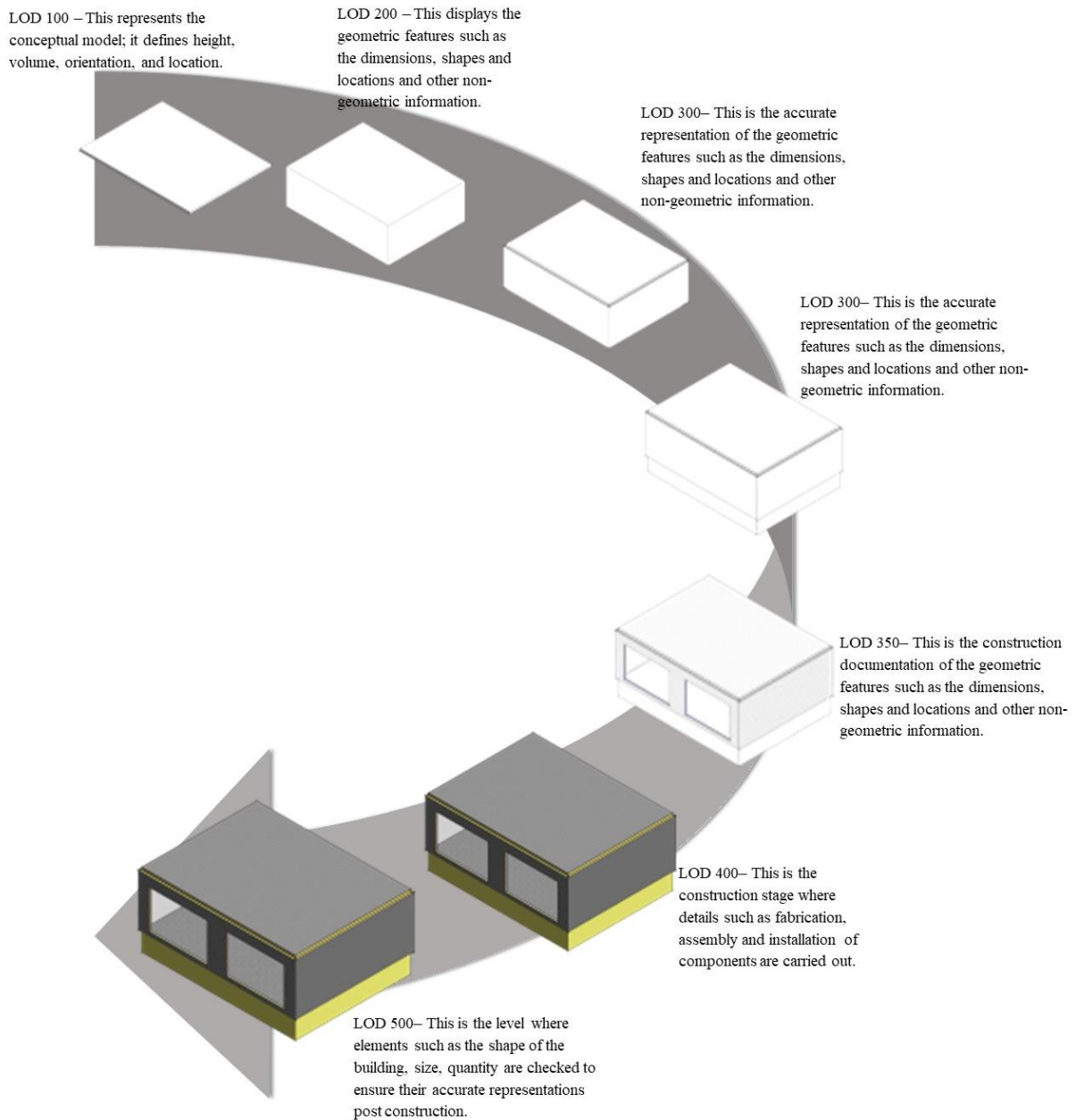


Figure 2: BIM different Levels of Development adapted from Ellis (2020) and Monarch Innovation (2021).

2.3 BEM

BEM is a vital aspect of building design, especially in the Early Design Phase (EDP) (Petersen & Svendsen, 2011). According to Gao et al. (2019), a simulation engine has three basic components, which include a simulation manager, a heat and mass balance simulation module, and a building systems simulation module. Some of the challenges of using a conventional BEM process were highlighted by Bazjanac (2008). Inconsistent processes in building geometry preparation in simulation tools are among the most prevalent means of getting feedback on performance during the EDP, and because whoever prepares the simulation and analysis always uses their thermal view to generate building geometry, the process of preparing inputs for simulations and analyses is laborious, lengthy, and expensive. The quantitative results of BEM cannot be repeated due to arbitrary assumptions and choices made in simulation model definitions, and the results cannot be relied upon except under specific circumstances, and the BEM cannot begin until some fundamental design decisions have been made (e.g., building design and HVAC design are developed) to provide adequate information needed to generate the model. Another study conducted concluded that in a conventional design approach, BEM is generally incorporated at the final design stage because it lacks input variables early on, yet critical

contradictions always occur between design decisions and BEM analysis in the final design period, when no changes can be made (Zhu, 2014). Attia et al. (2013) stressed the importance of decision-making during the EDP. Usually, the most important decisions that influence energy efficiency are made during the concept design phase, when little information is available and sometimes before the opportunity to collaborate with specialists is available (Bleil De Souza, 2013). According to Bogenstätter (2000), 20 % of the design decisions taken during the EDPs subsequently influence 80 % of all design decisions. Negendahl (2015), highlighted that most of the tools and methods used in the EDP are insufficient to provide valuable feedback, while still being flexible enough to accommodate a constantly changing process. However, the development of viable BIM-BEM interoperability processes is necessary to tackle some of the problems posed by the conventional BEM process.

2.4 Application of BIM-BEM in the Building design process

The design process of a new building project includes three phases: preliminary concept design (or program pre-design), final concept design (or schematic design), and design development (ASHRAE, 2018). When planning an architectural project, it is important to obtain estimates of energy use for different design options so that options can be compared (Kota et al., 2016). In addition, the greatest potential for building design optimization is in the EDP, because of its strong influence on the cost of design changes, energy efficiency, and general performance (Ahuja et al., 2015). According to Bambardekar & Poerschke (2009), the EDP is considered by simulation experts and non-experts as very productive in designing energy-efficient buildings. However, some key factors limit the use of BEM during the EDP such as ES experience, client preferences, aesthetics, and less priority on energy performance (Ahuja et al., 2015). Nonetheless, at each phase of the design process, BIM-BEM can be executed to run the ES to achieve the design targets (Klitgaard et al., 2006). Multiple iterations toward an optimized design can be achieved in a shared environment by including a BIM-BEM procedure in the design process (Farzaneh et al., 2019). BIM-based BEM prevents arbitrary data improvisation and preserves the integrity of the original data and makes sure that the original data transformation is implemented under explicit rules embedded in the methodology (Bazjanac, 2009). Based on the results of a survey of building energy professionals in which BIM and energy analysis integration were incorporated for the construction of the world's first positive energy building, the following factors ranked highest in importance when choosing a method of building energy analysis; accuracy (88.9%), quality of the output (77.8%), ease of use and level of detail (61%), sensitivity during analysis (50%), speed and cost of learning and use (44.4%) (Samuel et al., 2017). However, these factors alone do not determine the success rate of a building energy analysis in several cases.

2.5 BIM-BEM interoperability

Interoperability facilitates the exchange of data among applications, as well as the interaction of multiple applications. As such, it helps to improve workflows and reduces the need to manually copy data from one application to another (Utkucu & Sözer, 2020). According to Kota et al. (2016), the definition of boundaries by the centerline of enclosing architectural elements provides either precision or ease of use, using walls as separation in zones defined by the thickness of walls, the use of centerlines produces less errors when compared to using the inside face and outside faces, the use of centerlines produces a watertight model without any gaps, name of elements should be preserved between the BIM and the BES input model, unique identifiers should be embedded into comments in the BES input model to allow association of the element back to the BIM, using Front, Back, Left and Right is preferred for orientation studies rather than North, East, West, and South. All these details must be included in BES input models and maintained appropriately. BIM enables the use of data available from the architectural model by sharing and exporting the information required to create a BEM, saving model re-creation time, and speeding up the project design while allowing for more design iterations (Krygiel & Nies, 2008). To mitigate the risks of model divergence, errors, and misunderstandings in BIM-BEM projects, the architectural BIM model is shared in the EDP of design to create the BEM and complete the ES (Klitgaard et al., 2006). Figure 3 illustrates the ideal workflow for energy performance simulation tools.

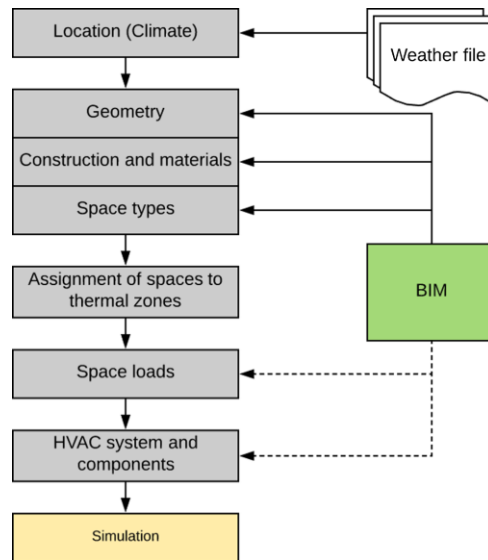


Figure 3: Ideal workflow for energy performance simulation tools using BIM adapted from Maile et al. (2007).

2.5.1 BIM-BEM integration approaches

BIM-BEM integration can be executed through different types of model methods. According to Negendahl (2015), there are three methods for model integration: combined, central, and distributed methods. The combined method requires a specific software package supporting both the design and the ES to be produced simultaneously (Farzaneh et al., 2019). Combined models are manipulated and simulated only by a hybrid practitioner. This facilitates monitoring the accuracy of the model for all design and ES phases (Farzaneh et al., 2019). In addition to modelling and simulation at runtime, the combined model offers consistency in the environment, which is attractive for users (Negendahl, 2015). This is the most used model integration approach for BIM projects (Babič et al., 2010). This method has the main disadvantage of restricting the user to the options and features offered by a given program or environment (Hensen, 2004).

The central model method is based on the BIM concept where it incorporates the design tool and translates the BIM data to the BPS. In the absence of operator-controlled calculation models, this unidirectional method provides little useful feedback to the building designer (Negendahl, 2015). Using this method, semantic information can be translated between BIM and BEM tools using a coupling medium or data scheme as the interoperability gateway (BuildingSMART, 2016).

In the distributed model integration method, one or more middleware elements convert the BIM model into a BEM tool (Negendahl, 2015).

Integrated dynamic models may combine a design tool, a visual programming language, and a BPS tool to give greater support for the designer during the EDP than alternatives such as the existing implementation of IFC or gbXML or the single usage of simulation packages (Negendahl, 2015).

2.5.2 Types of BIM files schemes

A data scheme describes the organization, structure, and relationship of data sets. It acts as an interoperability gateway between software so that specific portions of the platform's native data model are translated via its gateway. It puts the data (from BIM) into the format required by the receiver tools (BEM) (Cerovsek, 2011).

The most well-known and important forms of data schemes used for BEM are gbXML and Industry Foundation Classes (IFC). According to Bazjanac (2005), these data schemes' software compatibility is of three types: directly compatible, not compatible, and indirectly compatible.

IFC facilitates the interchange of building information between a set of tools by providing an extensible, intelligent, and comprehensive data representation of the building information. They are object-oriented and describe the behaviour, relationship, and inherence of the component object within a model (Plume & Mitchell, 2007). The IFC scheme is a neutral and open data exchange format for interoperability within the AEC industry (Liebich et al., 2006). The IFC scheme is generally regarded as the most common format for exchanging data

within the AEC industry (Eastman, 2008). Although it is a rich product model scheme, it lacks formal logic rigidity and is highly redundant (Belsky et al., 2013).

Green Building eXtensible Markup Language is one of the complete data schemes to transfer the required information for preliminary building energy analysis such as the envelope, thermal zone, and mechanical equipment (Lam et al., 2012). Its purpose is to assist BIM authoring tools and energy analysis tools in exchanging data. The gbXML format possesses specificity regarding energy simulation compared to the IFC, which aims to manage data exchange for entire building projects using a comprehensive and generic approach (Dong et al., 2007). Based on the research carried out by Gao et al. (2019), the gbXML format is supported by BEM tools, and most of the gbXML based methods can facilitate the geometry, material, and thermal zone transformation.

2.6 BIM-BEM challenges and issues

The main challenge is largely to abstract and simplify the BIM data so that it can be modelled in BPS tools. Accurate modelling of light-frame construction is not well represented for the framing elements. However, this impacts the framing on heat transfer significantly. BIM does not specify the design or designation of active or passive solar heating and cooling systems. However, the representation of HVAC systems and plant models can be greatly enhanced. According to van Leeuwen & Timmermans (2004), the combined methodology creates a limitation that is covered by other available simulation tools. It was suggested by Bazjanac (2001), that a BEM tool can import building geometry in 3D using IFC (two-dimensional format) into a central model. This format of IFC had interoperability issues in terms of building data transfer, especially for HVAC data. The constraint of this strategy are as follows: architects or engineers must identify thermal zones during the EDP. In general, employing the proposed data schemes for BIM-BEM applications is currently inconclusive and frequently necessitates manual verification for correctness. (Pinheiro et al., 2018). As a result of BEM not being sufficiently integrated and synchronized with the digital planning and design process, energy-efficient design strategies are not well implemented in the EDP. Furthermore, BEM does not yet benefit from continuous information flow in digital modelling. For instance, BEM-related information has to be manually re-entered into BPS tools, which is considered to be time-consuming, costly, and labour intensive, although this information is already available in digital design models (e.g., Building Information Model) (Gao et al., 2019). Negendahl (2015), identified one of the many symptoms of a disciplinary fragmented building industry as separated geometric and calculation models. However, the combined model method may be limited due to the limited number of BPS tools that can be integrated with it. Most of these problems can be associated with the lack of semantic uniformity in the way BIM tools map their internal objects to and from IFC entities and properties (Belsky et al., 2013).

Engineers who want to simulate the future behavior of building and system design alternatives frequently encounter the problem that some performance aspects or specific building and system components are only represented in one simulation environment, while other performance aspects or components are only available in other software (Hensen, 2004).

2.7 BPS tools evaluated.

Typically, BPS tools perform dynamic simulation over one-year using simulation engines based on mathematical models. During the analysis, three parameters will be considered: the building envelope, the equipment, and lighting, and the occupancy and control scenario. In addition, they analyze the annual energy demand and identify different energy efficiency options, indoor air quality, annual CO₂ emissions, and life cycle payback periods of energy saving measures.

In this study, an evaluation of the available BPS tools was performed. These tools were chosen based on the following criteria:

- i. Simulation engines and mathematical models,
- ii. Modelling and simulation time,
- iii. Adoption of these tools in the design stages,

- iv. An evaluation of the different model integration techniques.

2.7.1 Revit System Analysis

The System Analysis is a tool in Autodesk Revit used to create an annual energy simulation report for heating, cooling, airflow, and load calculations. Revit uses a workflow to run the energy analysis. Data from Revit is translated into EnergyPlus and a simulation is performed, and a report for design heating, cooling, and airflow is generated. The System Analysis is found in the Energy Optimization tab, which also includes options to set the location, create an analytical model, generate design options, and optimization through Insight, a web-based energy simulation tool.

Revit can be used in the BIM-BEM through a combined method supporting both the design and the energy simulation to be produced simultaneously. This approach makes use of Revit as the design and modelling tool and System Analysis as the BPS tool.

2.7.2 Climate Studio

ClimateStudio (CS) is a conceptual thermal simulation, advanced daylighting, and electric lighting software developed by Solemma. CS is a plugin for the Rhinoceros (Rhino) 3d modelling software developed and distributed by Robert McNeel & Associates (Solemma LLC, 2020). It uses the EnergyPlus simulation engine and includes a multizone thermal simulation capability. CS comprises a location panel, which uses Typical Meteorological Year (TMY) or EnergyPlus weather files (EPW), containing measured hourly data for a variety of climatic indicators required for environmental performance analysis to specify the site's geolocation and weather data, a thermal model panel. The thermal model is used to build up a multi-zone EnergyPlus model with the following geometric objects: zones, windows, adiabatic/ground surfaces, and shading for thermal analysis, a settings dialog to specify the start and end date of a simulation, heat balance settings, solar radiation algorithm settings, and other relevant environmental performance settings, and a vast material library that comprises of preset zone templates, occupational and operational schedules, opaque and glazing constructions. CS can also be run on Grasshopper, which is a visual programming language that runs in Rhino. CS has a component tab comprised of all parameters listed in the panels above. Although Grasshopper can be assessed in Revit through the Application programming interface (API) of Rhino, its use for environmental performance analysis is limited as of now and its capabilities are mainly for parametric design and optimizations.

CS can be used in the BIM-BEM through an integrated dynamic model approach. This approach makes use of Rhino as the design and modelling tool and CS as the BPS tool, hence the building after being modelled in the BIM software is remodelled in Rhino as closed "brep" to formulate the thermal zone. For ascertaining the cooling and heating loads and calculating the energy use of a building, the conduction heat transfer function (CTF) is utilized.

2.7.3 IDA ICE

IDA Indoor Climate and Energy (ICE) is a program for determining the indoor climate of individual zones in a building, as well as examining the building's energy use. IDA ICE uses weather files with consideration for the wind and temperatures. The weather files are either downloaded from the database or an EPW file can also be imported into IDA ICE. Additionally, the IDA ICE database includes preset building components, which can be imported into a project for an ES.

An environmental performance analysis is carried out in IDA ICE through two main templates, which are starting a building with a single zone and an Early-Stage Building Optimization (ESBO) (Equa AB, 2013). The ESBO user interface comprises minimal inputs required during the early phase of design to estimate the annual energy use and indoor thermal comfort. The ESBO comprises a room tab; this covers the geometry and construction properties, information on the internal gains, operational parameters such as the heating and cooling setpoints, heating, ventilation, and cooling system object and settings, an import option for several file formats including the Industry Foundation Classes (IFC) data format and a room summary table. The subsequent tab after the room tab is the building tab, which contains a location option. This includes the geographical location, which can be selected from the database if available or downloaded, and the orientation of the building,

infiltration, thermal bridges, ground properties, extra energy, and losses, building shading, distribution system, Domestic Hot Water (DHW) parameter, energy rates, and a schematic layout of the central HVAC system. Lastly, the simulation tab contains the simulation setup for heating and cooling design, annual energy use, overheating and daylight, and an option to export the results from the simulations.

IDA ICE can be used in the BIM-BEM through a central integration model approach. This approach makes use of data schemes such as IFC data files to translate the data such as the geometry properties of a building from the BIM software into IDA ICE.

IDA ICE uses several algorithmic models and are interconnected with input and output links. The algorithmic models used mostly for simulations include the Climate model, Energy model, and Envelope models.

3 Methodology

As discussed in the introduction, in the third section, all data needed for performing tests on the different BPS tools listed were collected. The BIM geometries were modelled, and data was collected for the test study and one main case study. The case studies included information about the building geometry, building orientation, and building construction materials and properties. The weather files were obtained from climate-onebuilding in EnergyPlus Weather Format (EPW). Malmö Sturup (latitude 55.6°N, longitude 13.0°E) weather file was for the first case study, and Lagos (latitude 6.5°N, longitude 3.4°E), Abuja (latitude 9.1°N, longitude 7.5°E), Jos (latitude 9.9°N, longitude 8.9°E), weather files were used for the other second case study. To better understand the weather data from the Malmö Sturup weather file, key climate indicators were compared such as the windspeed and dry-bulb temperatures.

Based on the building types and usage patterns, custom schedules were developed. Available information on the loads for detailed internal heat gain calculations and HVAC system specifications for heating and cooling energy use results were obtained from the design consultants and other parameters were assumed.

The BIM models for all two case studies were evaluated in the BIM authoring software. The BIM models were translated to a data scheme to be evaluated in IDA ICE and the exact models were remodelled separately in Rhino for translation into an energy model in CS. The overall methodology is explained in Figure 4 to show how this study was performed.

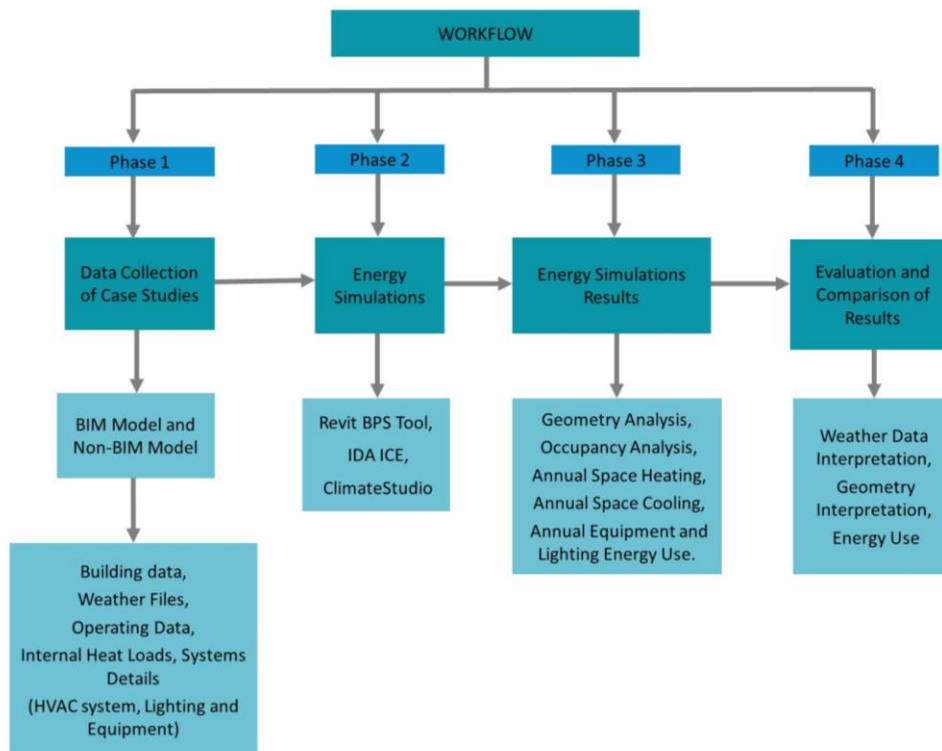


Figure 4: Workflow Methodology used in comparisons of BPS tools for the two case studies.

3.1 BPS Tools workflow

In the three case studies, three different workflows were employed. Three different model integration methods were used for all workflows.

3.1.1 Revit to BEM

For the first workflow, a BIM geometry is modelled in Autodesk Revit from the available building specific source data, operating data, and climatic condition information. The thermal properties for each building component (walls, floors, roofs, and windows) are entered in the materials type properties. An analytical space is assigned in the floor plan view accounting for the whole volume of each space. The assigned analytical space contains information about the space type properties for the energy analysis and HVAC system settings. To run an energy simulation, there are four modes that can be used in the energy analytical model; these are building elements, conceptual spaces, conceptual spaces, and building elements, rooms, or spaces. The building elements mode uses the thermal properties entered for each building component in the materials type properties. However, the detailed elements option is selected in the advanced energy settings tab. An in-place mass is modelled for the conceptual spaces mode to be activated. However, the energy simulation only uses the conceptual types material thermal properties in the advanced energy settings tab with predefined construction properties for each building model component. The Conceptual spaces and building elements use the conceptual types material thermal properties with predefined construction properties or the thermal properties entered for each building model component in the materials type properties. After the mode has been defined in the energy settings, an energy analytical model is generated, and the data is transferred to the EnergyPlus engine incorporated into Revit, then an energy simulation is generated through the systems analysis option. The energy model data is exported as a gbXML file to GBS to obtain the information on the weather data. Figure 5 shows the workflow.

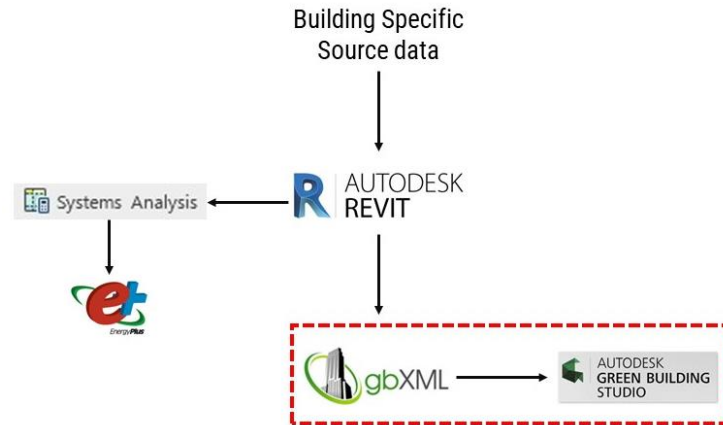


Figure 5: Workflow from Revit to BEM using System Analysis.

3.1.2 Revit to IDA ICE

In the second workflow, the building data is exported as an IFC file from Revit to IDA ICE. As shown in Figure 6, each studied case is exported as an IFC file with the building geometry exported in a 2D plan view into IDA ICE. The IFC building envelope data is mapped to the available building component construction in the IDA ICE database. The location and climate for each studied case are defined in the BPS tool as well as the Zone information, HVAC inputs (room units and air handling units), operating schedules, leaks inputs, information on the internal gains, building surface information (U-Values, g-values, solar transmittance, visible transmittance, frame area). Once all settings have been decided, the simulation is run to obtain the heating load, cooling load, overheating, and annual energy use. Figure 7 shows the workflow for exporting building data via a data scheme.



Figure 6: Workflow from Revit to IDA ICE using IFC.

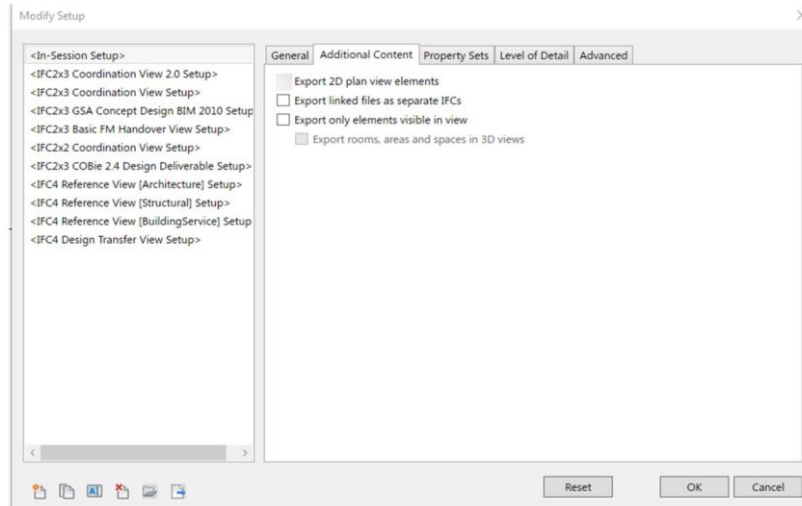


Figure 7: IFC setup for exporting building data to IDA ICE.

3.1.3 Rhino to CS

In the third workflow, the building data is used to remodel the building in Rhino and an energy model is created from CS. A Zone is created with building typologies available in the CS database, the relevant information obtained from the building data and operational data on the loads (people, equipment, and lighting) for the studied case is entered in the zone settings. The conditioning system for heating, cooling, and ventilation are also entered in the zone settings for each studied case. CS categorizes the faces of the energy model of each studied case into building components (roof, façade, partition, slab, external floor, ground slab, ground wall) depending on the complexity of the building. The building construction and infiltration value are entered in the envelope option in the zone settings for each studied case. Figure 8 shows the workflow. After all the input parameters have been set, an energy simulation is run to obtain the annual energy use, energy flows, and zone temperature curves.

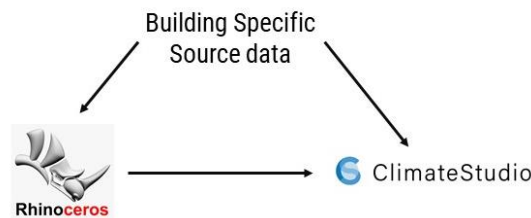


Figure 8: Workflow from Rhino to CS.

3.2 Case Study 1 - Test Building Methodology

To validate the three BPS tools, a basic test building was modelled using the BESTEST standard case 600 (Base Case Low Mass Building). This was based on the ANSI/ASHRAE norm standard 140–2001 “Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs” (ASHRAE, 2004). In evaluating similar input parameters in the three BPS tools, the windows were excluded for the first simulation. Figure 9 explains the workflow of the study for the first case study. For CS and IDA ICE, the same weather file was used for the simulations, the key climate indicators were then compared.

The location settings on Revit provide two options for defining the location to access the weather file, first by selecting the default city list as shown in Figure 10; this is a database of about 1500 cities in different countries in the world. However, this list is limited, secondly, the location can be defined using the Internet Mapping Service to select a weather station as shown in Figure 11.

For each step, an annual energy simulation was performed to examine and assess how each parameter affects simulation outcomes in all three BPS tools. In the first step, the heating setpoint for all evaluated BPS programs

was set to 21 °C, the heating supply air temperature was set to 31 °C on CS, both Revit and IDA ICE does not have this input parameter. The heating system was set to All-on for the annual building simulation in all three BPS tools. The cooling set point was set to 100 °C in Revit because it cannot be turned off. Also, on IDA ICE, the cooling set point was set to 100 °C. The max humidity control and min humidity control for all BPS tools were set to 70% and 40%, this was because this option could not be deactivated on Revit. After all, these settings were set and all other settings turned off or set to 0. In the second step, the settings activated in step one were all retained and two windows were introduced into the model for all BPS tools to assess the solar heat gain through the windowpanes. In step three, the cooling set point was activated and set to 26 °C in all programs and the cooling supply air temperature was set to 18 °C on CS. In step 4, the occupancy schedule was set to All-on for 24 hours and different energy simulations were run for 1, 2, 3, 4, and 5 people to evaluate how the BPS tools calculate the occupants’ internal heat gains. Increasing the number of occupants enabled the comparison of how each BPS tool calculates the internal loads to determine the differences in heating and cooling energy use. The metabolic rate of 1.2 Met was used in CS and Revit in the energy settings. In step five, the infiltration of 0.5ACH at 50 pa was used in all BPS tools. In step six, the mechanical ventilation is activated, the min fresh air per person and min fresh air per area is set to 7 L/s,p, and 0.35 L/s.m² in all three BPS tools. The mechanical ventilation schedule is set to All-on with no heat recovery type and efficiency. In step seven, the equipment power density was activated with a set value of 10 W / m² and a schedule set to All-on in all the three BPS tools. In step eight, the lighting power density was activated with a set value of 7 W/m² and a schedule set to All-on in all the three BPS tools.

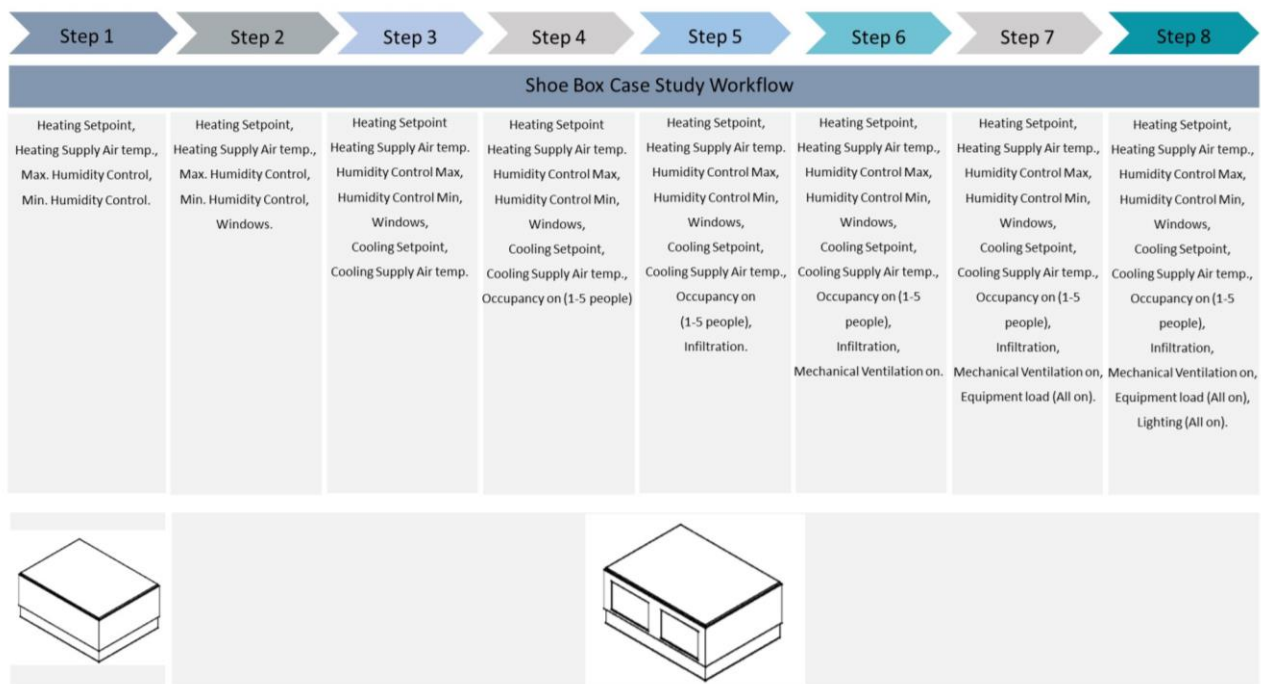


Figure 9: Workflow for the Shoebox building.

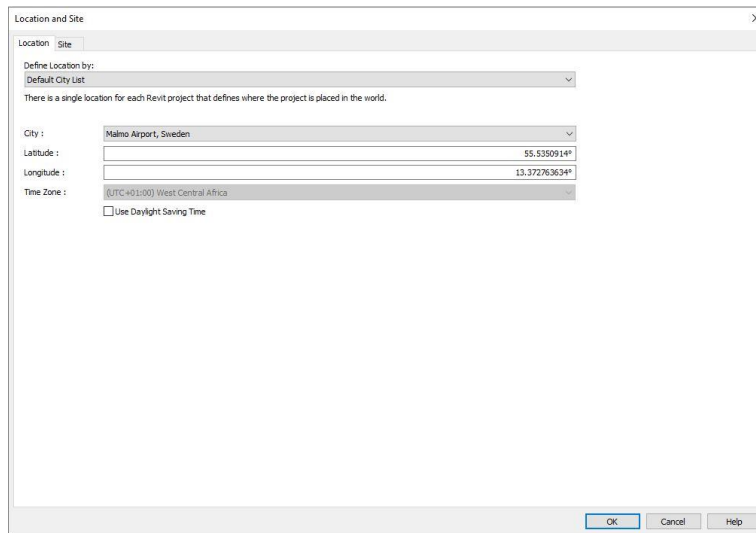


Figure 10: Selecting a weather file using the default city list.

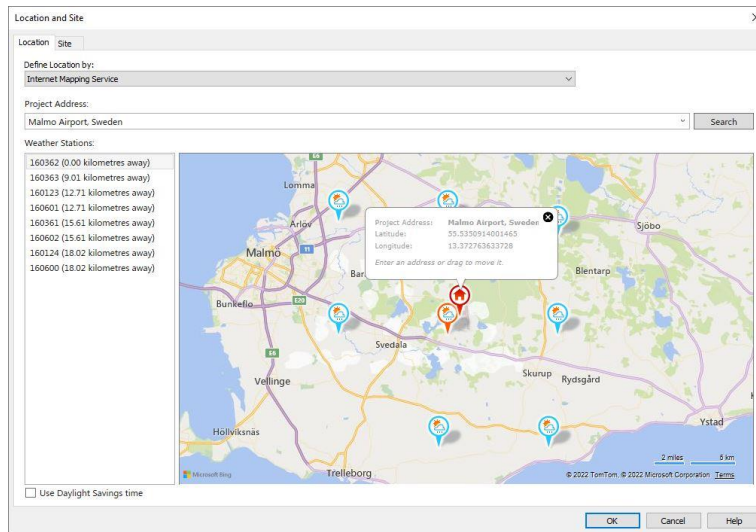


Figure 11: Selecting a weather file using the internet mapping service.

3.2.1 Test Building Geometry Details

The building is of lightweight construction with a rectangular single zone (8 m wide x 6 m long x 2.7 m high) with no interior partitions and 12 m² of windows on the south exposure. Figure 12 shows the Test Building Geometry without windows and with windows

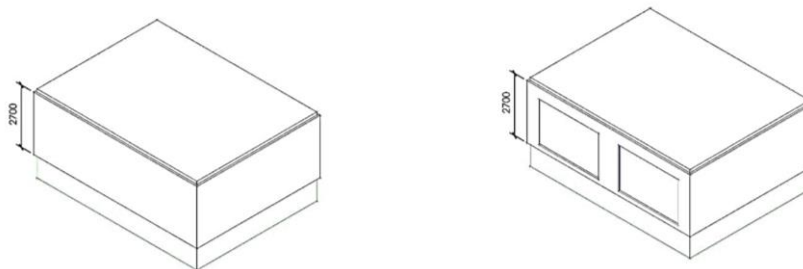


Figure 12: Test Building Geometry without windows and with windows.

3.2.2 Test building envelope details

The test building envelope used was selected according to the wall, roof, and floor construction from the standard case 600 (Base Case Low Mass Building). A double-pane clear window with a U-Value of 2.72 W/(m² K), visible transmittance of 0.812, and SHGC value of 0.764 was used in all three BPS tools.

The wall construction layers are shown in Figure 13 and Table 1 presents the properties of the wall construction layers.

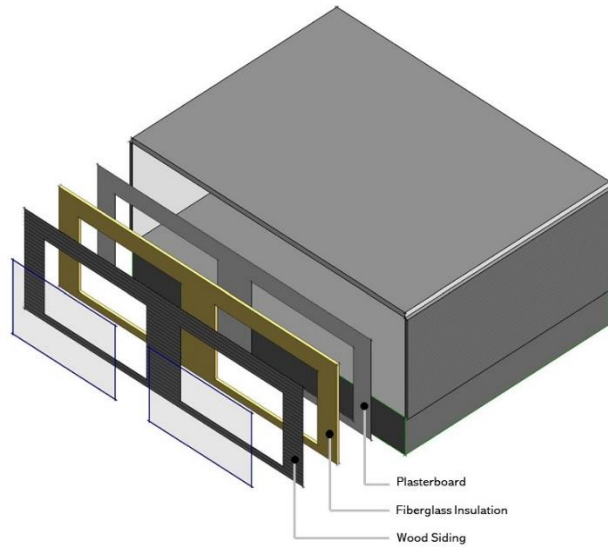


Figure 13: Wall construction layers for the Shoebox building.

Table 1: Shoebox building wall construction layer properties.

Wall Layers	Conductivity (W/m-K)	Thickness (m)	U (W/m ² .K)	R (m ² .K/W)	Density (kg/m ³)	Cp (J/kg.K)
Plasterboard	0.160	0.012	13.33	0.075	950	840
Fiberglass Quilt	0.040	0.066	0.606	1.650	12.0	840
Wood Siding	0.140	0.009	15.56	0.064	530	900

The roof construction layers are shown in Figure 14 and Table 2 shows the roof construction layers' properties.

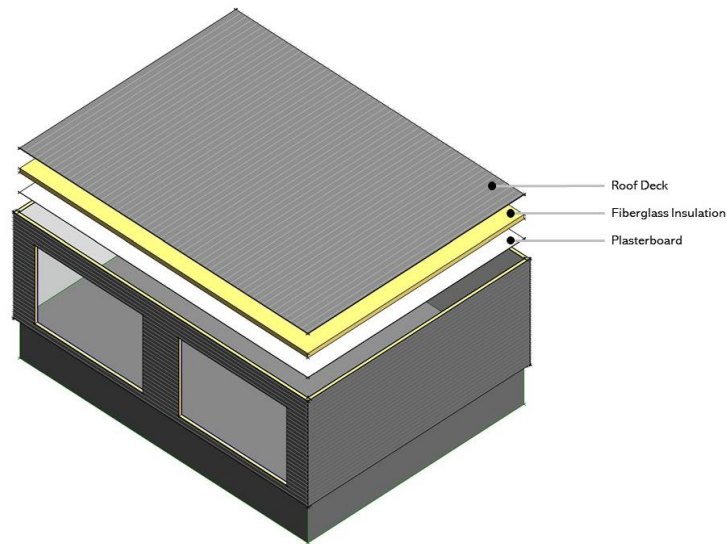


Figure 14: Roof construction layers for the Shoebox building.

Table 2: Shoebox building roof construction layer properties.

Roof Layers	Conductivity (W/m-K)	Thickness (m)	U (W/m ² -K)	R (m ² -K/W)	Density (kg/m ³)	Cp (J/kg-K)
Plasterboard	0.160	0.010	16.0	0.063	950	840
Fiberglass Quilt	0.040	0.112	0.36	2.794	12.0	840
Roof Deck	0.140	0.019	7.37	0.136	530	900

The floor construction layers are shown in Figure 15 and Table 3 shows the floor construction layers' properties.

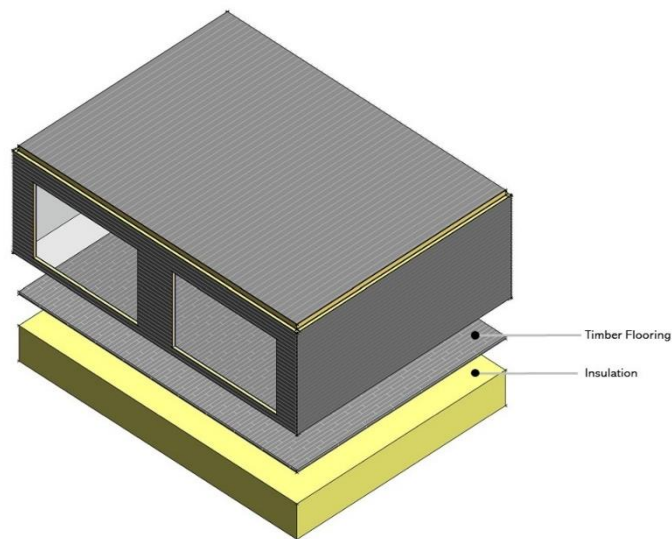


Figure 15: Floor construction layers for the Shoebox building.

Table 3: Shoebox building floor construction layer properties

Floor Layers	Conductivity (W/m-K)	Thickness (m)	U (W/m ² -K)	R (m ² -K/W)	Density (kg/m ³)	Cp (J/kg-K)
Timber Flooring	0.140	0.025	5.600	0.179	650	1200
Insulation	0.040	1.003	0.040	25.08	-	-

3.3 Case Study 2 – Q12

Q12 is a private residential development located at Cowrie creek estate, Lagos, Nigeria with a total gross floor area of 828 m², which has a dark geometric mass spanning three levels. The total building height from the ground level is about 12.1 meters and the residential development has glazing on the North, South, East, and West. The main entrance of the house is recessed inwards under a triple volume canopy, which frames a view of the interior. To the Eastern side, views of the master bedroom and study are shielded by an aluminum screen wall made of individual triangular panels in eight different modes, placed in square frames.

Q12 consists of several private, common, and ancillary spaces. The ground floor houses the ancillary spaces, the living and dining spaces. The First and Second floors comprised mostly of bedrooms, walk-in closets, and restrooms. The several spaces were divided into separate zones for detailed energy calculations. Figure 16 shows the private residential building.

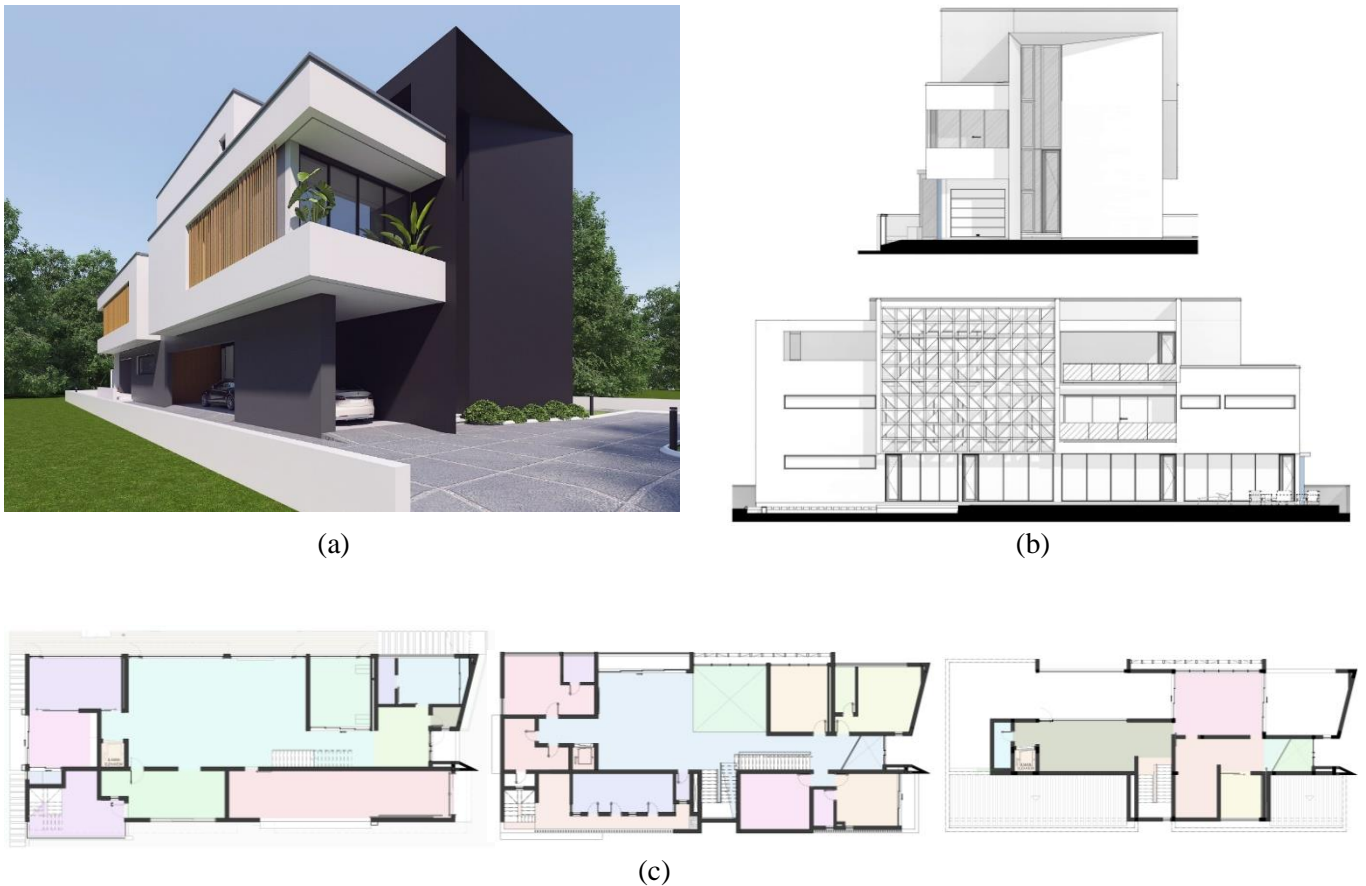


Figure 16: (a) View of the private residential building; (b) Elevations of the building; and (c) Ground Floor, First Floor and Pent Floor Plan zoning of the building.

3.3.1 Q12 Envelope Details

Table 4 provides detailed information on the materials used for the thermal envelope.

Table 4: Wall Types construction layer properties

Wall Construction 1		Wall Construction 2	
Thickness (mm)	Material type	Thickness (mm)	Material type
<i>Outside</i>			
15.0	Cement Plaster	15.0	Cement Plaster
230.0	Sandstone Block	150.0	Sandstone Block
15.0	Cement Plaster	15.0	Cement Plaster
<i>Inside</i>			

Table 5: Floor Types construction layer properties

Floor Construction 1		Floor Construction 2	
Thickness (mm)	Material type	Thickness (mm)	Material type
<i>Outside</i>			
700.0	Stone Aggregates	150.0	Structural Concrete
30.0	Concrete blinding	50.0	Cement screed
0.30	Damp Proof Membrane	30.0	Marble Flooring
175.0	Structural Concrete	<i>Inside</i>	
50.0	Cement sand screed		
10.0	Wood-like Tiles		
<i>Inside</i>			

Table 6: Roof Type 1 construction layer properties

Roof Construction 1	
Thickness (mm)	Material type
<i>Outside</i>	
5.0	Stone-coated aluminium roofing tiles
50.0	Hardwood Battens
150.0	Hardwood studs
12.0	Gypsum board
<i>Inside</i>	

Table 7: Roof Type 2 construction layer properties

Roof Construction 2	
Thickness (mm)	Material type
<i>Outside</i>	
50.0	Cement Screed with Waterproof additives
150.0	Sandstone Block
15.0	Cement Plaster
<i>Inside</i>	

Table 8: Window Type construction layer properties

Roof Construction 2	
Thickness (mm)	Material type
<i>Outside</i>	
50.0	Aluminium frames
6 + 6	Double glazed pane with argon gas
<i>Inside</i>	

3.3.2 Loads

Q12 as a residential building is mostly occupied and in use all weekdays except from 7:00 until 19:00 for some selected spaces. The ancillary spaces such as the staff bedrooms are mostly occupied during the day.

Table 9 presents the thermal properties of the building components, glazing details, infiltration details, internal heat loads, equipment, and lighting loads for each space.

Table 9: Thermal properties of the building components, glazing details, infiltration details, internal heat gains, equipment, and lighting loads.

Parameter	Value	Source/Comment
U-Values	W / m ² K	
Roof	0.77	BIM
Wall	Wall 1 - 2.1 Wall 2 - 3.1	BIM
Ground Floor Slab	Floor const. 1 - 1.5	BIM
Intermediate Floor Slab	Floor const. 2 - 3.5	BIM
Windows	1.0	BIM
Doors	2.4	BIM
Mechanical Ventilation		
Outdoor airflow per person	7.0 L / person	Custom
Outdoor airflow per area	0.35 L / m ²	Custom
Ventilation rate	0.35 L / sm ²	Custom
Infiltration		
ach	0.5	Custom
Technical Installations		
Cooling System	VRV System Solution	M&E consultant
Air Conditioning Efficiency		
EER	Ground Floor OU – 3.74 First Floor OU – 3.99 Pent Floor OU – 4.32	M&E consultant
Building Operation		
Setpoint Temperature	°C	
Cooling	25	Custom
Heating	20	Custom
User Behaviour		
Equipment	Varies per space	Custom
Lighting	Varies per space	Custom
Occupancy	Varies per space	Custom

4 Results

As stated in the methodology, this section discusses the weather data, geometry, their interpretation respectively and the results from the energy simulations in all three BPS tools studied.

4.1 Test building climate analysis

Before any simulation was performed, the weather data used in all three BPS tools were analysed and compared. The weather file comprises measured data for variables including dry bulb and wet bulb temperature, wind speed, and direction, solar radiation, relative humidity, solar altitude and azimuth, cloud cover, etc., for each hour of the year. To evaluate the energy simulation results of the test building, it is essential to select the right weather data as it is vital to use the proper location settings to reflect the local climate.

4.1.1 Dry-bulb temperatures

The comparison of the maximum, minimum and average dry-bulb hourly temperatures for all three BPS tools using the Malmö weather data file is presented in Figure 17. The maximum, minimum and average dry-bulb temperatures were similar for both CS and IDA ICE as the same weather data file in the EPW format was used in both BPS tools. The maximum dry-bulb temperature for the Revit BPS tool was lower compared with CS and IDA ICE. However, the average and minimum temperatures were higher than both CS and IDA ICE. The difference in the dry-bulb temperatures influences the energy simulations and the indoor thermal comfort of the building.

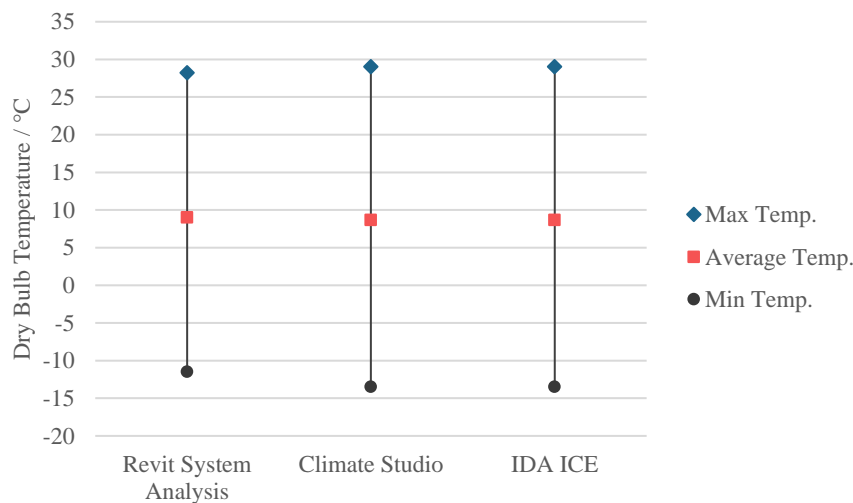


Figure 17: Maximum, minimum, and average dry-bulb temperature.

4.1.2 Ground Temperatures

The ground temperature for all three BPS tools was also assessed. Typically, the ground temperature is usually warmer than the air temperature, hence the ground radiates heat to space depending on the ground floor construction. The energy balance of the building is however impacted by the ground temperature all year round. Figure 18 shows the difference in the ground temperature for all three BPS tools.

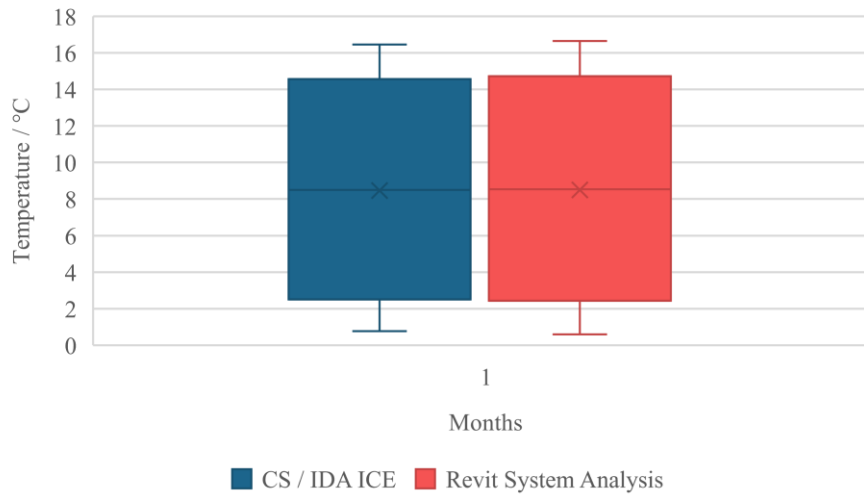


Figure 18: Ground Temperatures.

4.1.3 Wind Speed

Wind-driven infiltration causes pressure differences in a building. The wind rose diagrams provide a concise graphical representation of wind speed and direction for a particular location and time. This information is vital for utilizing passive ventilation strategies such as wind-driven ventilation, night-cooling, and the introduction of courtyards, etc. The maximum, minimum, and average wind speed were calculated manually by converting the weather data files to CSV files. Figure 19 shows the comparison of the windspeed variables. The maximum and average wind speed of the Revit BPS tool is shown to be lower than CS and IDA ICE. All BPS tools have a similar value of 0 m/s for the minimum wind speed. The maximum wind speed of the Revit BPS tool affects the energy balance of the evaluated building.

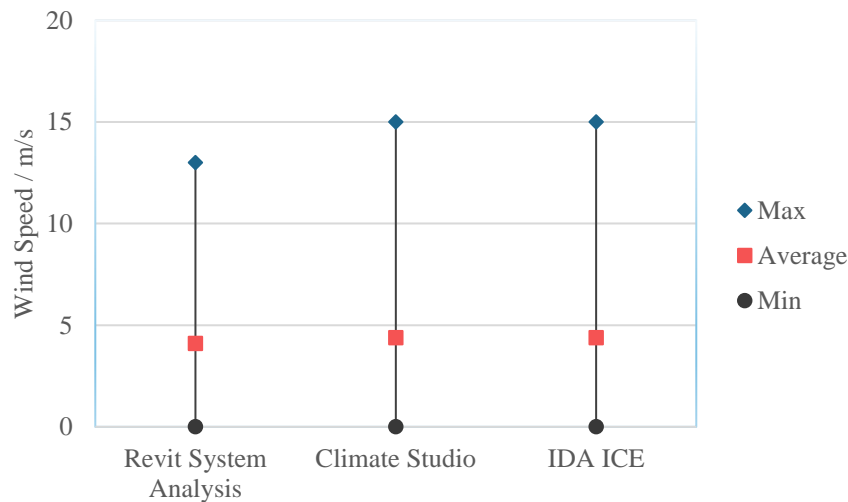


Figure 19: Maximum, minimum, and average wind speed.

4.1.4 Relative Humidity

The relative humidity (RH) for all BPS tools was also studied since this is one of the key indices for indoor thermal comfort. The relative humidity changes simultaneously with the air temperature, hence both thermal comfort indicators are interconnected and are essential to assess the accuracy of weather data files before performing energy simulations. Figure 20 presents the maximum, minimum, and average relative humidity values for all BPS tools. The maximum RH value for all three BPS tools was all the same at 100%, while the

average RH values varied slightly by 3% between Revit, CS, and IDA ICE. The minimum RH value between Revit and the other two BPS tools varied by a significant amount.

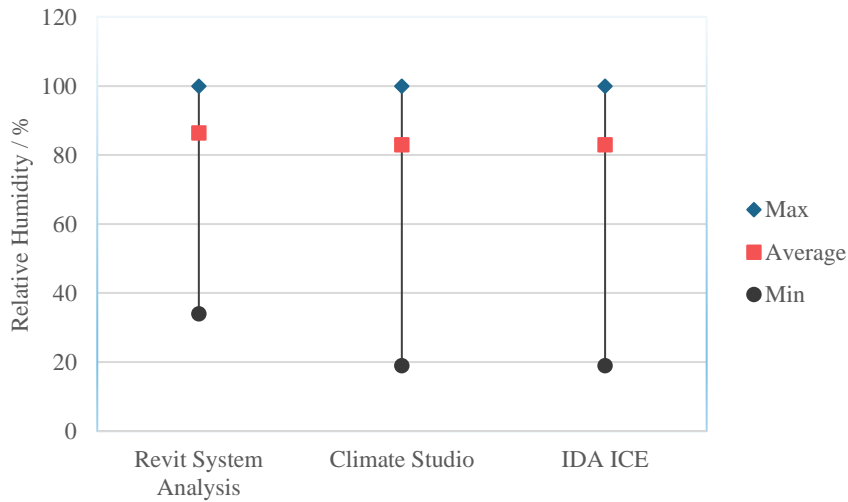


Figure 20: Maximum, minimum, and average relative humidity.

4.1.5 Solar Radiation

To determine the solar radiation received on the surfaces perpendicular to the sun, most especially the glazed surfaces, the weather data file for all three BPS tools was looked at closely. In determining the amount of heat gains through opaque and transparent surfaces, the direct normal radiation for each hour was compared. The direct normal radiation was higher for the Revit BPS tool compared with CS and IDA ICE. Figure 21 illustrates the solar radiation heatmap for the weather files in all three BPS tools.

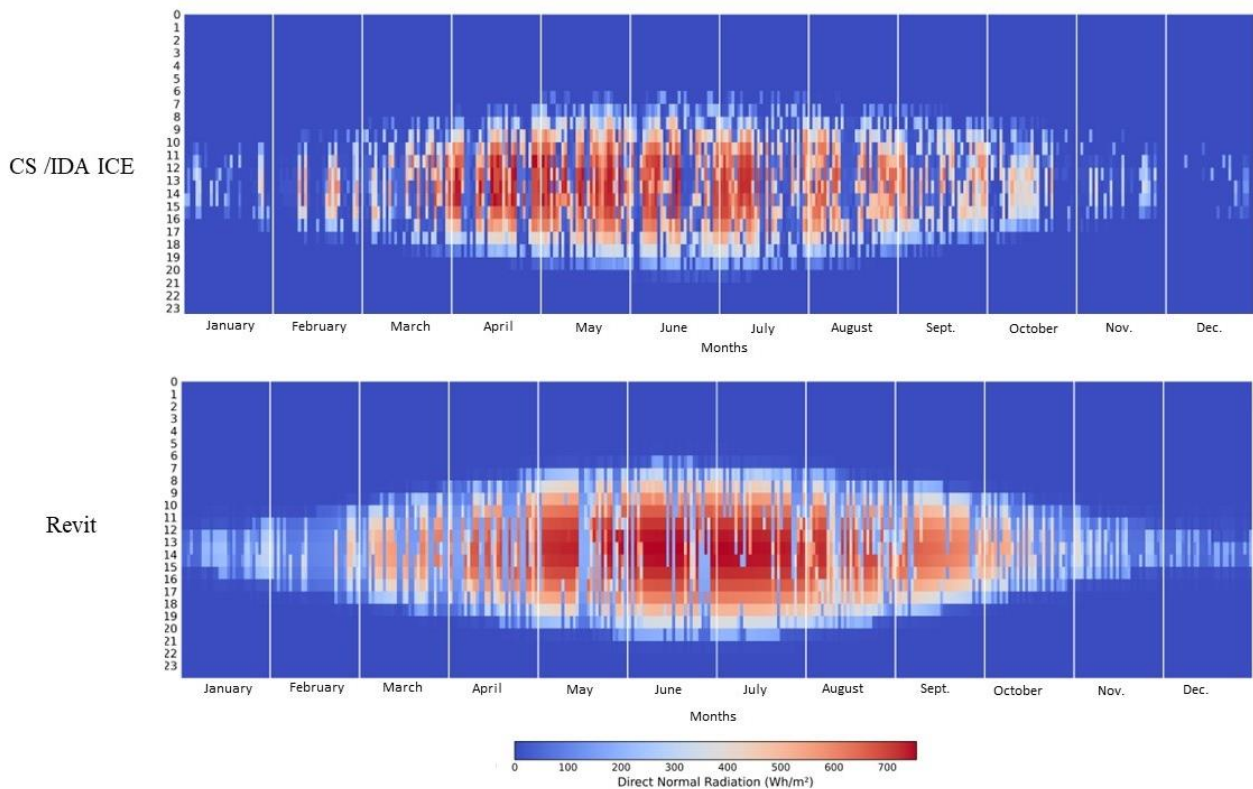
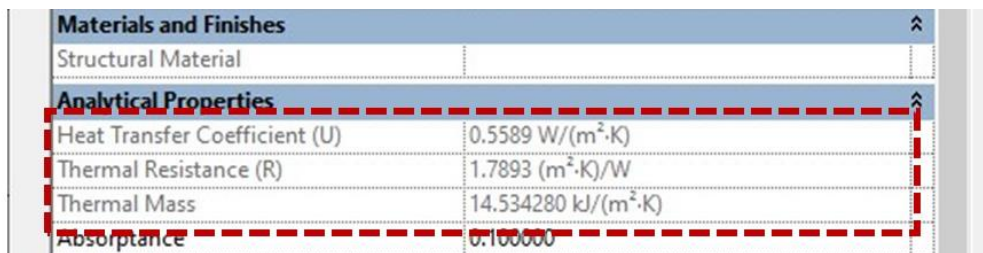


Figure 21: Direct normal radiation for Revit BPS tool, CS, and IDA ICE.

4.2 Test Building Geometry Analysis

The interpretation of the geometry by BPS tools is very important in the energy simulation results. It is however difficult to make a direct comparison between the geometry modelled in a BIM environment and a non-BIM environment. Replicating the model from a BIM environment in a non-BIM environment is very tasking and time-consuming, especially during all the stages of the design process as correcting the changes may require extra time and human resources. However, the possibility of running these energy simulations in a BIM environment proves to be advantageous in the long run.

The test building source data was used in modelling and setting the thermal properties of the construction layers of the building components, Revit calculates the U-values of all building components according to the thermal properties of each layer. The function of all building components is also specified to enable the simulation engine to use the correct details when performing the energy calculations. All information regarding the behavior of each assembly layer, the thermal conductivity, specific heat capacity and density, etc. are entered in the material browser. Figure 22 shows the calculated heat transfer coefficient value for the wall construction.



Materials and Finishes	
Structural Material	
Analytical Properties	
Heat Transfer Coefficient (U)	0.5589 W/(m ² ·K)
Thermal Resistance (R)	1.7893 (m ² ·K)/W
Thermal Mass	14.534280 kJ/(m ² ·K)
Absorptance	0.100000

Figure 22: Calculated heat transfer coefficient value for the wall construction on the Revit BPS tool.

Unlike IDA ICE, Revit does not consider thermal bridges in the building components thereby ignoring the heat transmission through the framing members. It was observed that the thickness of insulation in the floor for the building could not exceed 0.942 m before the simulation results could be generated, hence the thickness of the floor finish was increased to get the total U-Value of the floor construction.

The model with its source data is translated into IDA ICE through the IFC data scheme using the IFC 2x3 coordination view version. However, due to the interoperability issues, mapping the thermal properties of the building components was not completely viable. However, the space zone is mapped with the space type parameter inputs from Revit. Additionally, the translated data from Revit also includes the orientation of the building and the accurate height, width, and length of the building components. The glazing thermal properties were entered manually in IDA ICE.

CS generates the thermal model using the information from the modelled geometry in Rhino. The model surfaces in Rhino are automatically mapped as a facade, external floor, and roof. Figure 23 presents the modelled geometry and its translation to a BEM model. The envelope constructions are created manually according to the different layers and thermal properties by selecting the closest materials in the material database with the exact thermal properties. Although there is a vast number of materials in the CS database, getting the exact thermal properties for specific construction layers proved challenging.

Table 10 shows the information of the estimated geometry details and heat transfer coefficient values for all three BPS tools.

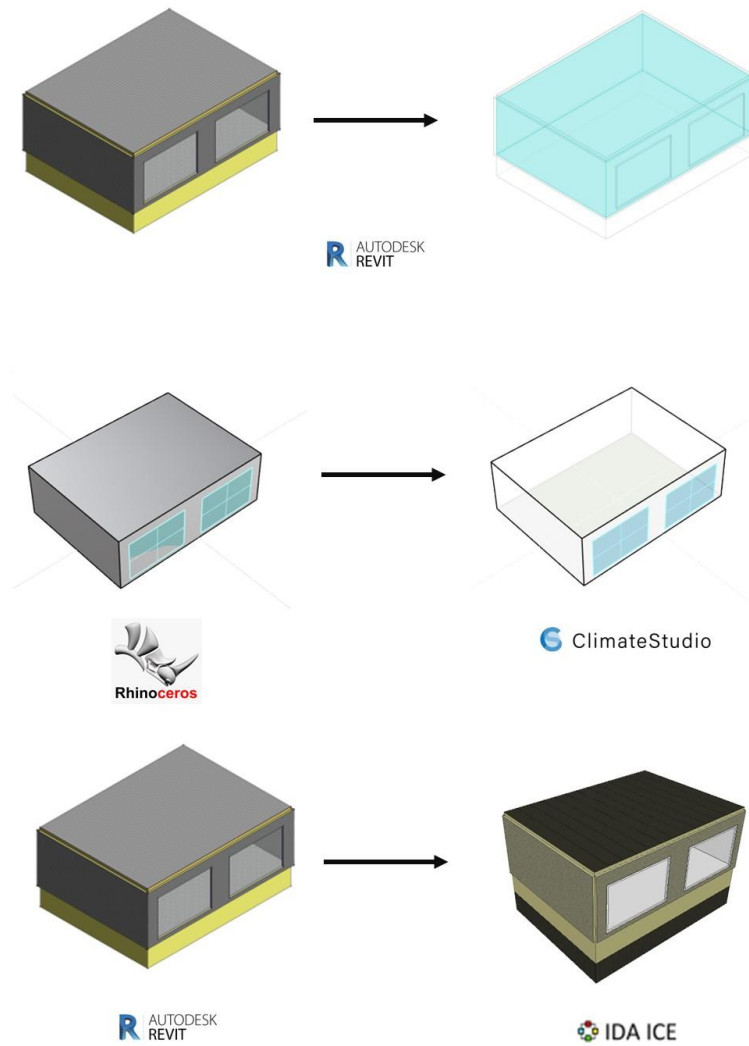


Figure 23: The modelled geometry and its translation to a BEM model for all three BPS tools.

Table 10: The estimated geometry details and heat transfer coefficient values for all three BPS tools.

Parameters	Values		
	Revit	CS	IDA ICE
Building Envelope			
Gross Opaque Envelope Area (m ²)	174.98	171.6	171.6
Internal Façade Area (m ²)	63.6	63.6	63.6
Roof Area (m ²)	48	48	48
Floor Area (m ²)	48	48	48
Glazing Area (m ²)	12	12	12
Internal Volume (m ³)	129.6	129.6	129.6
Envelope Thermal details			
Facade U-Value (W/m ² K) with film***	0.516	0.506	0.5104
Roof U-Value (W/m ² K)	0.319	0.313	0.3161
Floor U-Value (W/m ² K)	0.041	0.041	0.039

4.3 Test Building Energy Analysis

4.3.1 Heating Setpoint – 21 °C

Figure 24 presents the monthly energy use for all three BPS programs with only the heating conditioning system turned on, and no windows in the building geometry as described in Figure 9. The Revit BPS tool had the lowest heating energy demand for the winter months (January, February, March, November, and December) and slightly lower heating energy demand in the spring months. The Revit BPS tool and CS also had a significant amount of difference in the heating demand for the summer months except for July where the difference was 5 kWh. The maximum difference in heating demand between the Revit BPS tool and CS was about 25%, which was the month of June while the minimum difference was 2.5% in April. The maximum difference in heating demand between the Revit BPS tool and IDA ICE was about 45%, which was the month of July while the minimum difference was 6% in January. Figure 44 presents the annual heating energy demand for all three BPS programs with a difference of 8% and 15% between the Revit BPS tool, CS, and IDA ICE respectively. For IDA ICE, this difference is because the output link provides data to the building opaque surfaces based on the input from the climate file (EPW), it also uses the TQFACE model to compute the heat balance for an exterior wall surface.

Another reason is because of the zone heating units and their control model; a PI-controller is selected for the ideal room heater, which takes an input variable from the setpoint of the controller. However, the difference between the Revit BPS tool and CS is majorly because of the climate data since they both use the same algorithm. The key difference between all BPS tools is the way of computing surface heat fluxes through the opaque walls. IDA ICE uses an RCWALL model while both the Revit BPS tool and CS uses the state space method in their CTF calculations. According to a calibrated simulation study by Judkoff et al. (2011), a maximum difference of 17% was acceptable for simulation tests. Based on this evidence, the observed differences between all three BPS tools are acceptable.

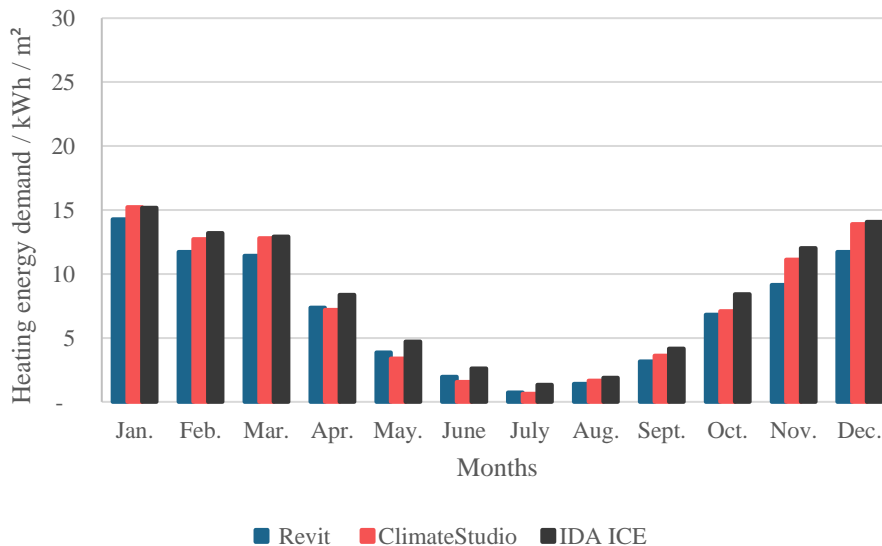


Figure 24: Monthly energy use for all three BPS programs with only the heating conditioning system turned on

4.3.2 Windows

Figure 25 presents the monthly energy use for all three BPS programs with the heating conditioning system turned on and 2 windows added to the south facade of the geometry.

IDA ICE had the lowest heating demand in January while the Revit BPS tool had the lowest heating demand for subsequent winter months (February, March, November, and December,). The Revit BPS tool and CS had a considerable difference in the heating demand for the spring and summer months. The maximum difference in heating demand between the Revit BPS tool and CS was about 30%, which was the month of November

while the minimum difference was 0% in June, July, and August. There was a high difference in heating demand between the Revit BPS tool and IDA ICE for all months except February and December. Figure 44 presents the annual heating energy for all three BPS programs with a difference of 17% and 22% between the Revit BPS tool, CS, and IDA ICE respectively. In IDA ICE, a window model calculates the radiation and transmission through a window, it considers the convective heat transfer, long-wave radiation from the ground and sky, absorption of shortwave radiation, and transmission from the internal surface for both glass and frames. The thermal performance of the windows is calculated on CS using the ISO Standard 15099-2003, which uses equations for calculating the room-side of windows' heat flow direction. Although the Revit BPS tool also uses the ISO Standard 15099-2003 equation model, the 17% difference is a result of the previous simulation, the solar radiation in the climatic file, and how EnergyPlus interprets the simple model with windows from Revit. The difference between Revit and CS is acceptable while that between Revit and IDA ICE is 5% above the maximum acceptable difference of 17%.

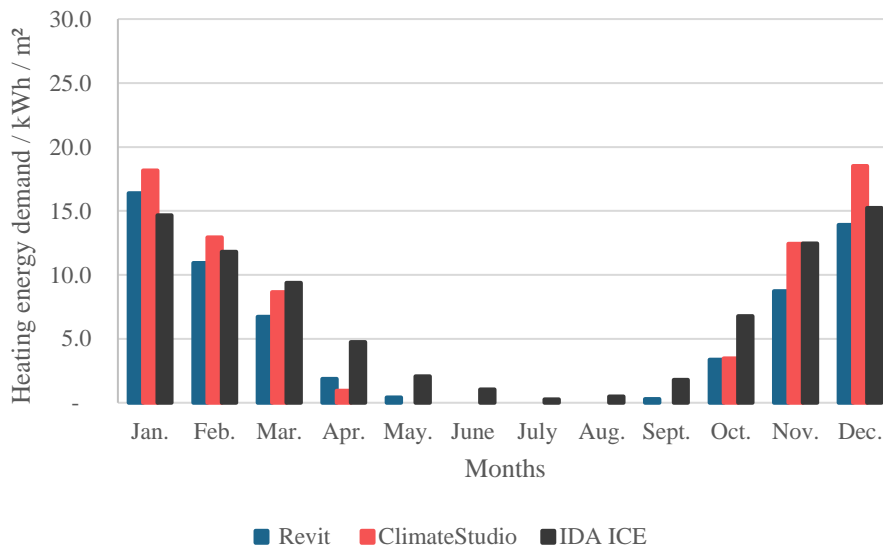


Figure 25: Monthly heating energy demand for all three BPS programs with the heating conditioning system turned on and 2 windows added to the south facade of the geometry.

4.3.3 Cooling Setpoint – 26 °C

Figure 26 presents the monthly heating and cooling energy use respectively for all three BPS programs with the cooling system turned on.

IDA ICE had the lowest heating demand in January while the Revit BPS tool had the lowest heating demand for subsequent winter months (February, March, November, and December). IDA ICE had the highest heating demand from March to November with CS having the highest demand in January, February, and December. The Revit BPS tool and CS had similar heating demands in the summer months. Figure 45 presents the annual heating energy demand for all three BPS programs with a difference of 15% and 28% between the Revit BPS tool, CS, and IDA ICE respectively. Revit and CS offered an acceptable difference, whereas Revit and IDA ICE were 11 % above the maximum acceptable difference of 17%.

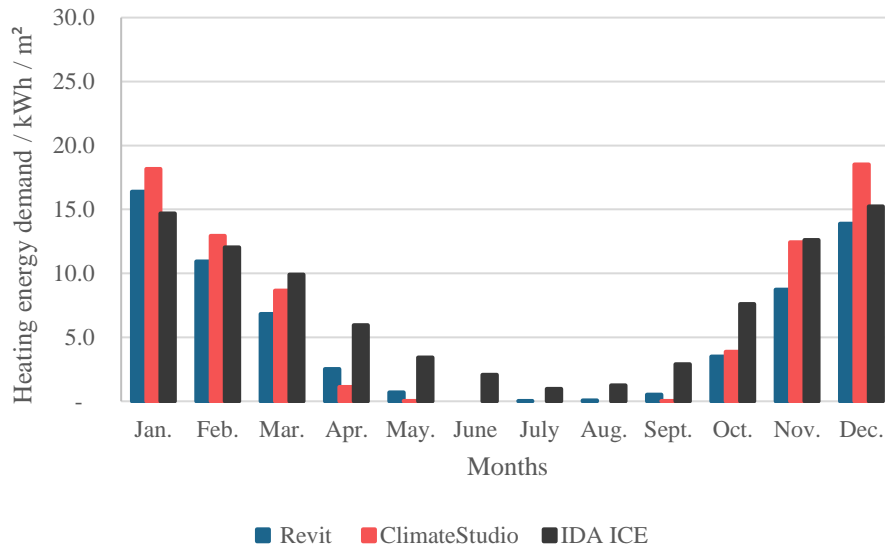


Figure 26: Monthly heating energy demand for all three BPS programs with the cooling conditioning system turned on.

Figure 27 presents the monthly cooling energy use for all three BPS tools studied. IDA ICE trend showed an increased need for cooling in all months except December. CS produced the highest monthly cooling energy use of all three BPS tools. Figure 45 shows the difference in the annual cooling energy demand for all three BPS tools, with a difference of 3% and 30% between the Revit BPS tool, CS, and IDA ICE respectively. The difference between Revit and CS is acceptable while that between Revit and IDA ICE was 13% above the maximum acceptable difference of 17%.

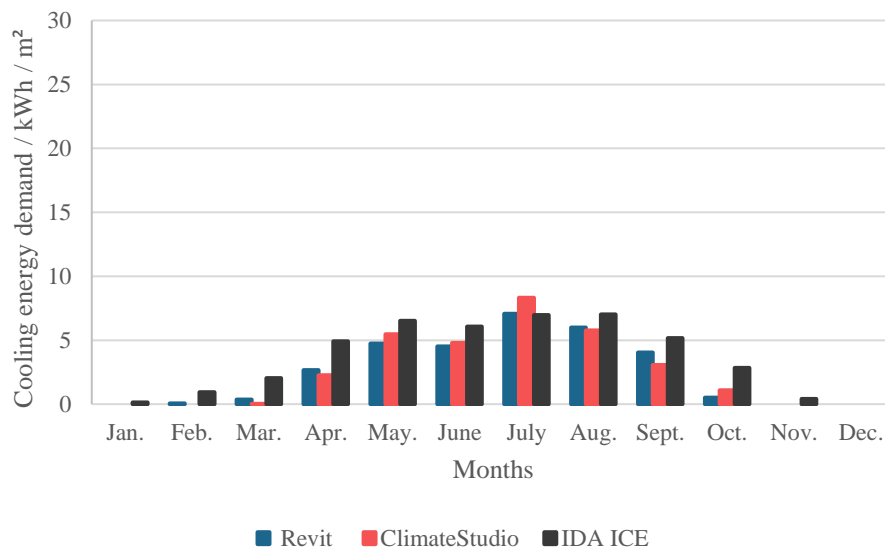


Figure 27: Monthly cooling energy demand for all three BPS programs with the cooling conditioning system turned on.

4.3.4 Occupancy

Figure 28 presents the monthly heating energy use for all three BPS tools with a one person occupancy and 8760 operational hours. IDA ICE generated the lowest heating energy use in January and December.

Figure 44 presents the annual heating energy demand for all three BPS tools with a difference of 18% and 3% between Revit BPS tool, CS, and IDA ICE respectively. The difference between CS and Revit BPS tool could be due to the heat load calculations and how Revit interprets the total metabolic heat gain. IDA ICE uses the ISO 7730 1984, which uses the equations of the convective heat load from the occupant, convective heat transfer coefficient between clothing and air, and radiative heat load from the occupant for its occupancy calculations. The difference between Revit and CS is 1% above the acceptable maximum of 17% while that between Revit and IDA ICE is within the acceptable range.

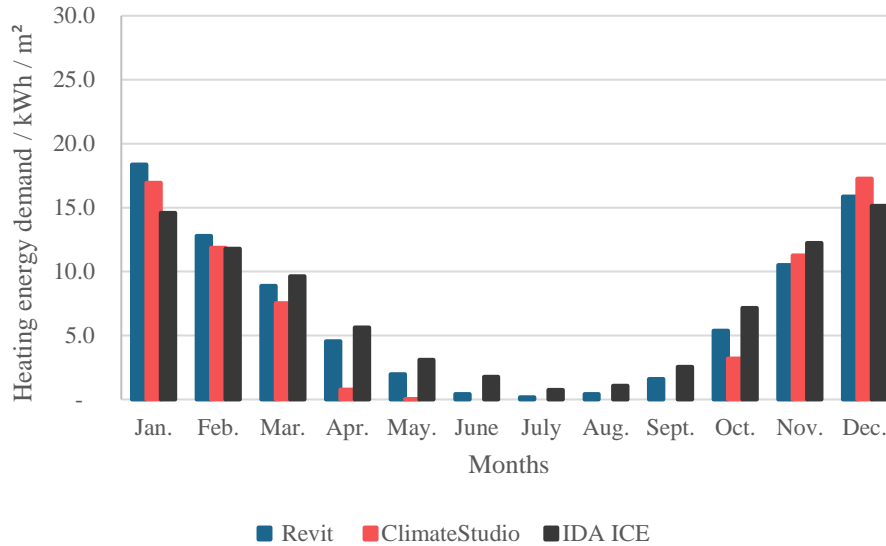


Figure 28: Monthly heating energy demand for all three BPS tools when 1 occupant was added to the building.

Figure 29 presents the monthly cooling energy use for all three BPS tools studied. CS produced the highest monthly cooling energy use in July slightly above the Revit BPS tool. Figure 45 shows the difference in the annual cooling energy for all three BPS tools, with a difference of 7% and 2% between the Revit BPS tool, CS, and IDA ICE respectively. The difference between the BPS tools was lower than the acceptable difference value of 17%.

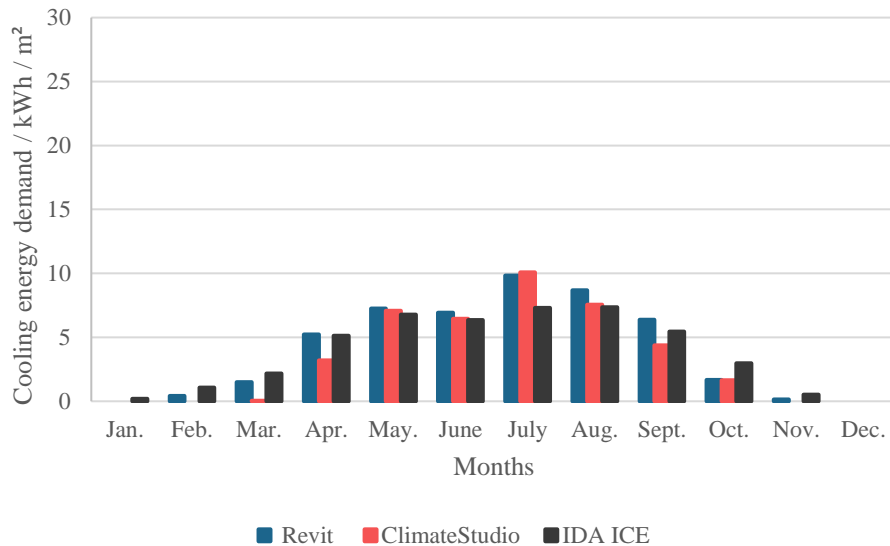


Figure 29: Monthly cooling energy demand for all three BPS tools when 1 occupant was added to the building.

Two people

Comparative analyses of the occupancy were performed with two individuals in the building for 24 hours each day throughout the year. IDA ICE produced the lowest amount of heating energy in January as shown in Figure 30. The lowest heating energy demand was recorded during February, March, April, May, September, and October for CS. As compared with the CS and IDA ICE, Revit BPS generated the highest heating demand in January and similar heating energy demand in the summer months.

With CS, there was no heating energy demand in summer, yet the energy use was the lowest. The summer months, especially June, saw some slight heating energy demand from IDA ICE. According to Figure 44, the annual heating energy use varied by 5% between the Revit BPS tool and IDA ICE, while that of CS and Revit BPS tool was about 18%. These differences can be attributed to the occupancy calculation methods of calculating the internal heat gains for occupants and their relation to the yearly schedule. CS uses the number of people calculation method of People per zone floor area (p / m^2). An internal algorithm is used to specify the fraction of latent heat gain and sensible heat gain while on Revit both heat gains are specified for the number of occupants. Revit uses the Zone floor area per People (m^2 / p) method. The difference between Revit and CS is acceptable while that between Revit and IDA ICE is 1% above the acceptable difference value of 17%.

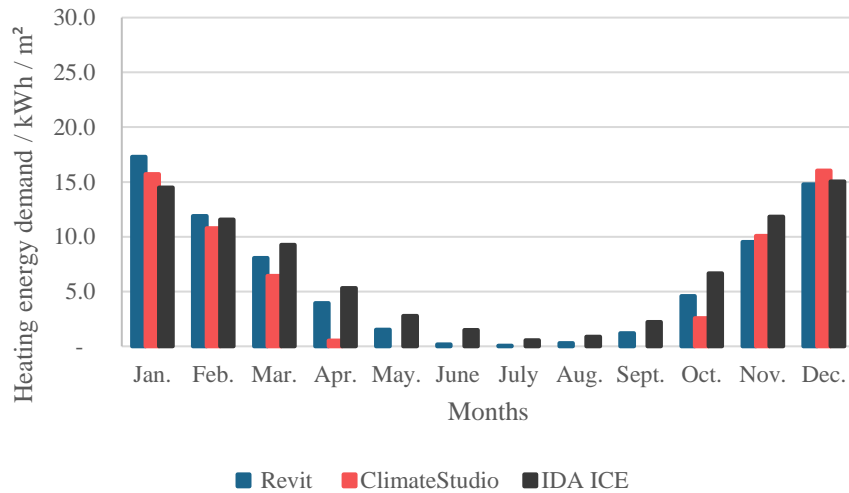


Figure 30: Monthly heating energy demand for all three BPS tools when 2 occupants were added to the building

Figure 31 presents the monthly cooling energy use for all three BPS tools studied. A notable difference between the cooling energy demand for a single occupant and two occupants was an increased demand in January. CS produced the highest monthly cooling energy demand in May, June, July, October, November, and December. IDA ICE had the lowest cooling demands in May and the summer months. Figure 45 shows the difference in the annual cooling energy demand for all three BPS tools, with a difference of 12% between the Revit BPS tool and CS. IDA ICE and Revit BPS had a difference of 1% in cooling energy demand. The difference between the BPS tools was lower than the acceptable difference value of 17%.

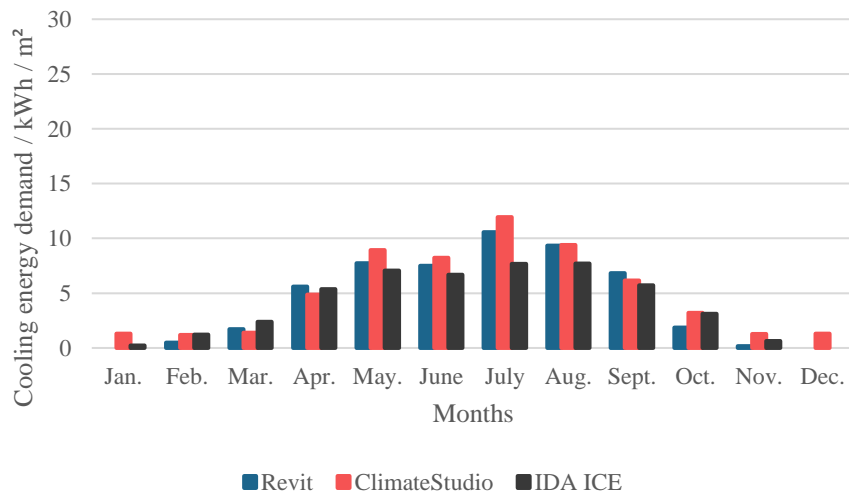


Figure 31: Monthly cooling energy demand for all three BPS tools when 2 occupants were added to the building

Three People

A further study was performed on the impact of the number of occupants in the building year-round, considering three people in the building. CS had the lowest heating energy demand for all months except in January and November. IDA ICE had the highest heating energy demand for the winter months except in January and December. According to the results as presented in Figure 32, the CS had no heating in May, the summer months and September. As illustrated in Figure 44, the annual heating energy demand of the Revit BPS tool and IDA ICE varied by 7%, compared to 19% for CS and Revit BPS tool when occupancy was increased to three people. The difference between Revit and CS was lower than the acceptable difference value of 17% while that between Revit and IDA ICE was above the acceptable maximum by 2%.

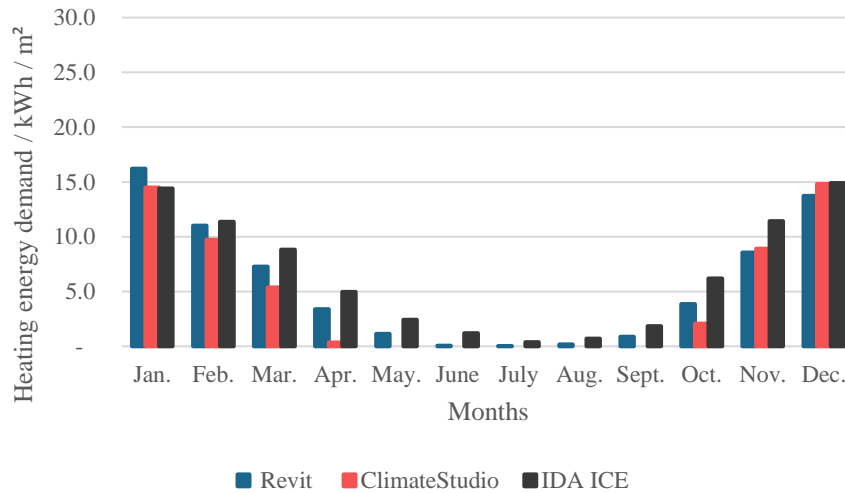


Figure 32: Monthly heating energy demand for all three BPS tools when 3 occupants were added to the building.

All three BPS tools examined are shown in Figure 33 with monthly cooling energy use. CS had the highest cooling energy demand for all months except for March when IDA ICE had the highest. IDA ICE had the lowest cooling energy demand in the spring and summer months and the Revit BPS tool had the least in the winter months. Figure 45 shows the difference in the annual cooling energy demand for all three BPS tools, with a difference of 24% between the Revit BPS tool and CS. IDA ICE and Revit had a difference of 2% for the annual cooling energy demand. The difference between Revit and CS is above the acceptable maximum by 7% while that between Revit and IDA ICE was within the acceptable range.

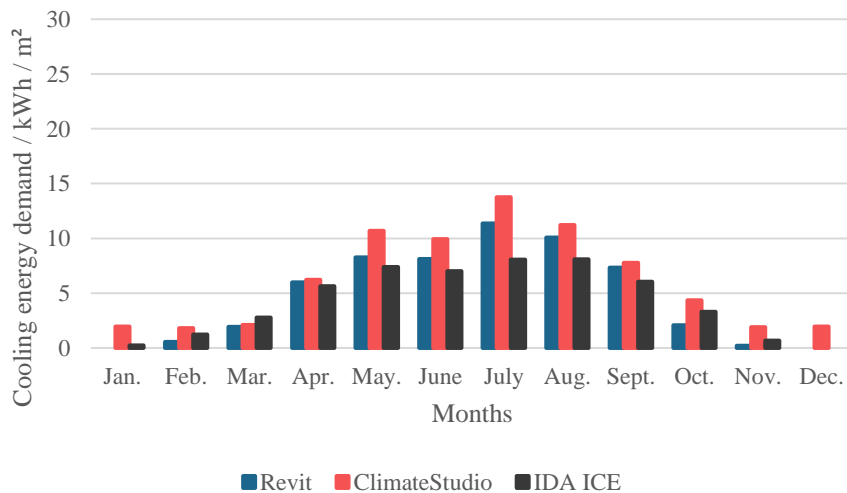


Figure 33: Monthly cooling energy demand for all three BPS tools when 3 occupants were added to the building.

Four People

Further evaluation was performed regarding the effect of occupancy year-round, considering four occupants at the same time. CS had the lowest heating energy demand for all months except December. All months except January when the Revit BPS tool had the highest demand for heating energy, IDA ICE had the highest demand for heating energy. Figure 34 shows how the Revit BPS tool had similar heating demands as CS for the summer months, as seen in the previous results. As illustrated in Figure 44, the annual energy use of the Revit BPS tool and IDA ICE varied by 9%, compared to 20% for CS and Revit BPS tool when occupancy was increased to three people. The difference between Revit and CS was above the acceptable difference value of 17% by 3% while that between Revit and IDA ICE was within the acceptable range.

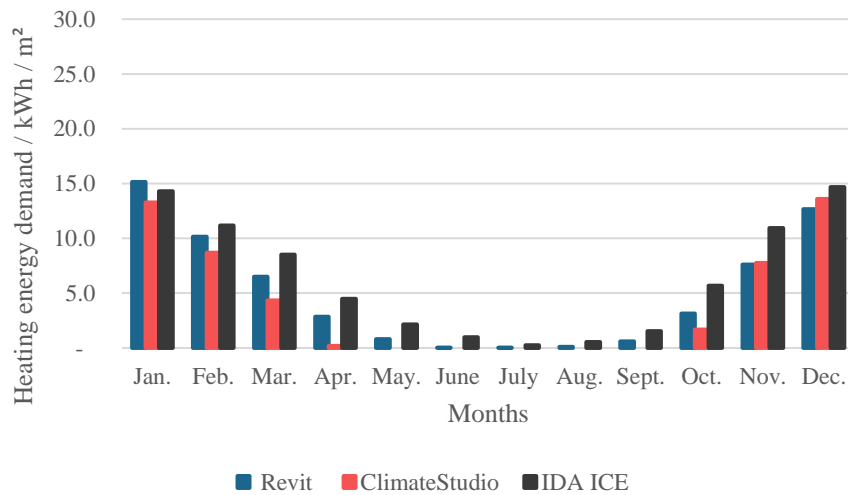


Figure 34: Monthly heating energy demand for all three BPS tools when 4 occupants were added to the building

The cooling energy demand for CS was the highest for all months except in March, where the demand was the highest for IDA ICE as shown in Figure 35. IDA ICE had the lowest cooling demands in only the summer months and the Revit BPS tool had the lowest in the winter months. Figure 45 shows the difference in the annual cooling energy demand for all three BPS tools, with a difference of 24% between the Revit BPS tool and CS. IDA ICE and Revit BPS had a difference of 2% for the annual cooling energy demand. The difference between Revit and CS was above the acceptable maximum by 7% while that between Revit and IDA ICE was lower than the acceptable value.

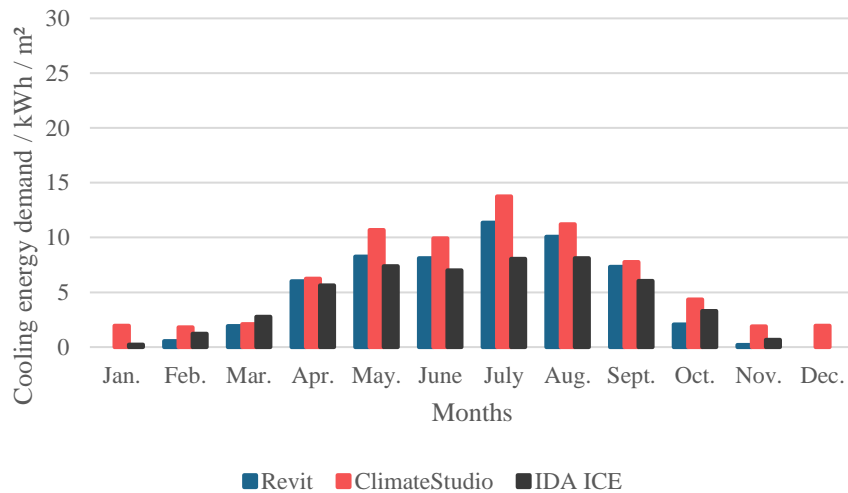


Figure 35: Monthly cooling energy demand for all three BPS tools when 4 occupants were added to the building.

Five People

An additional occupant was included in the building to further validate how the programs calculate internal gains. Figure 36 shows CS had the lowest heating energy demand for all months except November and December. All months except January when Revit BPS tool and IDA ICE had the same demand for heating energy, IDA ICE had the highest demand for heating energy for all other months. As illustrated in Figure 44, the annual heating energy demand of the Revit BPS tool and IDA ICE varied by 10%, compared to 22% for CS

and Revit BPS tool when occupancy was increased to three people. In the case of Revit and CS, the difference was over the acceptable maximum by 5%, while that in Revit and IDA ICE was lower than the acceptable value. Increasing the occupancy from one to five presented a linear progression for both heating and cooling demand as presented in Figure 44 and Figure 45

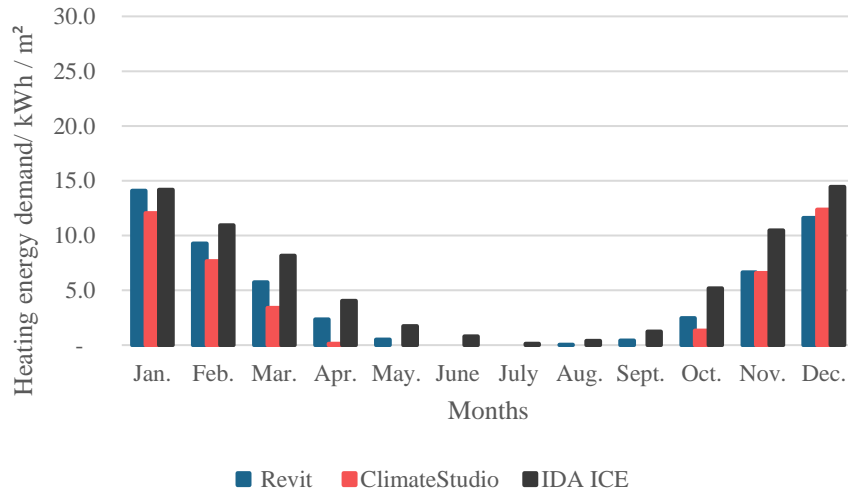


Figure 36: Monthly heating energy demand for all three BPS tools when 5 occupants were added to the building.

The cooling energy demand for CS was the highest in all months. IDA ICE had the lowest cooling demands from April to September as shown in Figure 37. Figure 45 shows the difference in the annual cooling energy demand for all three BPS tools, with a difference of 37% between the Revit BPS tool and CS. IDA ICE and Revit BPS had a difference of 3% for the annual cooling energy demand. The difference between Revit and CS was about 20% higher than the acceptable maximum while that between Revit and IDA ICE was lower than the acceptable value.

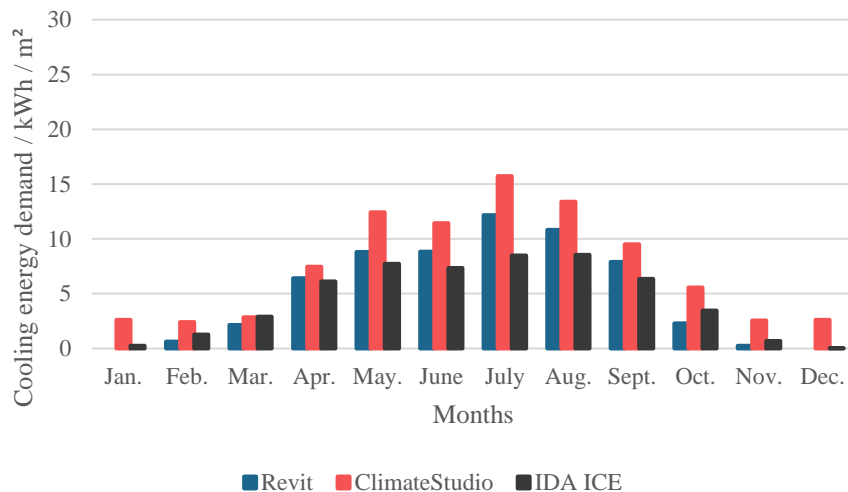


Figure 37: Monthly cooling energy demand for all three BPS tools when 5 occupants were added to the building.

4.3.5 Air Leakage

The effect of infiltration was observed on the calculation of heating and cooling energy demands using all three programs. The results as presented in Figure 38 shows IDA ICE had the highest heating energy demands from March to November this was due to the infiltration method, the wind-driven flow method was used. CS produced

the highest heating energy demand in January and December, as it interprets the infiltration value at 4 Pa. The Revit BPS tool had the lowest heating energy demand in the winter months and similar heating energy demand in summer with CS. However, Revit BPS did not incorporate the air leakage into the heating energy demand. Figure 44 shows the annual heating energy demand of the Revit BPS tool and IDA ICE varied by 19%, compared to 6% for the Revit BPS tool and CS. The difference was because of the specific air infiltration rate methods. CS uses the EnergyPlus effective leakage area model in its calculations based on the ASHRAE standard, it uses the local wind speed and the temperature difference between the zone air and outdoor air. IDA ICE uses a model CELEAK. However, the Revit BPS tool only considers air leakage for energy optimization on the web-based energy simulation tool Insight. In Revit and CS, the difference was lower than the acceptable value, while in IDA ICE, the difference was higher by 2%.

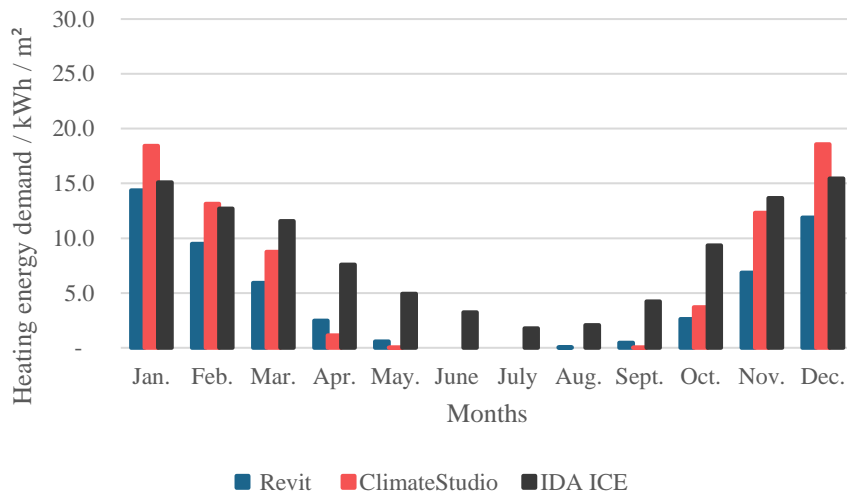


Figure 38: Monthly heating energy demand for all three BPS tools when Air leakage was activated.

Figure 39 presents the cooling energy demand for Revit BPS was the highest for all months except in January and December. IDA ICE had the least cooling demands in May and the summer months. Figure 39 shows the difference in the annual cooling energy for all three BPS tools, with a difference of 57 % between the Revit BPS tool and CS. IDA ICE and Revit BPS had a difference of 47% for the annual cooling energy demand. Differences between Revit, CS, and IDA ICE were way above the acceptable threshold of 17%.

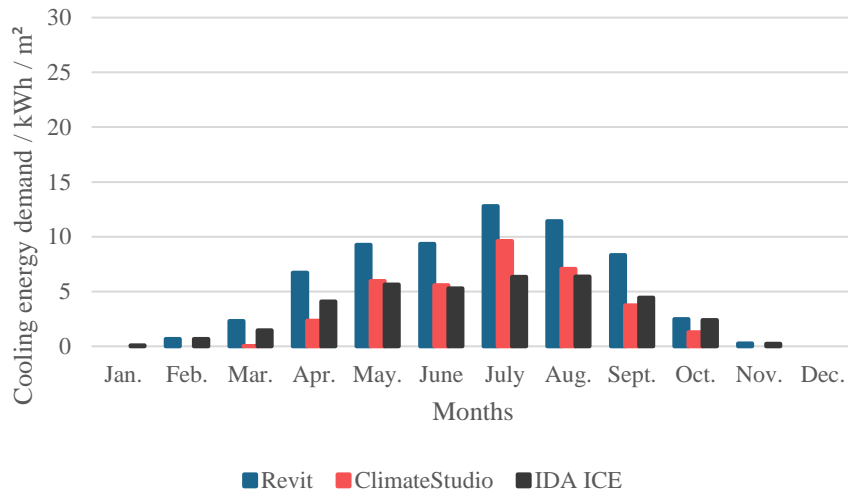


Figure 39: Monthly cooling energy demand for all three BPS tools when Air leakage was activated.

4.3.6 Mechanical Ventilation

Mechanical ventilation was activated for all three BPS tools, CS produced the highest heating energy demand in the winter months and the lowest heating energy demand in the spring and summer months as shown in Figure 40. Figure 44 shows the annual heating energy demand of the Revit BPS tool and IDA ICE varied by 1%, compared to 7% for CS and Revit BPS tool. The Revit BPS tool and IDA ICE had less differences in heating energy demand because of the variety of inputs for the HVAC systems, hence they are controllable. However, the air system equipment in the Revit BPS tool had predefined values for all components in the AHU. In IDA ICE, the VAV system uses a CentralMode, which controls airflow when the outdoor temperature reduces. CS uses a simple ventilation method, which took into account the design flow rate, and is controlled by a schedule with varying temperatures. Differences between Revit, CS, and IDA ICE are within acceptable threshold.

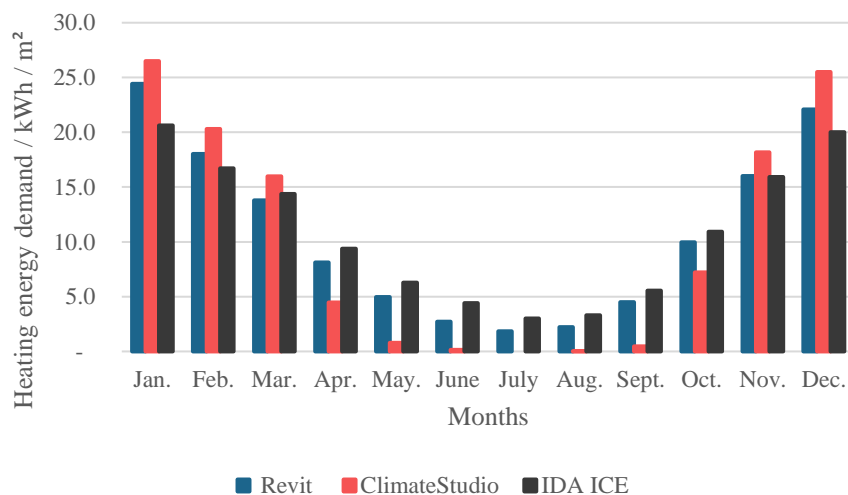


Figure 40: Monthly heating energy demand for all three BPS tools when Mechanical ventilation was activated.

As shown in Figure 41, Revit BPS tool had the highest cooling energy demand during all summer months, but IDA ICE had the highest in the winter months with no cooling in December for all three BPS tools. Figure 45 shows the difference in the annual cooling energy for all three BPS tools, with a difference of 41% between the Revit BPS tool and CS. IDA ICE and Revit BPS had a difference of 5% for the annual cooling energy demand.

The difference between Revit and CS was about 21% higher than the acceptable difference value, while that between Revit and IDA ICE was lower than the acceptable value of 17%.

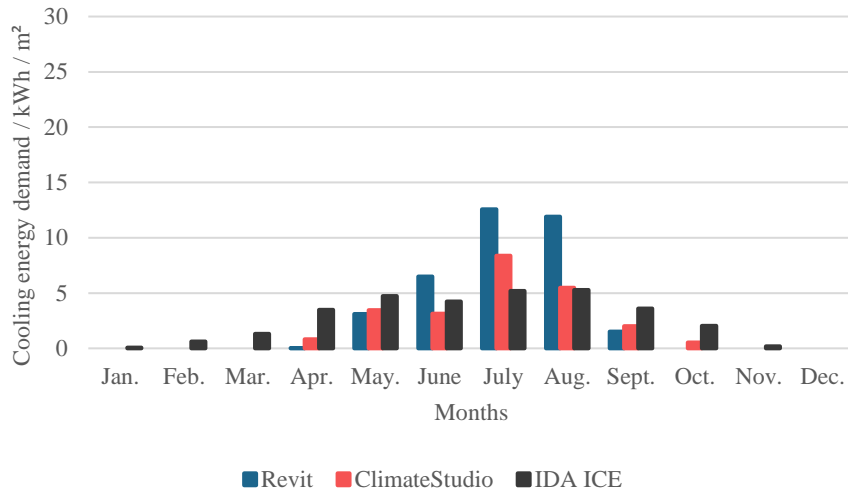


Figure 41: Monthly cooling energy demand for all three BPS tools when Mechanical ventilation was activated.

4.3.7 Equipment load

After assessing the influence of the mechanical ventilation system on all three BPS tools, the equipment load was activated with a 10 W / m² input for all tools. The distinctions between the three BPS tools were minimal. As shown in Figure 42, both CS and IDA ICE had the same value of 87.6 kWh / m², whereas the Revit BPS tool had a value of 89.8 kWh / m². Differences between Revit, CS, and IDA ICE are within the acceptable thresholds for the equipment loads.

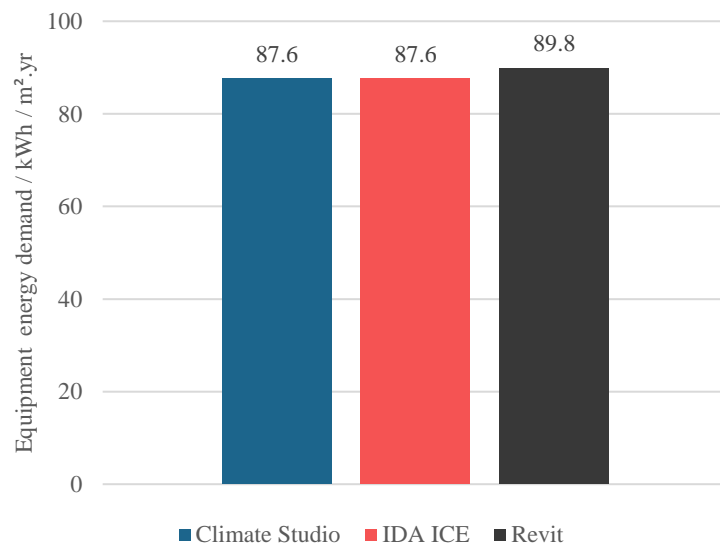


Figure 42: Annual equipment energy demand for all three BPS tools.

4.3.8 Lighting load

CS and IDA had the same EUI for the lighting load for a 7 W / m² lighting load, while Revit differed from both BPS tools by 1.6 kWh / m². Figure 43 shows the annual lighting EUI for all three BPS tools. The difference

between the BPS tools could be because of the program interpretation of the lighting heat load input. Differences between Revit, CS, and IDA ICE are within the acceptable thresholds for the lighting loads.

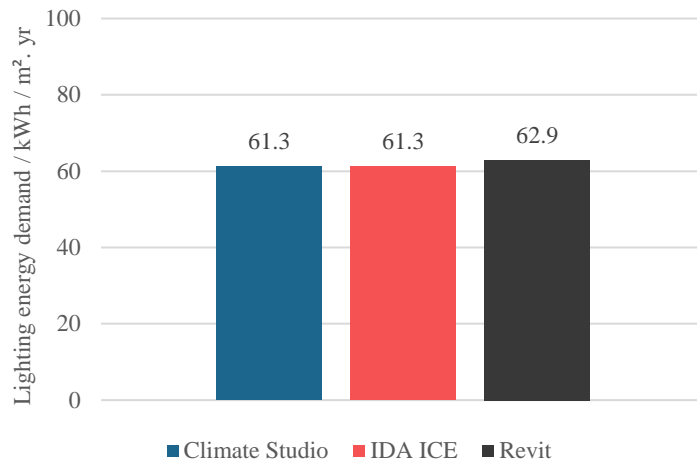


Figure 43: Annual lighting energy demand for all three BPS tools.

Figure 44 and Figure 45 show the annual heating and cooling demand respectively for each step performed in all three BPS tools.

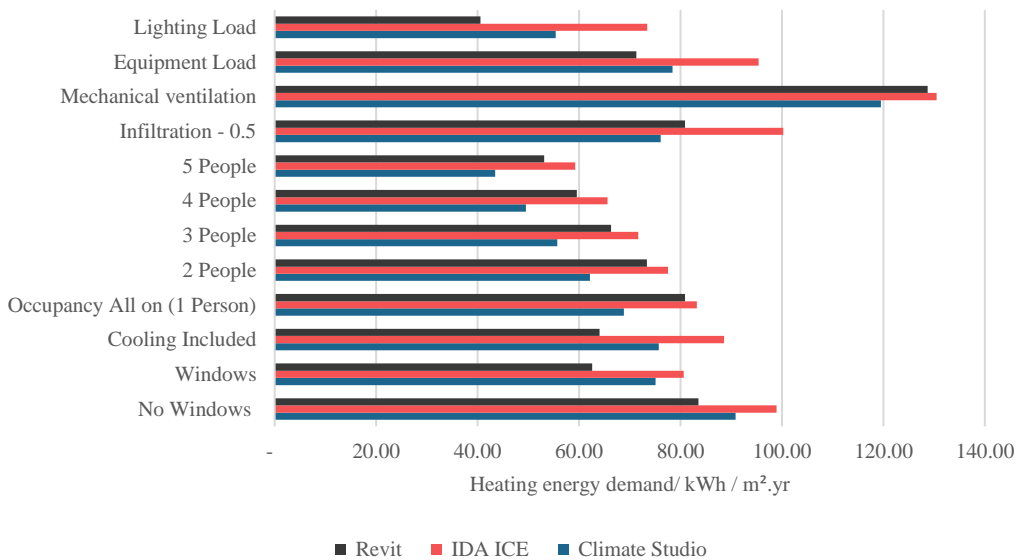


Figure 44: Annual heating energy demand for all three BPS programs.

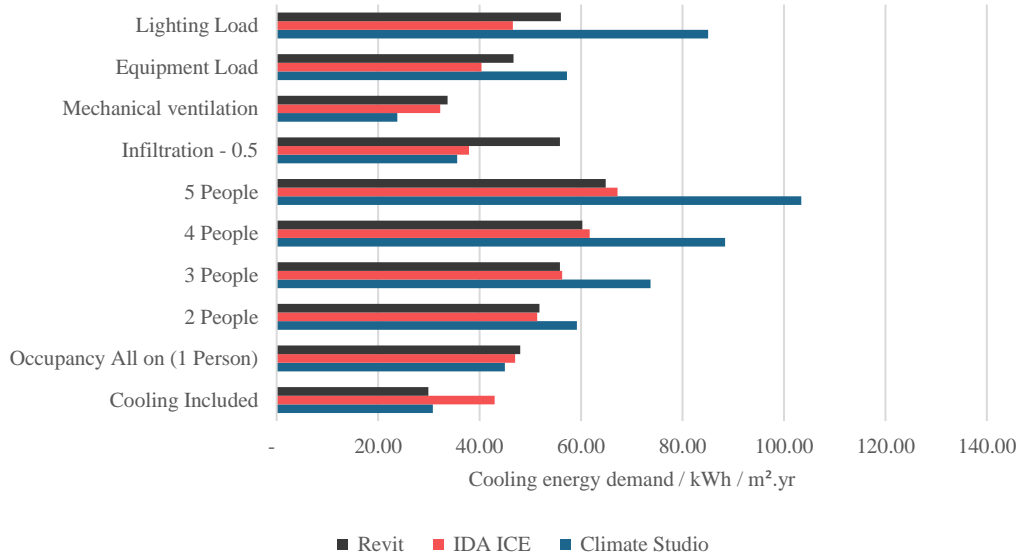


Figure 45: Annual cooling energy demand for all three BPS programs.

4.3.9 Simulation Time

The simulation for every step was observed to determine the speed at which the ES results were calculated. Although remodelling the building in CS and entering the thermal properties of the building components was time-consuming. However, CS had the most optimized simulation time while Revit had the highest calculation time.

The Revit BPS tool simulation time varied for every step, this could be attributed to the internet speed and connection because it uses the weather file from the Autodesk Climate Server, which contains about 1.6 million virtual weather stations based on numerical meteorological simulations. Figure 46 shows the time variations for CS, Revit BPS tool, and IDA ICE for every assessed step.

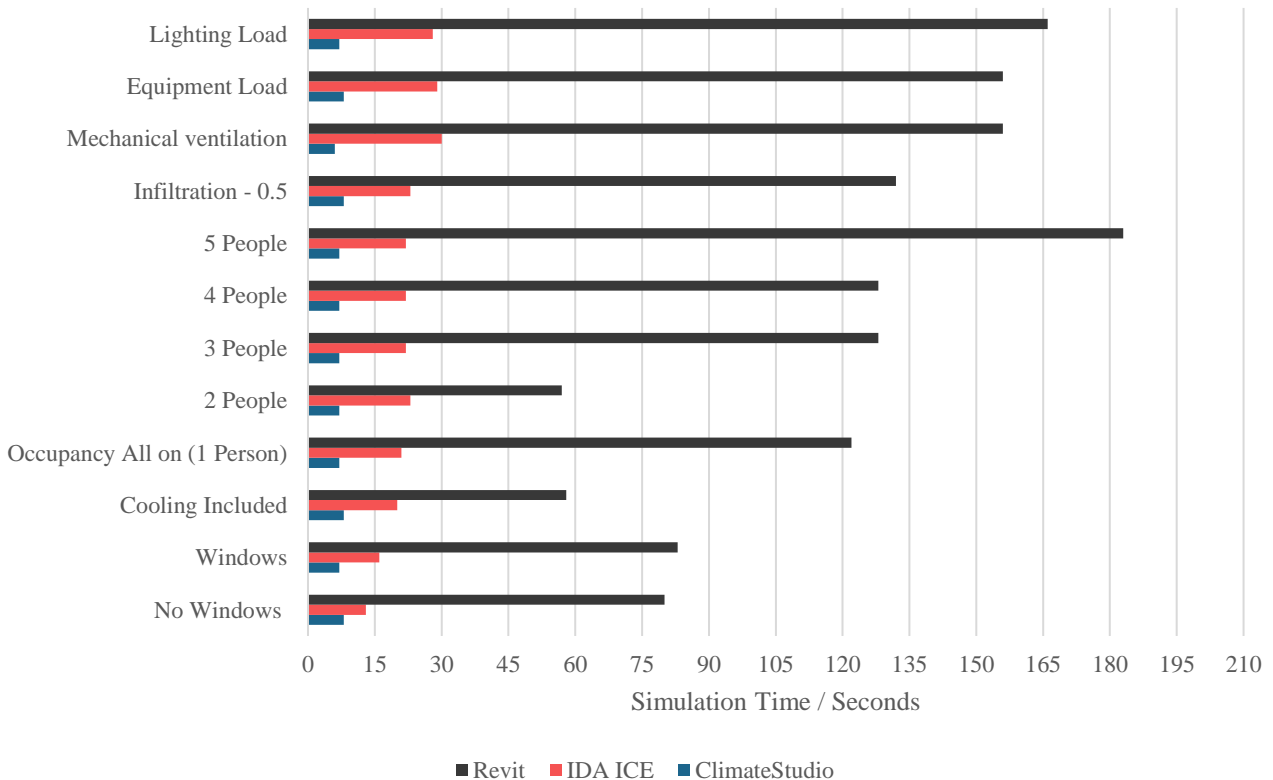


Figure 46: Simulation time for energy calculations for each step assessed.

4.4 Q12 Geometry

Figure 47 shows the Q12 geometry and its translation to a BEM model for all three BPS tools. From the images, both CS and Revit takes the shading into account. The shadings for IDA ICE were missing on import which is one of the challenges in interoperability between BIM and BEM. Although reproducing the model was quite straightforward using CS, the spaces in the building had to be modelled intersecting each other. This increased the floor areas of some spaces slightly.

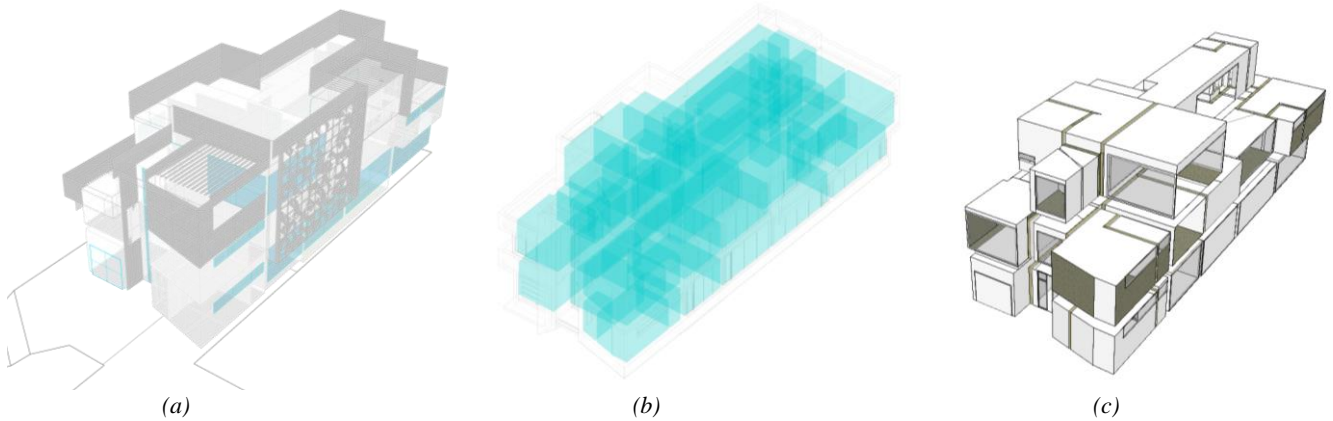


Figure 47: The Q12 geometry and its translation to a BEM model for all three BPS tools (a) CS (b) Revit (c) IDA ICE.

4.5 Q12 Energy Analysis

The results of the energy performance simulations for the weather file of Jos, Abuja, and the building location, Lagos are shown in Figure 48, Figure 49, and Figure 50 respectively. CS and IDA ICE had a slight difference in cooling energy use intensity, although CS is limited in defining the active systems, the inputs for the active systems in IDA ICE were well defined. While the active system was defined, the Revit BPS tool Cooling EUI did not match the other programs. The cooling EUI difference between Revit and CS and IDA ICE was way above the acceptable value. It can be assumed that this result was majorly due to a difference in the weather files.

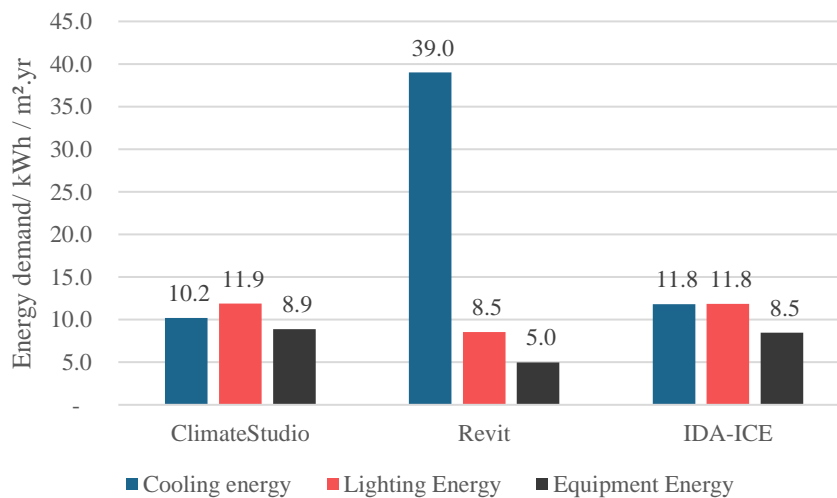


Figure 48: Annual cooling energy demand for Jos weather file

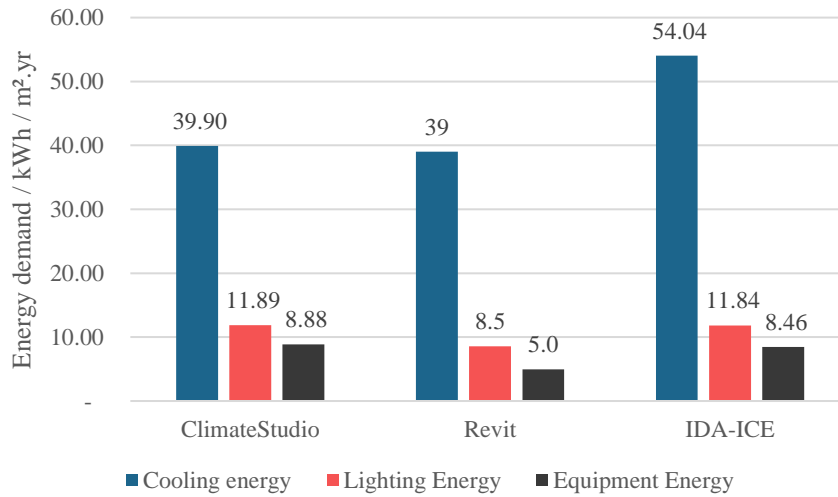


Figure 49: Annual cooling energy demand for Abuja weather file.

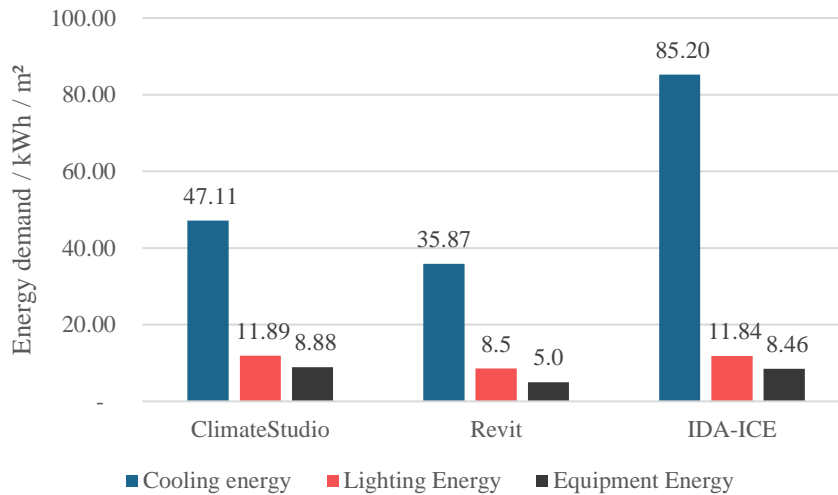


Figure 50: Annual cooling energy demand for Lagos weather file.

4.6 Q12 Simulation Time

The simulation for Q12 was observed to determine the speed at which the ES results were calculated for the combination of all inputs. CS had the most optimized simulation time while IDA ICE had the longest calculation time. This was due to the complexity of the building geometry and the number of zones defined for the building, which led to the increase in the simulation time of IDA ICE. Figure 51 shows the difference in simulation time for CS, Revit BPS tool, and IDA ICE for Q12.

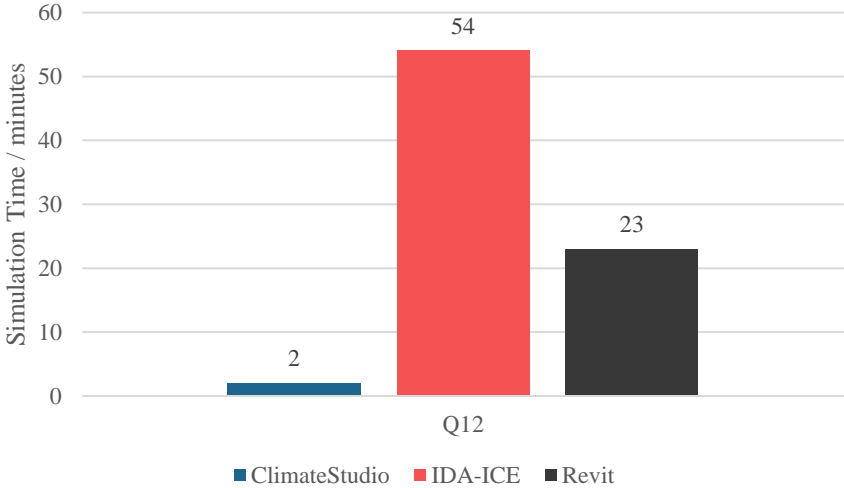


Figure 51: Simulation time for Annual energy calculations for all three BPS tools.

5 Discussion

The three BPS tools evaluated have shown some disparity in the results for both case studies evaluated. The input-to-input study showed that all three BPS tools calculate the building energy simulation in various ways based on the calculation methods. Although the Revit BPS tool uses the same simulation engine as CS and the same algorithm, there were still some large differences in the energy simulation results obtained for all steps evaluated.

According to the results obtained, the differences in these results could be attributed to the calculation methods of each BPS tool, the weather file used, and how the BPS tools interpret the models and the thermal properties of the building construction (façade, roof, floor, windows). Although IDA ICE and CS had the same weather file, there were some notable differences in the energy demand for heating and cooling. The differences could be attributed to the fact that the BPS tools calculate the heat losses and gains differently as well as the losses due to infiltration. A fixed infiltration value of 0.5 at 50 Pa was used in IDA ICE and Revit BPS tool while an infiltration value of 0.1 was used on CS. This is because CS requires the infiltration rate at 4 Pa.

The difference in the key climate indicators such as the dry bulb temperature, ground temperatures, wind speed, relative humidity, and solar radiation also impacted the differences in the produced results.

There was a negligible difference in the model geometry for the shoebox model. This is because it was a simple geometry, the shoebox model was exported as an IFC file into IDA ICE, hence it had the same heights, volumes, and wall, floor, roof, and window areas. However, there were some slight differences in the thermal properties for all BPS tools as shown in Table 10, the façade and roof U-values were slightly higher than CS and IDA ICE, because Revit calculates the U-value differently from the other two BPS tools. This was evident in the energy simulation results in step one as the difference in the results could be explained as the losses due to transmission of opaque surfaces, the key climate indicators of the weather file, and the calculation methods.

For the addition of windows to the southern façade, the difference in the energy demand between the Revit BPS tool and the other two BPS tools (CS and IDA ICE) was significant. This is due to the heat gain transmission through windows, which were relatively high compared with CS and IDA ICE as shown in Figure 21. There was also a notable difference in the results between CS and IDA ICE, the IDA ICE simulation tool considers the window frames and solar transmittance of the glazing while the Revit BPS tool only considers the SHGC value. The thermal properties of the window frames were turned off in CS since Revit only considered the thermal properties of the glazing panes. According to Winkelmann (2001), the EnergyPlus window calculation considers the Layer-by-layer input of glass, gap, and shade layers, Spectral or spectral-average glass optical properties, iterative heat balance solution to determine glass surface temperatures, anisotropic sky model for calculation of incident sky diffuse solar radiation and shading of sky diffuse radiation, tracking where solar radiation from windows falls inside room, sub-hour time steps. CS considers optical properties such as the solar transmittance, front reflectance (radiation incident on the side of the glass closest to the outside environment), and back reflectance (radiation incident on the side of the glass closest to the inside environment) of the individual glass layers in its heat balance calculations (Winkelmann, 2001).

IDA ICE uses a specified capacity for the heating and cooling room units for its energy calculations, although the Revit BPS tool and CS have this parameter, the EnergyPlus engine calculates the required energy demand for the heating and cooling systems based on the calculation methods. The difference in the energy demand was also prominent for occupancy, the three programs calculate the sensible heat internal gains of the occupants differently.

In the Revit BPS tool, the mechanical ventilation system was selected based on the pre-existing values of the zone equipment, the air system selected in the Revit BPS tool had the following settings of a sensible heat

exchanger of 0.76 at 100% effectiveness similar to that of CS, a preheating coil from electric resistance assumed to be 100% efficient, chilled water cooling coil, a hot water heating coil with a varying air temperature value and a variable air volume with a pressure rise of 996 Pa slightly similar to that of CS which uses 1000 Pa for Emsfanenergy. CS was able to use the district heating and cooling system once the mechanical ventilation system was activated unlike the Revit BPS tool, where EnergyPlus was not able to make use of the same heating and cooling system as CS.

The difference in the equipment and lighting load was seen to be equal for CS and IDA ICE, although there was a slight difference in that of the Revit BPS tool, this could be attributed to some differences in the interpretation of the schedule.

In case study 2, the results obtained were as a difference in the customization options of all three BPS tools, and the weather files for all three locations studied. One notable observation from the Revit BPS tool was that the weather file was not available in the Autodesk climate server database, hence it selected the closest weather file fitting the climate location. This explanation could be a major reason for the difference in the EUI results most especially for Jos. IDA ICE also did not have these weather files in its database, however, all three EPW files were imported for the ES as in the first case study when the Malmö weather file was also imported.

It is challenging to draw a definite conclusion on which BPS tool provides the best results and is very reliable in BES. The differences in the results could be attributed to the different calculation methods, differences in weather files and the inputs specific to each BPS tool. A summary of the comparison of the BPS tools is shown in the Appendix, with IDA ICE proving to be the most reliable in terms of the inputs and outputs, while CS is shown to be the most reliable in terms of usability, flexibility, and speed.

6 Conclusion

After a comprehensive study on all three BPS tools using the BIM file and building specific data presented in this study, it can be concluded that using BIM for energy simulation is challenging. Although Revit uses the same energy simulation engine as CS, it can be well-developed to perform accurate building energy simulations in the BIM environment in the future.

The interoperability between BIM and BEM also proved challenging as the BIM data to create complete building energy models was not completely viable using IDA ICE. Generating thermal zones from the imported IFC files was achievable, however, the IFC-based geometry translated generated some errors such as collisions of objects and missing objects. These challenges could be seen to impact the results of the case studies.

The difference in the customization options of all three BPS tools most especially the HVAC systems, occupancy, and operation schedules are seen as a likely cause of the difference in the energy results obtained. The Revit BPS tool has preset values for its HVAC systems with no option to alter it on the GUI of Revit unlike on IDA ICE where inputs such as the coil supply temperatures can be edited. The CS HVAC system had fewer controllable inputs, which simplified its use.

Based on the results of the energy simulations for Q12, CS and IDA ICE had similar values even though one of the weather files was by a wide margin. This difference could be attributed to the way both BPS tools interpret weather data files, calculates thermal values of the building components, and energy calculations. Although Revit and CS uses the same simulation engine and calculation method, the thermal values are calculated within the Revit GUI and not estimated by EnergyPlus.

Additionally, there is also a problem with localization when using IDA ICE as earlier highlighted in the discussion section. Although the IDA ICE library is internationally applicable as it uses the ASHRAE systems models and does not include remnants of any national building code, its design is influenced by the Scandinavian model of a very detailed zone (Axel Bring, Per Sahlin, Mika Vuolle, 1999). This is also applicable to the Revit BPS tool when specifying a mechanical ventilation system.

Overall, CS is an effective BPS tool for the EDP and for further stages as the design develops because it has superior performance, efficiency, simulation speed, flexibility, and simplicity. Although IDA ICE results were reliable, the simulation time was longer than the other BPS tools. In terms of flexibility, Revit was reliable since it served as a data transfer link to IDA ICE, however, its results were not accurate compared to the other two state-of-the-art BPS tools.

In conclusion, as technology evolves, BPS tools in BIM environments could become a dependable tool for practitioners in the AEC industry in designing more sustainable and energy-efficient buildings in the future. Nevertheless, the BIM to BEM translation process is a non-conforming approach that can result in different building energy models depending on who is involved and what the models are being used for. It is, however, important to distinguish the capabilities of this approach. It should be noted that Revit does not offer flexible customization options, like dynamic schedules, HVAC operation schedules, and systems, which might prove useful for EDP analysis to help with issues such as building mass and orientation. Additionally, CS and IDA ICE are the best options for a validated energy assessment at both the early and later phases of a project life cycle, however, the process might be time consuming due to constant design changes.

It is important to note that accuracy, flexibility, and speed were not fully achieved in the BIM environment. Several of the issues addressed in this study still needs to be further examined in future studies once there has been some progress in BIM-BEM compatibility, since only one building type (Residential) was examined in this study, and some areas still need further investigation, including thermal comfortability and daylighting.

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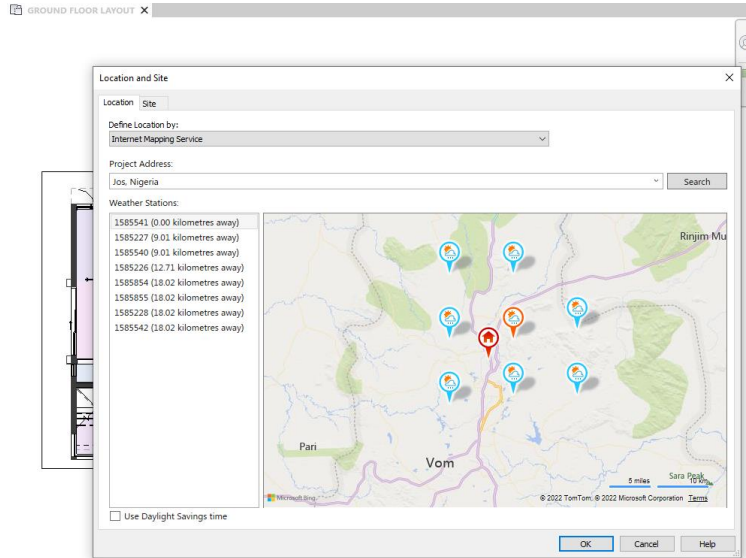
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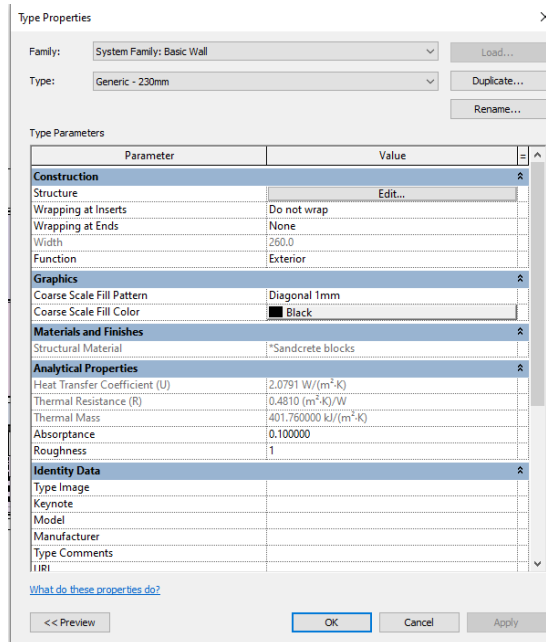
Appendix

Detailed workflow of the Revit Energy Analysis tool.

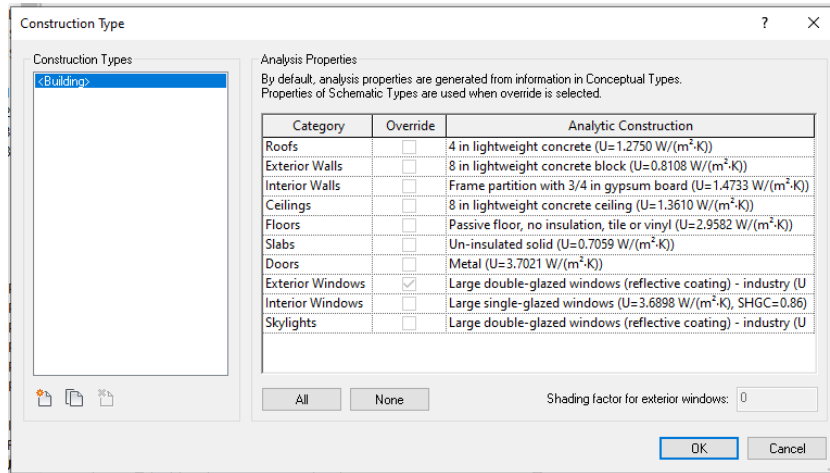
- Open Revit,
- The geometry is modelled,
- Set a geographic location,



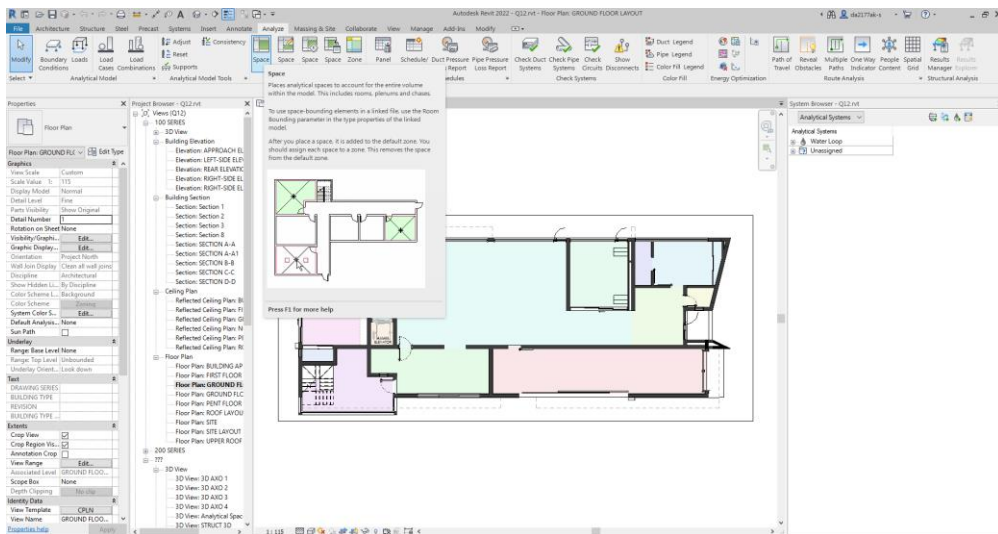
- Set thermal properties of the building construction.



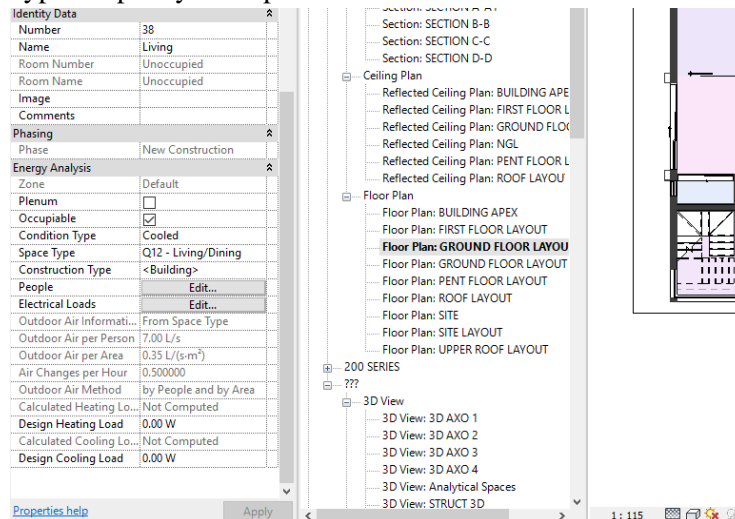
The thermal properties of the building construction can also be overridden in the Construction types settings tab.

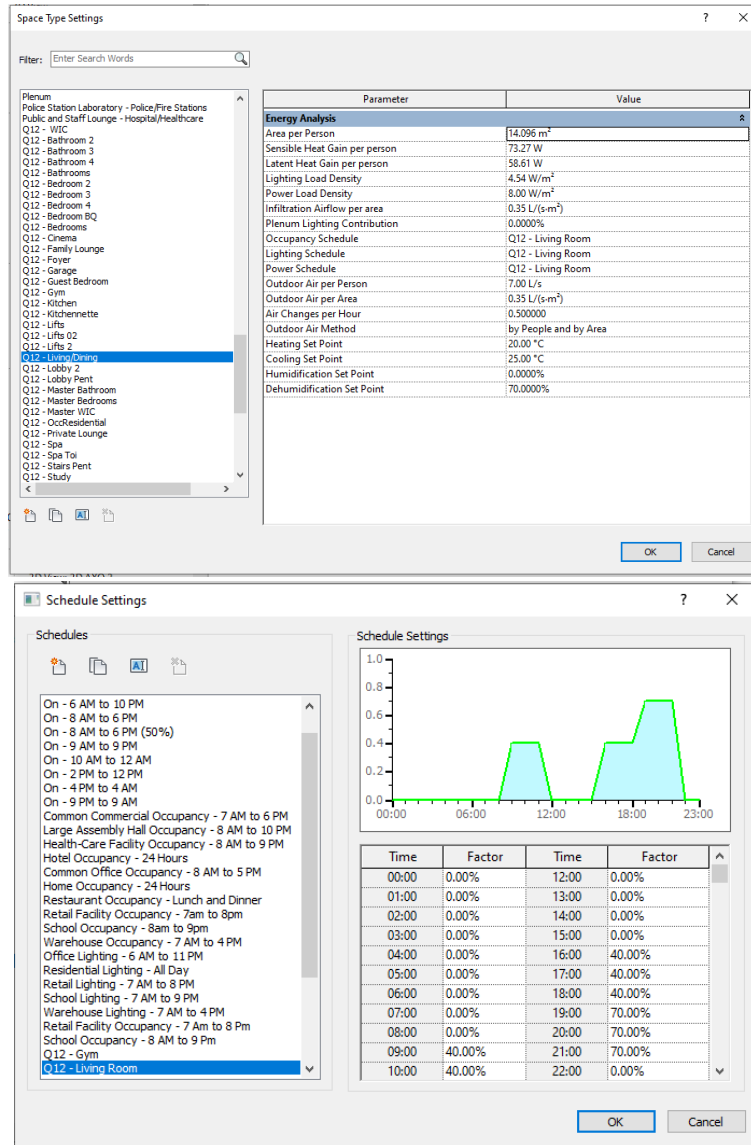


- Assign Spaces to the assumed conditioned and unconditioned rooms

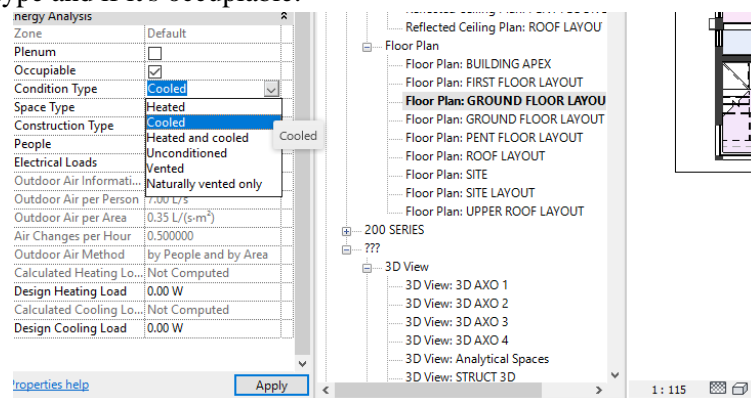


- Assign a preset Space type or specify the inputs

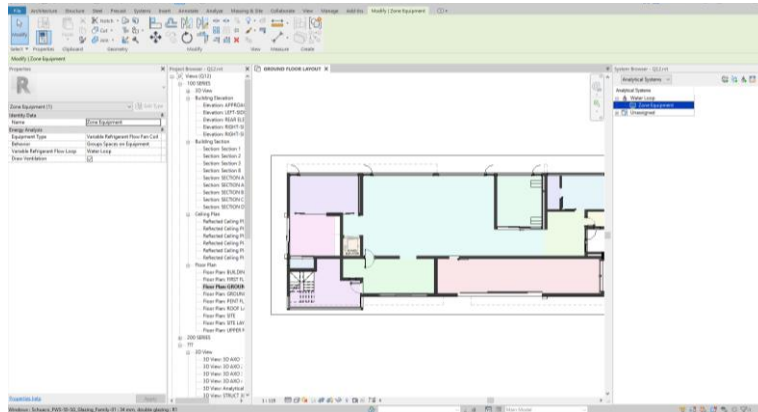




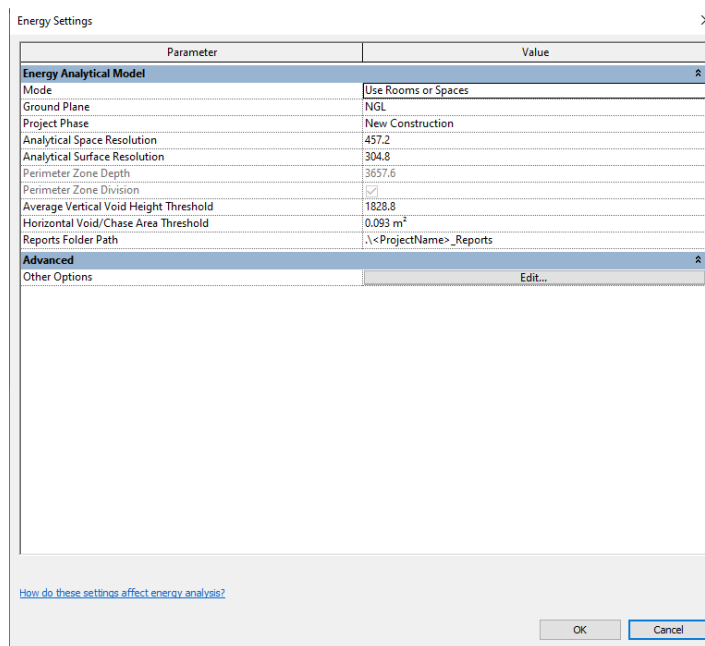
- Assign a Condition type and if it's occupiable.



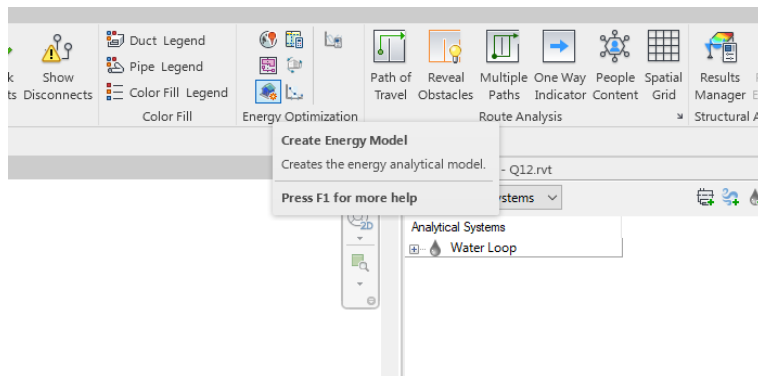
- Assign a Mechanical Ventilation system (Zone Equipment and/or Air System)



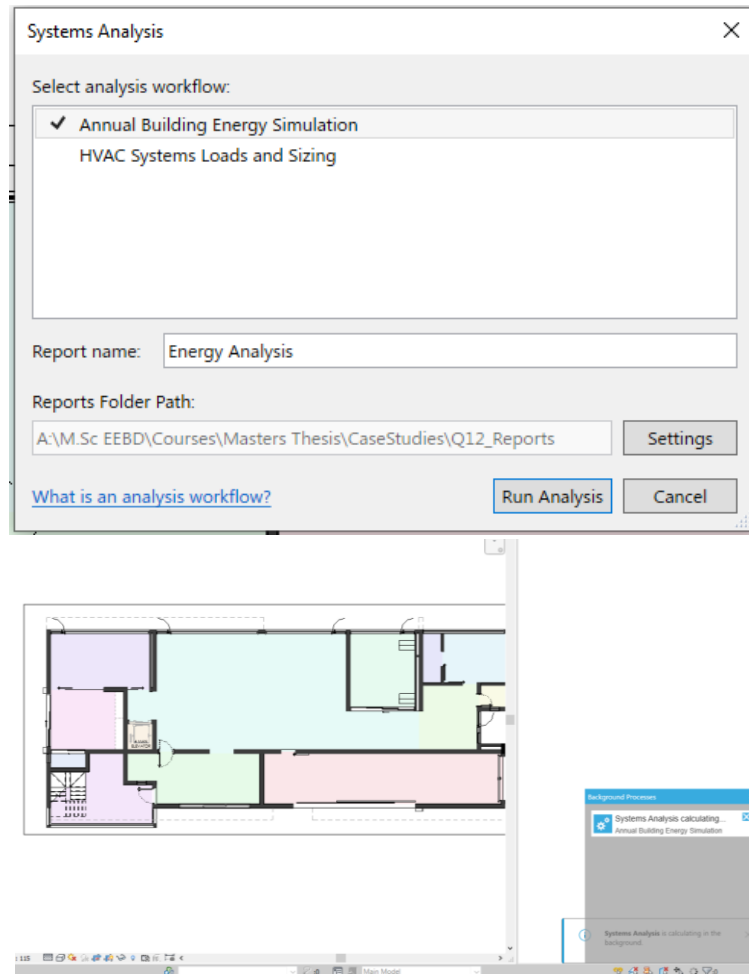
- Assign a mode for the Energy analytical model and other settings related to the analytical model.



- Create an Energy model.

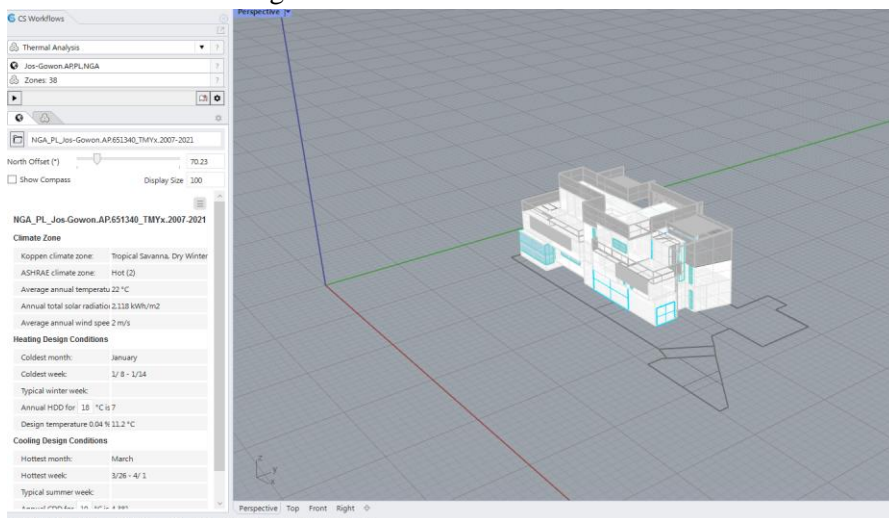


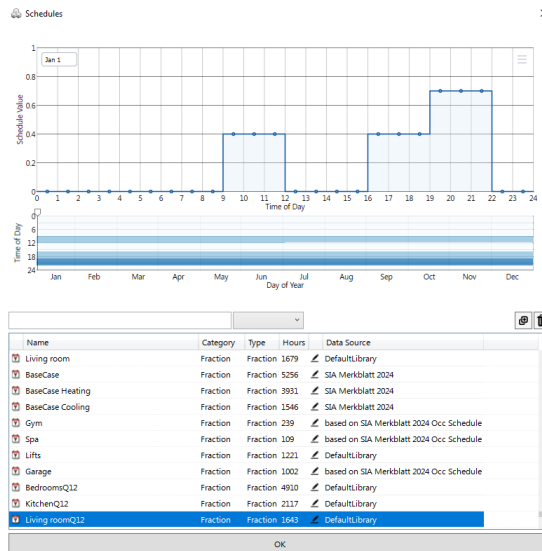
- Run Annual BES Analysis.



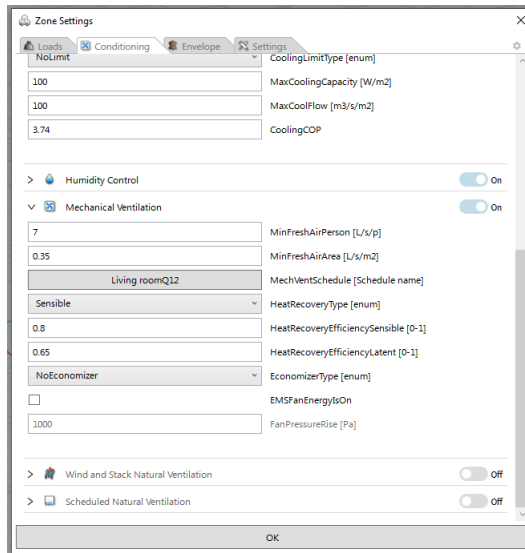
Detailed workflow of the ClimateStudio Thermal Analysis tool using the Rhino GUI.

- First, Rhino is opened,
- The geometry is modelled
- Load a climate file and set the building orientation

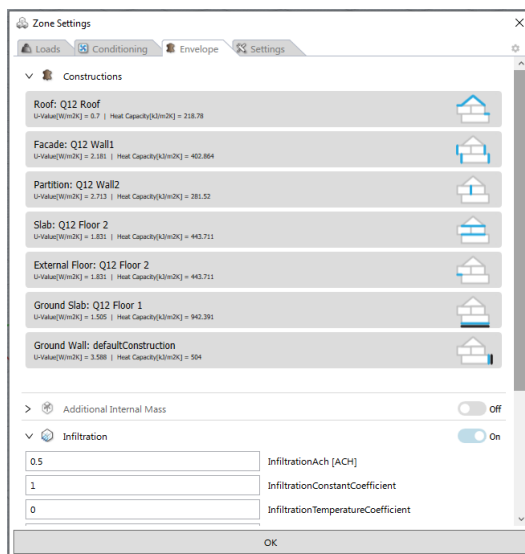




- Define the Humidity control and Mechanical Ventilation inputs



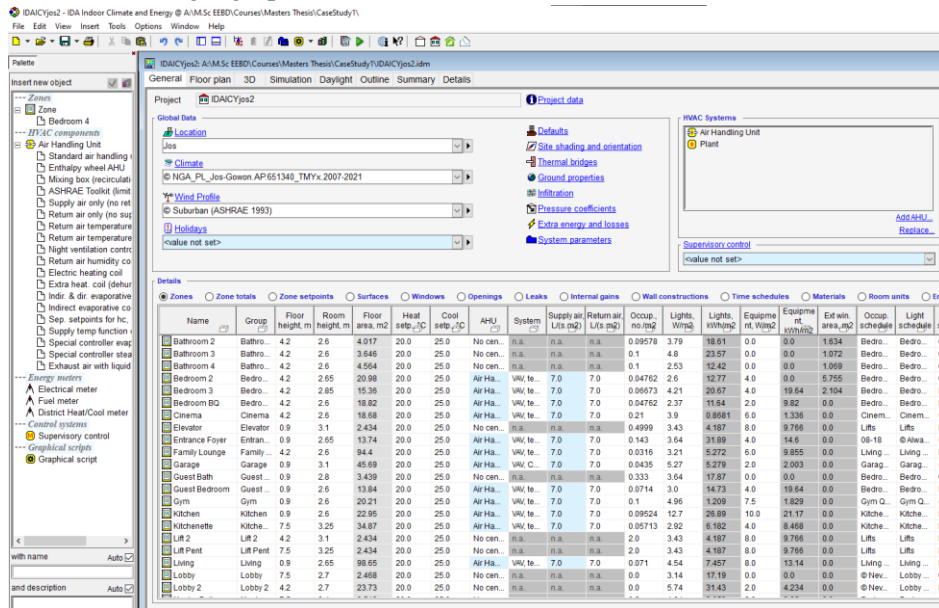
- Define the zone construction and Air infiltration inputs.



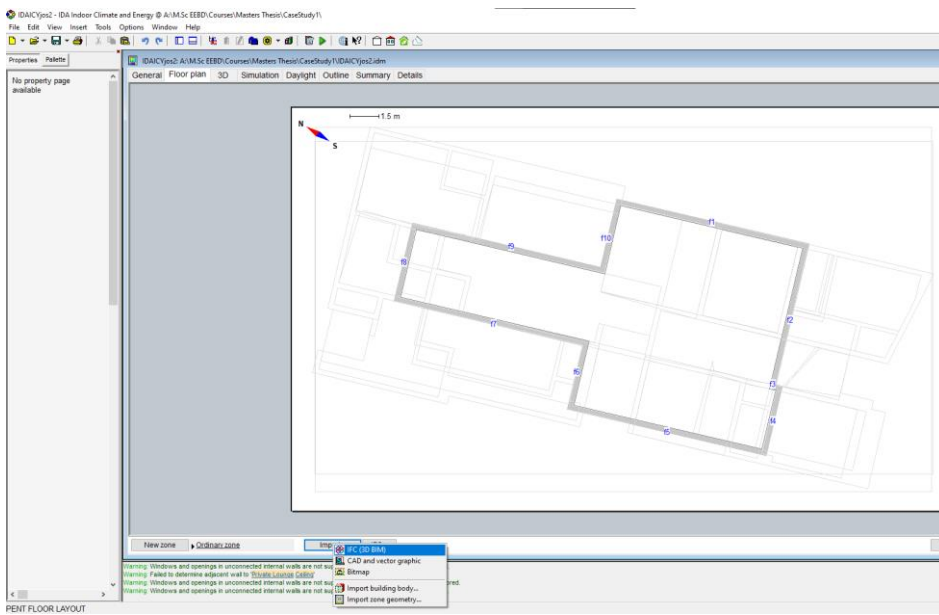
- After the zones are defined and all inputs set, a BES is conducted.

Detailed workflow of the IDA ICE Energy Simulation tool.

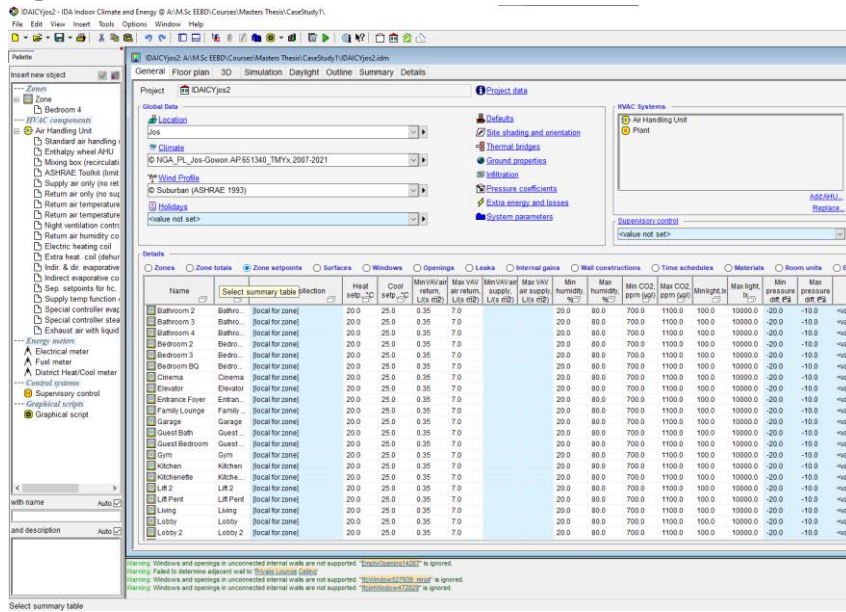
- First, IDA ICE is opened,
- Load a climate file and set a geographic location



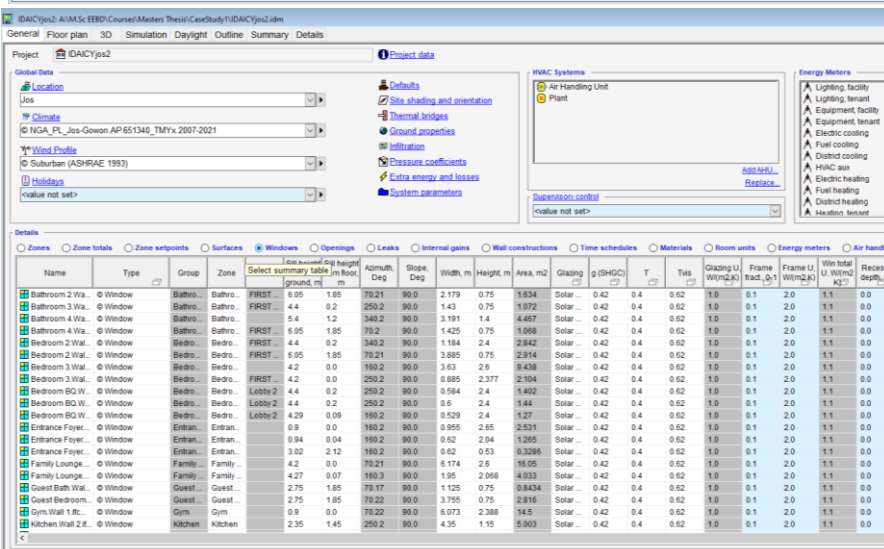
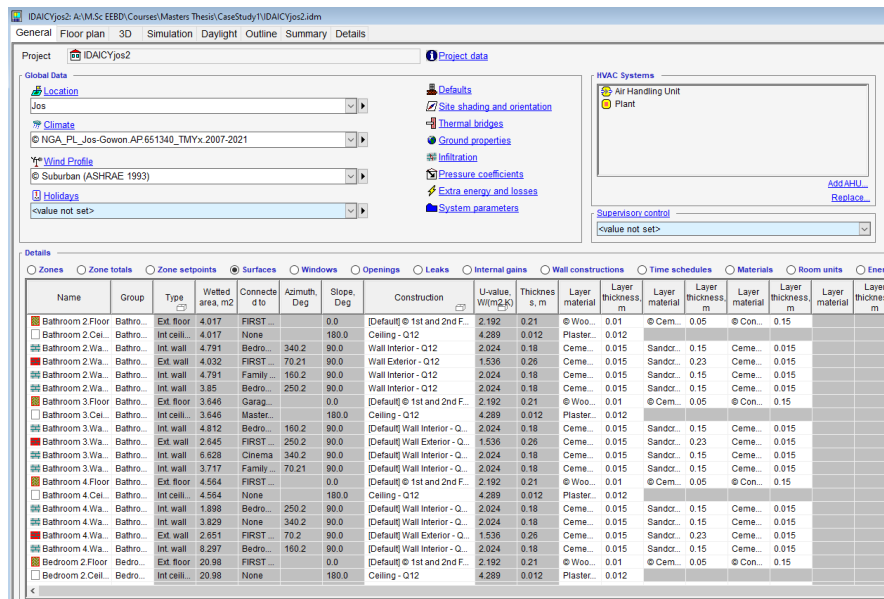
- Import geometry via IFC



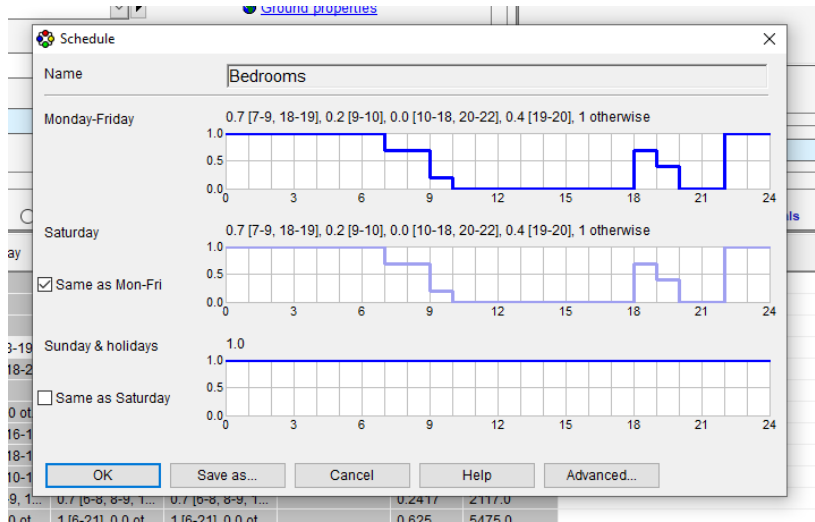
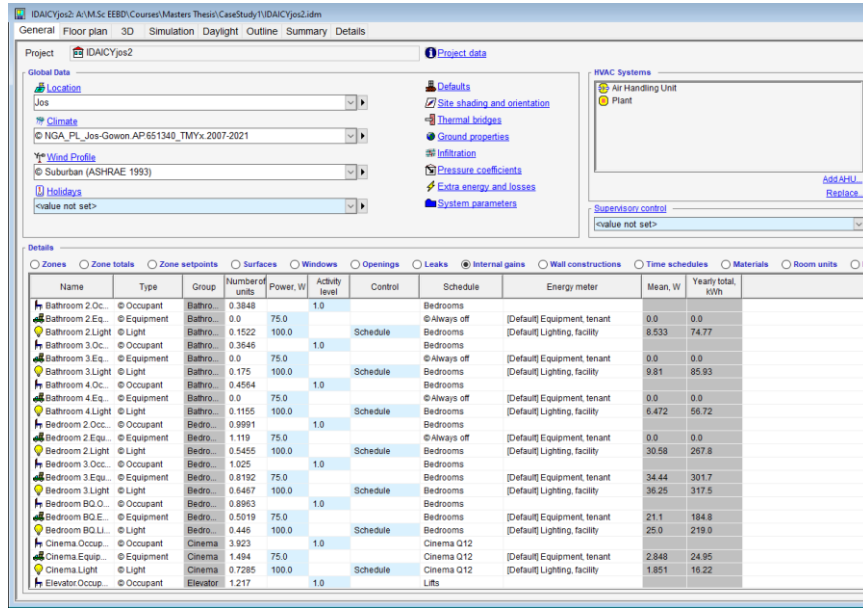
• Define the Zone setpoints



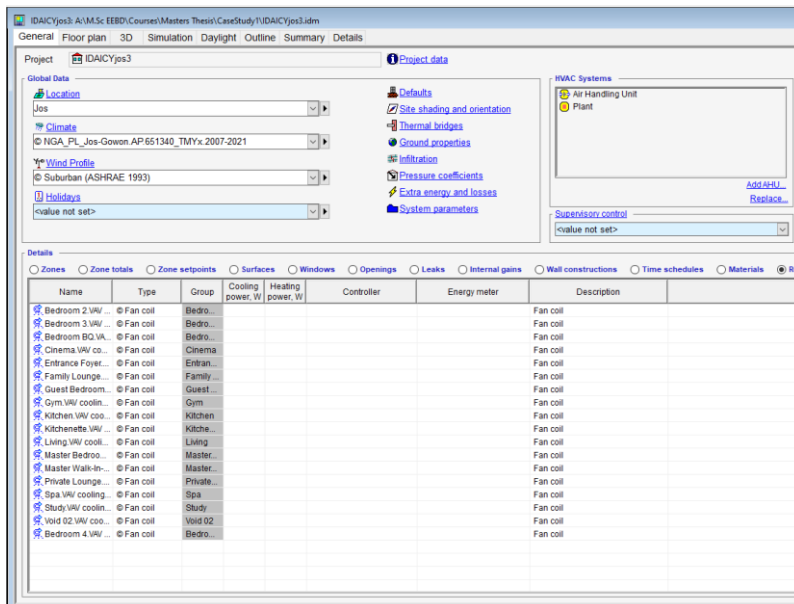
• Define the Zone constructions



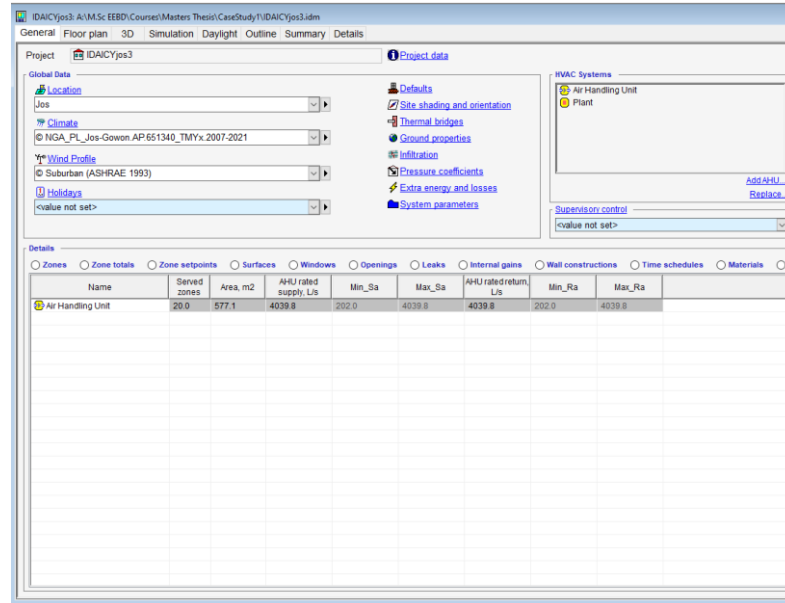
- Define the Internal loads inputs and schedules



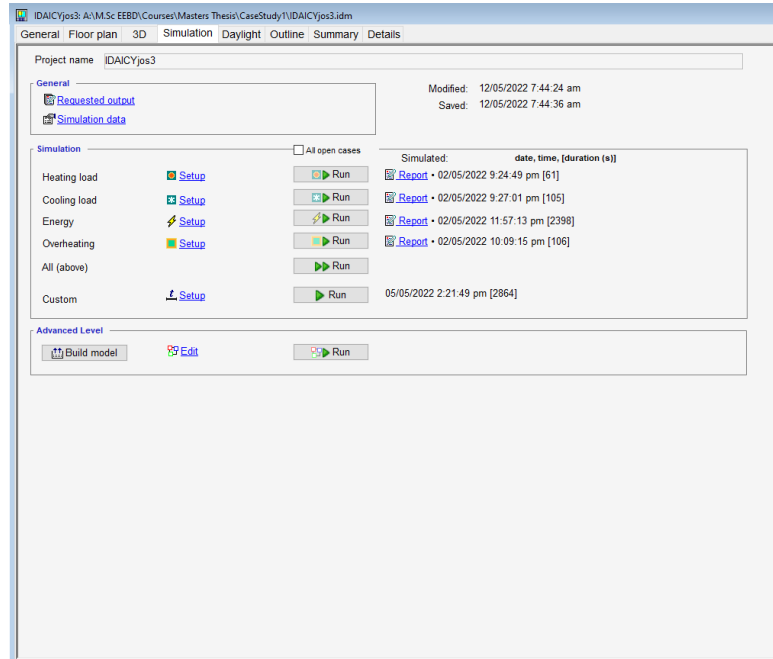
- Define the Room Cooling and Heating Units



- Define the Mechanical Ventilation system.



- Run BES and load calculations.



Comparative Analysis of the studied BPS tools.

BPS Tools		ClimateStudio	IDA ICE	Revit Energy Analysis Tool
Simulation Engine		EnergyPlus	Uses several models based on mathematical equations.	EnergyPlus
Software Requirements		Requires basic modelling skills in Rhinoceros 3D.	Requires good knowledge of building energy simulation.	Requires basic modelling skills in Revit.
Inputs		<ul style="list-style-type: none"> ✓ Climate file ✓ Orientation ✓ Geometry (modelled in Rhino) ✓ Internal loads (People, equipment, Lighting, Hot water) ✓ Conditioning system (Heating and Cooling) ✗ Different types of Mechanical Ventilation systems ✓ Construction U-Values ✓ Air Leakage ✓ Natural Ventilation ✗ Thermal Bridges 	<ul style="list-style-type: none"> ✓ Geographic location / Climate file ✓ Orientation ✓ Geometry (import via IFC/CAD) ✓ Internal loads (People, equipment, Lighting, Hot water) ✓ Conditioning system (Heating and Cooling) ✓ Different types of Mechanical Ventilation systems ✓ Construction U-Values ✓ Air Leakage ✓ Natural Ventilation ✓ Thermal Bridges 	<ul style="list-style-type: none"> ✓ Geographic location (Internet-based) ✓ Orientation ✓ Geometry ✓ Internal loads (People, equipment, Lighting, Hot water) ✓ Conditioning system (Heating and Cooling) ✓ Different types of Mechanical Ventilation systems (limited customizable inputs) ✓ Construction U-Values ✗ Air Leakage ✗ Natural Ventilation ✗ Thermal Bridges
Outputs		<ul style="list-style-type: none"> ✓ Energy Use ✓ Energy Balance ✓ Thermal comfort Analysis ✓ Carbon Emissions ✓ Regulatory Compliance 	<ul style="list-style-type: none"> ✓ Delivered energy and systems energy ✓ AHU energy ✓ Load Analysis (Heating and Cooling) ✓ Energy Balance ✓ Thermal comfort details ✓ Regulatory Compliance 	<ul style="list-style-type: none"> ✓ Energy Use ✓ Load Analysis (Heating and Cooling) ✓ Carbon Emissions ✓ Renewables ✗ Regulatory Compliance
Software Performance	Complexity	Low to Medium	Medium to High	Medium
	Flexibility	Useful for all Design stages (modelling can be time-consuming)	Useful for all Design stages (specifying detailed HVAC inputs at EDP might prove undecisive)	Useful for all Design stages (specifying detailed HVAC inputs at EDP might prove undecisive)
	Calculation Speed	Fast	Slow (Speed could be increased by adjusting the tolerance and max timestep)	Slow (Dependent on Internet speed most times)
Availability		Worldwide	Sweden, Denmark, Finland, Norway, Germany, Switzerland, Austria,	Worldwide



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