Master of Science program in ARCHITECTURE FOR THE SUSTAINABILITY DESIGN

Thesis of Master's degree

From Building Information Models to Building Performance Simulation:

Parametric workflow for high-performance building envelope design for energy and thermal comfort evaluation

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I dedicate my thesis dissertation work to my family and friends. A special feeling of gratitude to my loving parents, Velko and Lidija, without whose support I could not achieve this important milestone in my life. Also, a special thanks to my dear brother, Kristijan, who has always been here to encourage me to keep pushing forward. And finally, to all my loving friends, who over the years became family, thank you for being the emotional support that I desperately needed in this period.

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Abstract

Building sciences and architecture are connected but quite different fields that complement one another. Due to growing sustainability concerns, evaluating building performance and its effects on the environment has practically become a requirement for all new projects. The complex process of building environmental performance (BEP) analysis includes energy performance, daylight analysis, thermal comfort, indoor air quality, acoustics, and other factors. Each of these factors has its own specific research criteria. This research focuses on finding the link between the BIM (Building Information Modelling) programs and the BPSTs (Building Performance Simulation Tools) to achieve a smooth interoperability in order to minimize the data loss. It was crucial to understand the possibilities and capabilities between the two types of software programs once a connection between them had been made. The thesis is more specifically focused on energy optimization and thermal comfort in a building during the early design stages using Revit as a BIM program and Grasshopper within Rhino to create an analytical model.

List of Acronyms

AADCC	Accuracy of tools and Ability to simulate Detailed and Complex and building Components
AEC	Architecture, Engineering, and Construction
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEM	Building Energy Modeling
BEP	Building Envelope Performance
BIM	Building Information Model
BPST	Building Performance Simulation Tools
BREEAM	Building Research Establishment Environmental Assessment Method
BTO	Building Technologies Office
CAD	Computer-Aided Design
CEN	Comitee European de Norme
CFD	Computational Fluid Dynamic
COBie	Construction Operations Building Information Exchange
CRT	Conventional Reverberation Time
DB	DesignBuilder
DOE	Department of Energy
DXF	Drawing Exchange Format
EF	Efficiency factor
EP	EnergyPlus
EPW	Energy Plus Weather
gbXML	Green Building XML
HB	Honeybee
HVAC	Heating, Ventilation and Air Conditioning
IBDP	Integration with Building Design Process
IBM	Interoperability of Building Modelling
IDF	Intermediate Data Format
IEQ	Indoor Environmental Quality
IFC	Industry Foundation Classes
IIKB	Integration of Intelligent design Knowledge-Base
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LB	Ladybug
LEED	Leadership in Energy and Environmental Design

NZEB	Nearly Zero Energy Buildings
OP	Open Studio
PEF	Primary Energy Factor
PEU	Primary Energy Use
PMV	Predicted Mean Vote
PPD	Predicted Percentages of Dissatisfied
RIR	Rhino inside Revit
SDK	Software Development Kit
SRI	Sound Reduction Index
UI	User Interface
UIM	Usability and Information Management
VPL	Visual Programming Language
ZEB	Zero Energy Building

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1. Introduction

Building sciences and architecture are connected but quite different fields that complement one another. Evaluation of building performance and environmental implications has practically become a requirement for all new projects due to rising sustainability concerns. Energy performance, daylight analysis, thermal comfort, indoor air quality, acoustics, and other factors are all included in the complex process of building environmental performance (BEP) analysis, and each of these factors has its unique research criteria. Building performance studies are increasingly being conducted in a digital context, where a variety of technologies and platforms must cooperate in order to produce valuable data. In this research, it was important to understand which of the surrounding exterior and interior factors affect the building envelope performance and understand in which stadium of the design process could the energy and thermal comfort be predicted and calculated. Nowadays, Europe is facing a serious energy crisis, so it is more important than ever for all the measures to be undertaken.

This research focuses on the technologies that can help the architecture and building sector to overcome the issue of uncertainty when it comes to the performance evaluation of a construction. In the next chapters, a detailed literature review and two case studies lead to a conclusion of the today's status of the building performance simulation tools and how they can be implemented in the design process. An overview is made makes of what is on today's market regarding software programs that later narrows it down to the most accessible programs, but also on the ones that offer a wide variety of solutions to some of the most common issues nowadays. This research is a collaboration with the colleague Mila Shoshev, and the two-thesis function as extensions from one another, where different research methods are used in order to understand the issues regarding the subject.

1.1. Research context

Buildings are the second most energy-intensive market sector, accounting for almost one-third of global energy consumption (Cozzi, 2020). The use of energy in buildings is currently being reduced on a global scale. This issue has been present in all the different building typologies, however, in practice, due to the nature of their operations, location, rent, and operational requirements, office buildings are more likely to be designed with high-performance requirements in mind. If these strategies are not considered, office buildings may be responsible for high operational emissions.

From the 1990s to the 2000sseveralof voluntary rating programs that have been accepted by governments, the construction industry, and professionals all over the world made significant progress in certification efforts on a global scale. One of them is the Building Research Establishment's Environmental Assessment Method, one of the first and most widely used green building rating systems in the UK (BREEAM). A system called BREEAM is used to assess, rate, and certify several sustainability-related aspects of buildings, including their energy efficiency. BREEAM measures a project's performance against best practices in the following areas: management, health and well-being, energy, transport, water, materials, waste, land use and ecology, and pollution (BRE, 2014).

Building form, façade form, and façade construction are three categories into which variables for optimization can be divided in the early design stage, according to studies on BPE optimization. The building form would include the floor plan, building orientation, building shape, and controlling parameters as variables in the digital building form. The size of a single window, the size of a shading component, and the arrangement of windows and walls are all variables in a façade's form. As opposed to the façade construction, which considers variables like opaque insulation parameters, glazing light transmission, and insulation parameters. All these variables are important to have a highly functional building where the thermal comfort and energy performance are optimized, and the longevity and quality building could be promised.

This specific research was focused on understanding how the thermal comfort and energy efficiency of a building can be calculated. Firstly, it was important to understand which factors and attributes are important in order to get to the results. Here two different software programs were used in order to get the desired outputs:

I. As a BIM software Revit was used, since it is the most used software amongst architects and engineers;

II. As a VPL software Rhino's Grasshopper was used, since it offers a wide range of tools with different engines what allow the users to do a wide range of analysis and calculations.

1.2. Research problems

The design of the building and the calculation of the building performance are two very different and yet very complex tasks that correspond to one another. Nowadays, there are many software programs that can provide accurate results for the desired analysis. Many architects are introduced with many BIM software programs in the early stages of the education, and later in the work, they are still relaying on these software programs for visualizing the design that they have created. However, this is not the case for the BEM and EAM software programs. Even though these programs can provide information and solution for many issues that the modern-day architects and engineers come across, the education about these software programs it is insufficient. In the first glance, the programs can be overwhelming, however with some education and practice they can lead to much more polished and sustainable designs in the future.

Once the issue with the learning of the programs is overcome, there is another issue that the users are facing. That is the data flow between the various software programs. The two programs used for this research are ones that students and professional architects and engineers are relying on the most. Interoperability was a problem that this research tried to understand.

1.3.Research goals

This research focuses on finding the link between the BIM (Building Information Modelling) programs and the BPSTs (Building Performance Simulation Tools) to achieve a smooth interoperability in order to minimize the data loss. Once the connection is established between the two types of software programs, it was important to realize what are the possibilities and capabilities amongst them. More specifically, the focus of the thesis is on energy optimization and achieving thermal comfort within a construction in the early stages of the design process using Revit as a BIM program and Grasshopper within Rhino to construct an analytical model. This research aims to understand and answer the next research questions:

I. What is the smoothest workflow when converting the model from BIM to VPL with the least percentage of data loss?

II. What are the common issues when using software programs and how can they be resolved?

III. How do parametric simulation tools help the design process and decision-making process?

IV. What are the capabilities of the simulation tools and in which stages of the design can they be used?

1.4. Potential benefits of the research

If the research questions that are mentioned in the previous chapter are answered and explained with this research, this thesis could serve as a manual to all potential users. The usage of the integrated design process could be something that all architects and engineers could incorporate in their work to ensure a better building environment for the future. This thesis aims to explain the process that starts from a BIM model to results regarding Energy and Thermal analysis in depth.

1.5. Structure of the thesis

The thesis is divided into six chapters where the process of the research is explained. It starts with literature review that explains what the situation is nowadays according to the information that is accessible to the public. It explains the concept of Nearly Zero Energy Buildings (NZEB) and the importance of Building Envelope Performance (BEP). It continues with research on Building Performance Simulation Tools (BPSTs) and their importance, Building Information Modelling (BIM) process and the available software programs nowadays, as well as Building Energy Modelling (BEM) and Visual Programming Language (VPL) software programs. It explains the users experience nowadays and their capabilities. Later on, the energy and thermal comfort Key Performance Indicators (KPIs) are mentioned and how they can be calculated using the specific programs. The next chapter focuses on two case studies that were designed to test the capabilities of the programs in order to calculate the specific KPIs mentioned before. Next, the results of the simulations are explained and analysed. Finally, discussions and conclusions (both singular and common with the collaborator Mila Shoshev) are constructed to explain the experience regarding this whole process.

2. Literature review

Before doing the specific experiments done on the case studies designed to acknowledge the issue in depth, it was important to do a literature review so that it can be understood what other researchers' experiences regarding this subject were. Various articles, books, and columns were taken into consideration for the base of the research, to understand the main issues and obstacles in order to have a vivid picture of what specific programs and software programs have to offer nowadays. More specifically, the research's focal point is analyzing the capabilities of the software programs that aid both engineers and architects to predict the functionality of a construction. Firstly, it was important to clarify the differences between the types of software programs and what they offer. It starts with understanding the importance of Building performance Simulation Tools (BPSTs), Building Information Model (BIM) and Building Energy Model (BEM) with a focus on the specific key performance indicators (KPIs). The basis of the research is energy and thermal analysis.

2.1. Importance of building envelope performances

The physical partition separating a structure's inner and outside environments is known as the building envelope (Hagentoft, 2001). The building envelope, in general, is made up of several parts and systems that shield the interior space from environmental factors like precipitation, wind, temperature, humidity, and UV radiation. The inhabitants, furniture, building components, lighting, machinery, equipment, and the HVAC (heating, ventilation, and air conditioning) system make up the interior environment. The building envelope has many functions, however, these functions can be divided into three categories: structural (providing support against external and internal loads), aesthetic (making the building aesthetically pleasing and to create pleasant indoor atmosphere) and controlling (to control the airflow, temperature, humidity and others, to ensure comfortable environment for the use of the inhabitants). Improving the building envelope of a building is one of the ways to ensure a better energy efficiency (Arnold, 2016).

The energy usage and comfort requirements of any building are significantly influenced by the envelope of the building. It has become obvious that technologies and tactics that enable us to keep our satisfaction with the interior environment while consuming less of these resources are significant aims for the current façade designs as energy and other natural resources continue to be depleted (Gasparri, 2021).

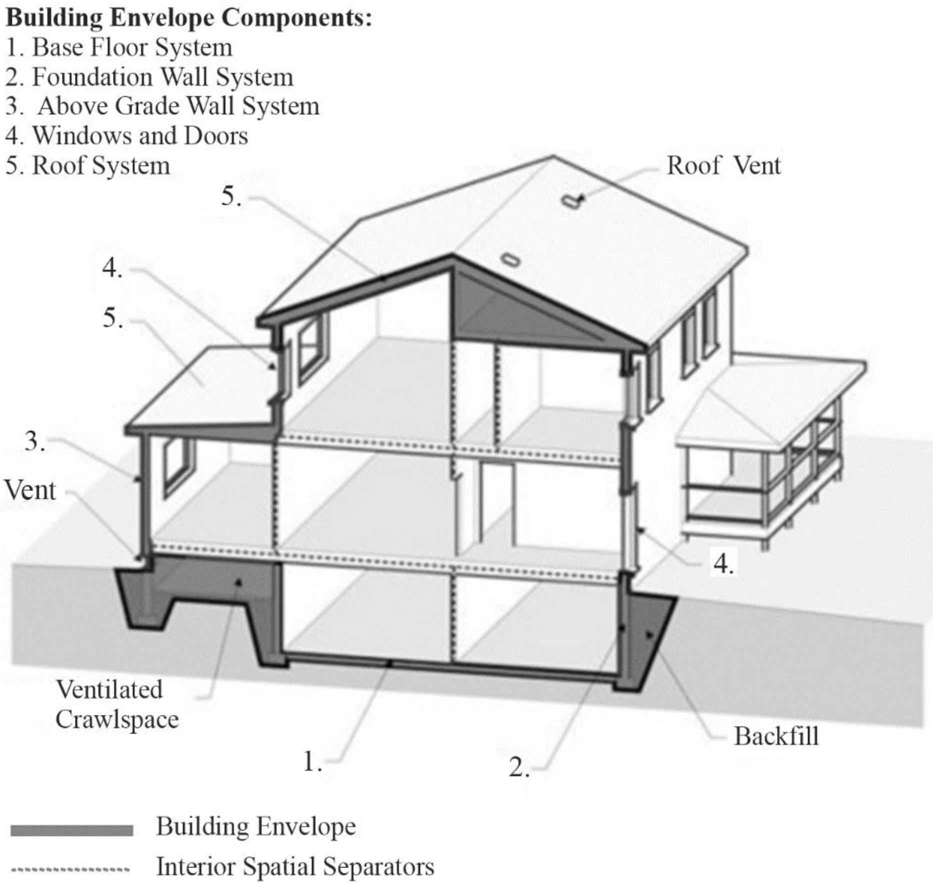

Figure 2.1 Building envelope components

Additionally, life cycle concerns for the engineering, construction, design of façade, installation, upkeep, and disassembly are essential for the development of envelope construction. Moreover, it is crucial to use a systematic and integrated strategy for design, engineering, building, and operation. High-performance facades are outside enclosures that utilize the least amount of energy feasible to provide a comfortable interior climate that supports building occupants' health and their wellbeing. High-performing facades, then, are not just barriers separating the internal and exterior environments, rather, they are building systems that actively respond to the exterior environment of the structure to produce comfortable interiors while considerably lowering the energy consumption of buildings (Gasparri, 2021). The components of the building envelope can be seen on Figure 2.1*.

* *Note:* Reprinted from "Building Science Digest 018 - The Building Enclosure", by J. Straube (2006) Retrived from:https://www.buildingscience.com/documents/digests/bsd-018-the-building-enclosure_revised#F01

2.2.Nearly Zero energy buildings

At the European level, energy consumption in buildings is a major concern. Buildings are thought to be responsible for 36% of greenhouse gas emissions and 40% usage of primary energy (D'Agostino, 2018). The idea of Zero Energy buildings is to decrease use of non-renewable energy in the building industry while generating enough renewable energy to cover their own annual energy needs. ZEBs include renewable energy systems that can produce enough energy to cover remaining needs while also reducing energy consumption through energy efficiency (Figure 2.2*). Moving toward ZEBs has several long-term benefits, such as fewer negative effects on the environment, lower operating and maintenance costs, improved resilience to power outages and natural disasters, and increased energy security (Peterson, 2016).

Figure 2.2 Near Zero Energy Building goals

The 2030 Climate & Energy framework has set new goals in addition to the 2007 Climate and Energy package's 20% reduction in building primary energy consumption by 2020, 20% increase in renewable energy production, and 20% reduction in greenhouse gas emissions from 1990 levels (D'Agostino, 2018). This package fixes the share of renewable energy at 27%, the decrease in greenhouse gas emissions from 1990 levels at 40%, and the increase in energy efficiency at 27%. Finally, the European Roadmap 2050 seeks to cut greenhouse gas emissions by at least 80% from 1990 levels by 2050 (Lu, 2015).

Over the past ten years, new policies have introduced technical and regulatory measures to support a more sensible use of energy. Their adoption led to an increase in energy savings in buildings in Europe. The establishment of Nearly Zero Energy Buildings (NZEBs) as the new

* *Note*: Reprinted from "Park City Passes Resolution to Adopt Net-Zero Energy Performance Requirements for Municipal Buildings and Facilities" by: C. Peterson (2017)
Retrived from: https://www.parkcity.org/departments/sustainability/energy-efficiency/net-zero-buildings

building target is a crucial measure aimed at lowering energy consumption in buildings (Kylili, 2015).

However, each country has its own definitions for “nearby” and the primary energy source that will be used in the numerical performance indicator (total, non-renewable, or renewable). In order to cut energy use and stimulate indoor comfort, a building energy management and control prototype system must be defined and implemented in accordance with NZEB guidelines. Starting with a strong dynamic model representative of the building’s energy performances (using the commercial energy simulation model software), a dynamic simulation-based control system for a building could predict a scenario representative of the future real building conditions and an optimization process to determine the best configuration for the control parameters. The various scenarios are influenced by the weather, the site’s location, the building’s structure, shape, and elements, as well as occupant behavior.

2.3. Introducing building performance simulation tools (BPSTs)

Building performance modelling tools are being utilized more and more to forecast a building’s performance, including how much energy it will use, how it will affect its occupants, and how it will affect its surroundings. Programs for simulating energy performance are effective instruments for evaluating thermal comfort and energy performance over the course of a building’s life.

There are many such tools available today, and they vary greatly in terms of their thermodynamic models, graphical user interfaces, purposes of use, relevance to life cycles, and the capacity to share data with other software programs. The majority of the thermal simulation software contains an “engine” that allows thorough thermal simulations based on basic text-based input and output files. According to the engine’s underlying concept, these engines feature mathematical and thermodynamic methods that are utilized to calculate their energy performance. The graphical user interface, which makes it easier to create input and analyze output and shows the user the functionality of the engine, is crucial for the practical use of these tools. However, simple user interfaces do not make energy analysis available to everyone; understanding thermal processes and the program’s limitations is necessary for generating and comprehending precise and accurate simulation results. Additionally, the graphical user interfaces serve different purposes and typically do not make full use of the related engine's functionality (Maile, 2007) (Figure 2.3*).

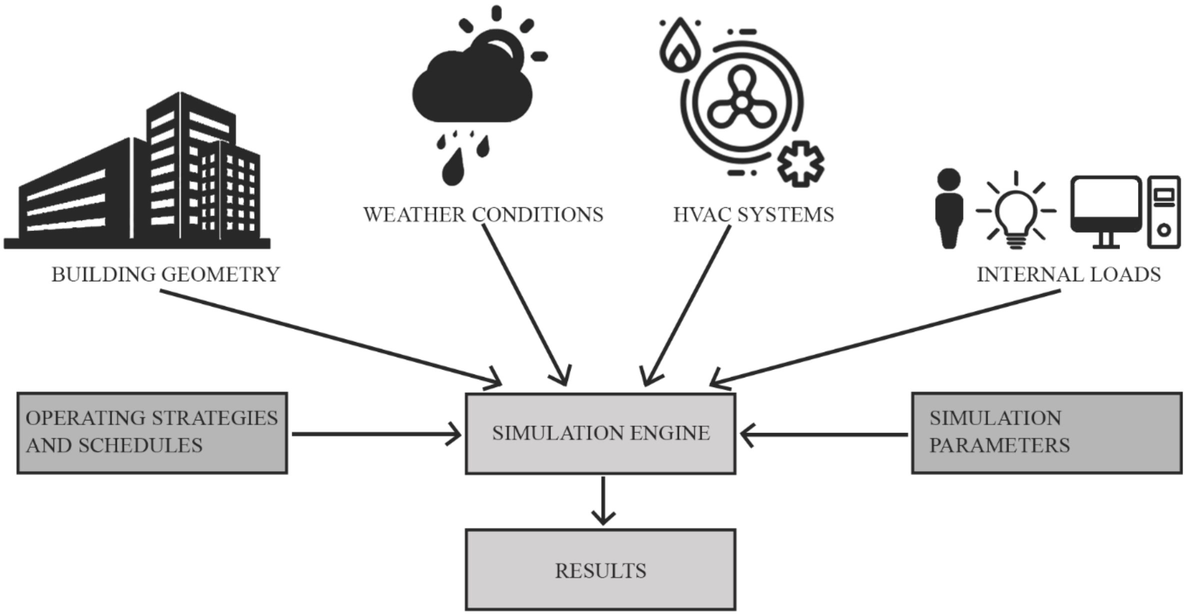

Figure 2.3 Data flow using simulation engines

These tools are typically created to be used during the design stage of the life cycle of a building, however, more recent innovations enable a wider use throughout all stages of a building's life. The two types of software programs that are mainly used today are the design software programs and the simulation software programs. For example, to enable the selection of the HVAC equipment size, design tools base their calculations on the worst-case scenario. The size of the HVAC system is typically determined by the extreme summer and winter design days for the building in question. Typically, they are founded on static calculations. The annual energy performance of a building and its HVAC system is predicted by annual simulations. They typically have a sizing function, but they can forecast how the energy consumption of various design options will differ. Based on various thermodynamic equations, they frequently include dynamic calculations (Maile, 2007).

* *Note*: reprinted from "Development of a Building Data Model for a Performance-Based Optimization Environment", by: N. Ghiassi, retrived from: https://www.researchgate.net/publication/263138765_Development_of_a_Building_Data_Model_for_a_Performance-Based_Optimization_Environment

2.3.1. Five major challenges of the Building Performance Simulation Tools

Building thermal performance was the focus of the initial foundational research for building simulation in the 1960s and 1970s, which also addressed load calculation and energy analysis (Kusuda, 1999). The focus shifted from energy consumption to many other aspects of building performance at the start of the 1990s. One such instance is integrated modeling, which considered the performance's visual and acoustic, air flow, heat and mass transfer, and other factors. This change resulted in the creation of a relatively wide range of fully functional tools. The building design profession underwent four significant changes as a result of the maturation of building simulation: diversifying tool users, emphasizing the entire design team more, adapting the tools to early and late design phases, developing a wide range of functionally complete tools, expanding the number of tools, and localizing the tools' capabilities. The first significant change was the tendency to promote the use of BPS tools by the entire design team. A wider view of BPS has been developed as a result of the increased complexity of the building delivery process, which has increased the user base (Attia, 2010).

The criteria and needs of BPS tools have been the subject of numerous studies and surveys conducted in the past. Some of the most influential studies were: DOE sponsored Workshops (1995 and 1996), a study by Tianzhen Hong identify the vital capabilities of BPS Tools (2000), Augenbroe in his paper addressed the option of interoperability between programs (2002), Lam conducted a study that involves the development of a comprehensive classification schema for comparing five tools and running a comparative analysis (2004) etc. (Attia, 2010).

The results from these studies lead the researcher S. Attia to categorize the Building Performance Simulation Tools into five categories:

I. Usability and Information Management (UIM) of interfaces,
II. Integration of Intelligent design Knowledge-Base (IIKB),
III. Accuracy of tools and Ability to simulate Detailed and Complex and building Components (AADCC),
IV. Interoperability of Building Modelling (IBM),
V. Integration with Building Design Process (IBDP).

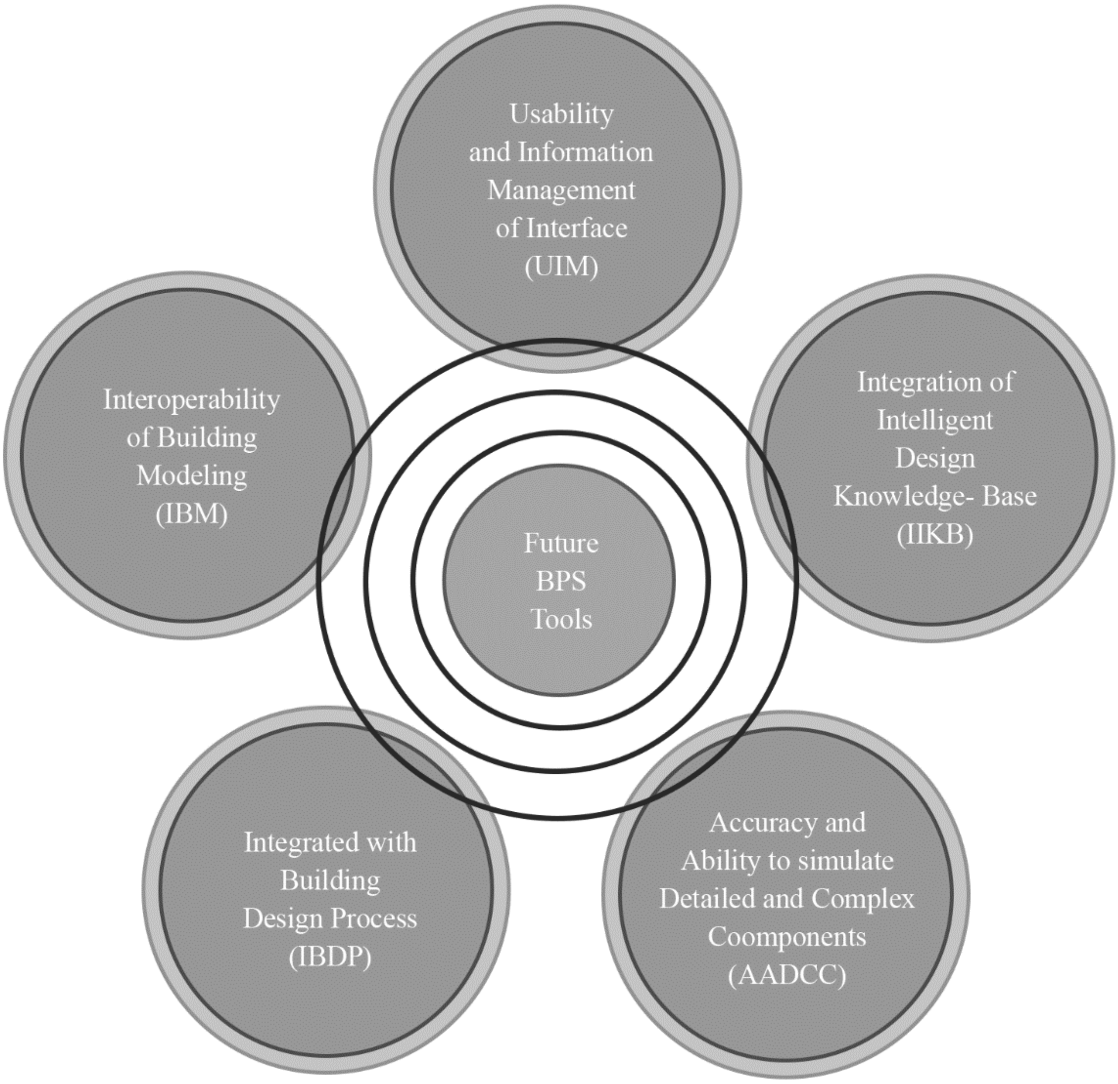

Figure 2.4 The five selection criteria of the BPSTs

Figure Figure 2.4* shows the categories for BPSTs selection.

2.3.2. User survey

Following up the previous chapter and literature review done by S. Attia, two user surveys were constructed following the five selection criteria of the BPSTs. The survey questionnaire's structure was based on the criteria for tool selection. The questionnaire's goal was to gather information from beginner simulation tool users who are interested in sustainable building design, including architects, engineers, designers, and recent graduates.

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* Note: reprinted from "Building Performance Simulation Tools: Selection Criteria and User Survey" by: S. Attia , retrived from: https://www.researchgate.net/publication/339273591_Building_Performance_Simulation_Tools_Selection_Criteria_and_User_Survey

The participants were put in two major groups: architects and engineers, and the number of participants was taken into consideration to be as similar as possible (Figure 2.5*). The paper provides also a comparison of ten major BPS tools: ECOTECT, HEED, Energy 10, Design Builder, eQUEST, DOE-2, Autodesk Green Building Studio, IES VE, EnergyPlus and Open Studio.

Question I :" How do you describe your current position?"

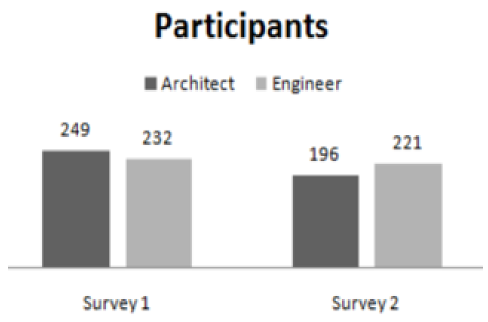

Figure 2.5 Number and occupation of responders

Question II:" What CAD/3D modelling software do you use?"

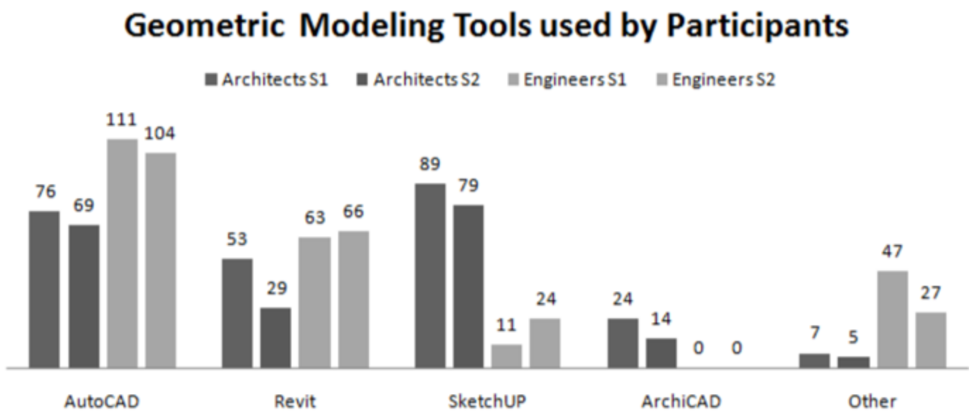

Figure 2.6 BIM tools used by the responders

The response to this question reveals a notable distinction between architects and engineers. Different tools are used by the two groups for geometric modeling. Architects prefer SketchUp over CAD software, while engineers prefer CAD programs as seen on Figure 2.6*.

* Note: reprinted from "Building Performance Simulation Tools: Selection Criteria and User Survey" by: S. Attia , retrived from: https://www.researchgate.net/publication/339273591_Building_Performance_Simulation_Tools_Selection_Criteria_and_User_Survey

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Question III: "What of the following energy simulation tools do you use?"

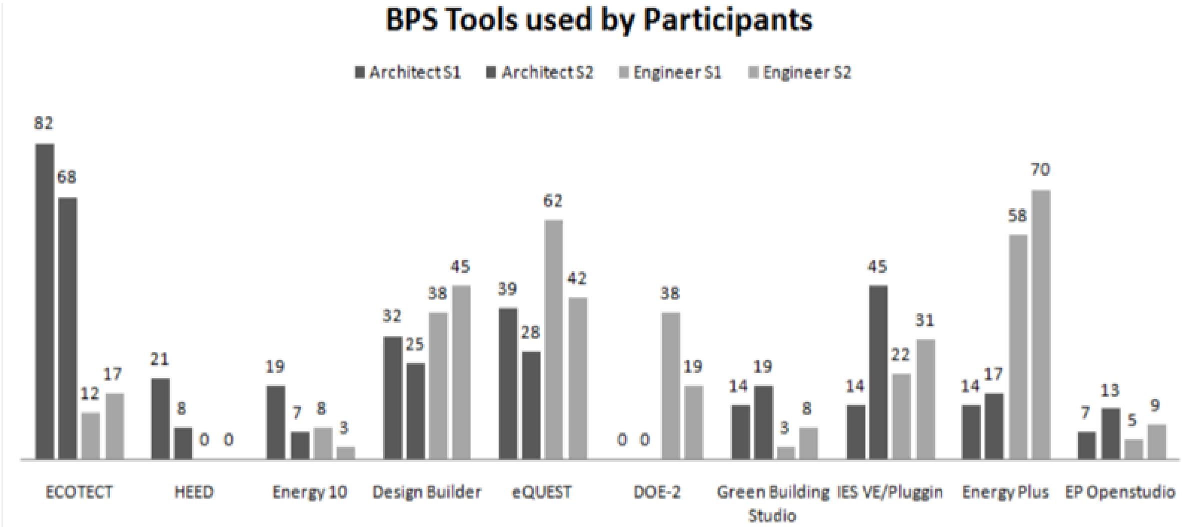

Figure 2.7 BPSTs used by the responders

As shown in Figure 2.7*, the majority of architects often used ECOTECT, eQUEST, Design Builder and IES plug-in. However, the majority of engineers have used eQUEST, EP OpenStudio, DOE-2, IES Plug-in.

Question IV: " How many tools do you use when performing simulations for a project?"

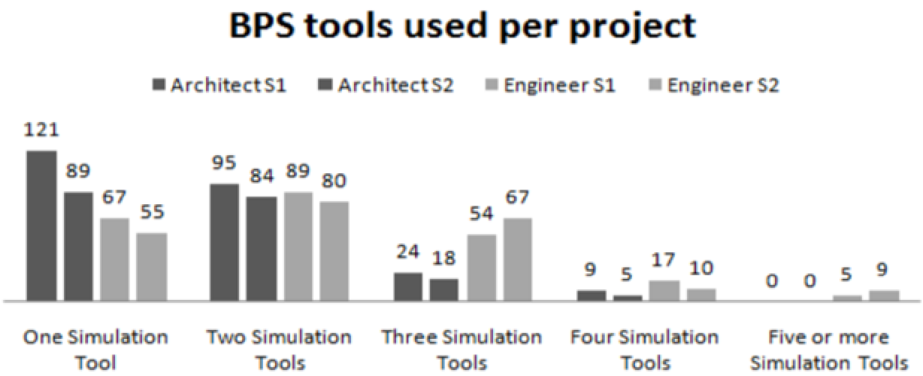

Figure 2.8 Number of BPSTs used per project according to the responders

The majority of architects (49% in the first survey and 45% in the second survey) only use one tool per project. However, a sizable portion of the responders (38% and 43%) use two instruments. On the other hand, 38% and 36% of engineers respectively use at least two BPS tools for each project. In the initial survey, 29% of respondents confirmed using just one tool,

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* Note: reprinted from "Building Performance Simulation Tools: Selection Criteria and User Survey" by: S. Attia , retrived from: https://www.researchgate.net/publication/339273591_Building_Performance_Simulation_Tools_Selection_Criteria_and_User_Survey

while 10% confirmed using three tools. In the second survey, 30% of respondents confirmed using three tools, while 25% said they only used one tool for each project (Figure 2.8*).

There is justification for using a simulation tool among architects. This may be because BPS tools are typically used less frequently and only in the initial stages of design by architects. Building services engineers, on the other hand, use tools during various design phases, are more familiar with BPS tools, and rely more on them for issues related to thermal energy calculation, systems sizing, and energy compliance.

Question V: "For which design phase would you use the following programs?"

Table 2-1 Ranking the tools according to design phases

	Pre-conceptual	Schematic Design	Design Development	Design Optimization (CD)
HEED	38	7	0	0
Energy 10	56	6	0	0
GBS	34	18	0	0
ECOTECT	86	107	13	0
eQUEST	56	110	67	9
DB	0	77	84	87
EP SU	0	4	23	27
EP	0	0	43	45
DOE-2	0	0	15	19

The typical usage phases for each of the ten tools are shown in Table 2-1*. There was no distinction in classification between engineers and architects. Early design tools that might be used during the pre-schematic design phases included HEED, Energy 10, and GBS. These were followed by ECOTECT and eQUEST, which are categorized for use during the schematic design phase. When it comes to comprehensive tools for in-depth analysis during the design development and design optimization phases, DB, EP SU, EP, and DOE-2 were considered.

* Note: reprinted from "Building Performance Simulation Tools: Selection Criteria and User Survey" by: S. Attia , retrived from: https://www.researchgate.net/publication/339273591_Building_Performance_Simulation_Tools_Selection_Criteria_and_User_Survey

Question V: "For which design phase would you use the following programs?"

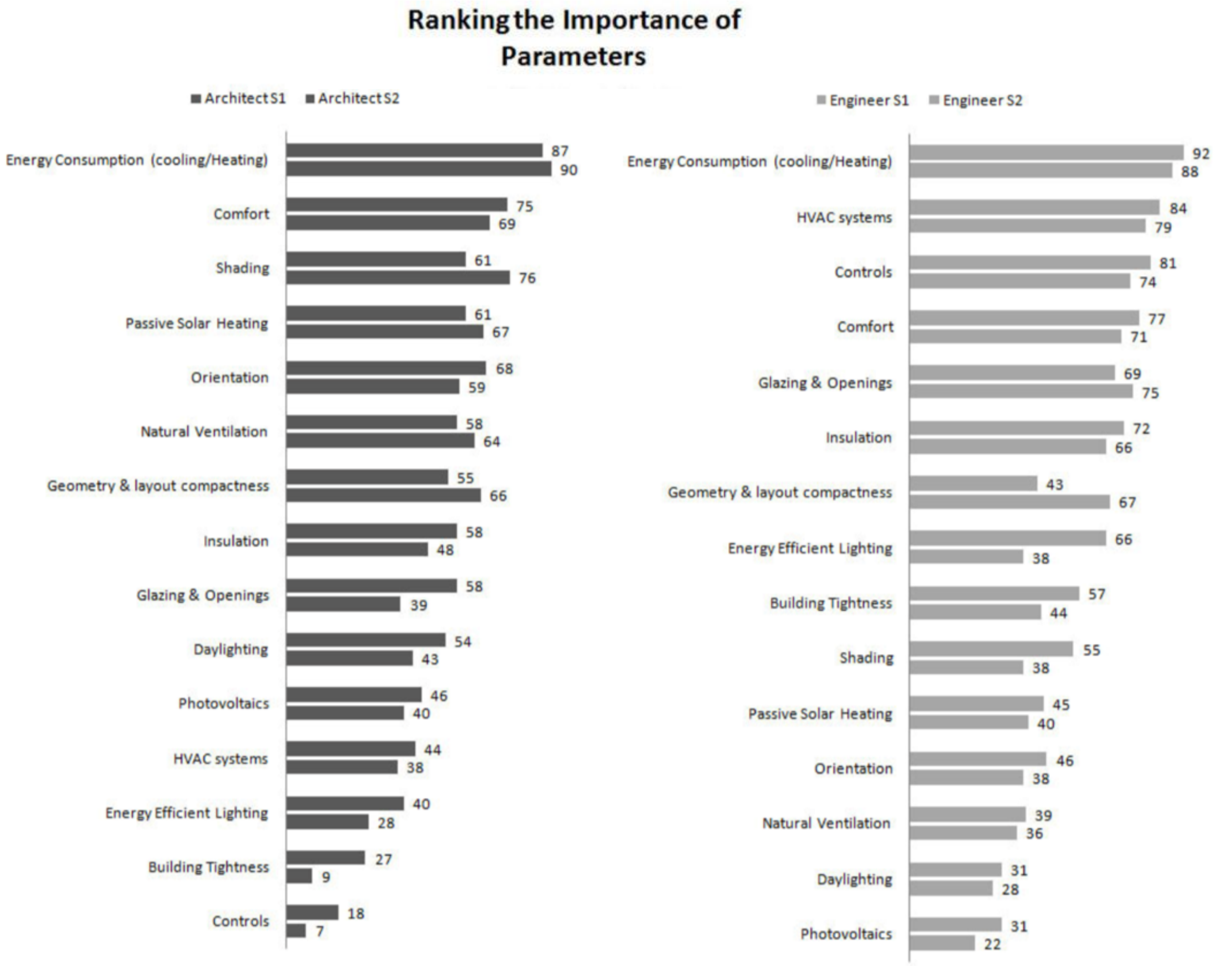

Figure 2.9 Ranking the importance of output parameters

For architects, the categories 2 through 6 were occupied by comfort, shading, passive solar heating, orientation, and natural ventilation. Building tightness, controls, and energy-efficient lighting were the three least significant factors. Engineers, on the other hand, placed energy consumption, HVAC systems, controls, comfort, glazing, and openings in the top five. The three least significant factors were photovoltaic, daylighting, and natural ventilation. A common finding was that both groups ranked comfort at the top of their lists. Surprisingly, the rankings of Controls and HVAC systems showed the biggest difference. Despite giving the energy consumption parameter priority, engineers placed them at the top of the list and architects placed them at the bottom (Figure 2.9*).

* Note: reprinted from "Building Performance Simulation Tools: Selection Criteria and User Survey" by: S. Attia , retrived from: https://www.researchgate.net/publication/339273591_Building_Performance_Simulation_Tools_Selection_Criteria_and_User_Survey

2.3.2.1. Visualizing the user survey results regarding the five major challenges

“Part I - USABILITY and GRAPHICAL VISUALIZATION of the interface”

Question 1: “Indicate how important you think each of the following objectives is, concerning USABILITY and GRAPHICAL VISUALIZATION of the interface”

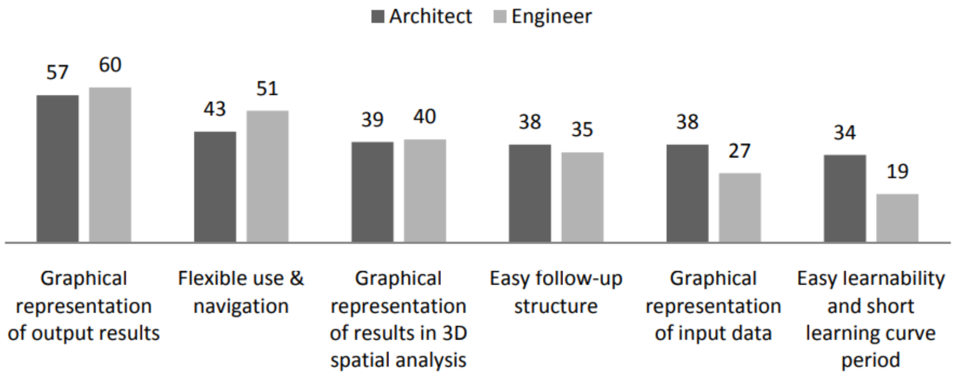

Figure 2.10 Ranking criteria concerning usability and graphical visualization of BPS interfaces

As seen in Figure 2.10*, 23% of architects and 26% of engineers concurred that the most crucial aspect of the usability and graphical visualization of the interface is the graphical representation of the output results. There was also agreement that the graphical representation of the results in 3D spatial analysis (16% architects and 17% engineers) is the second most important feature, followed by the flexible use and navigation (17% architects and 22% engineers). Unexpectedly, both groups concurred that the simulation tools' ease of use and short learning curve are the least important features.

Question 2: “Which tool(s) fulfill the following criteria?”

Table 2-2 Ranking criteria concerning the capabilities of the BPSTs regarding usability and graphical visualization

	IES VE	ECOTECT	Design Builder	eQUEST	Green Building Studio	HEED	Energy 10	Energy + SketchUp	DOE-2	Energy +
Graphical representation of output results	✓	✓	✓	✓	✓	✓	✓	☒	☒	☒
Flexible use & navigation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Graphical representation of results in 3D spatial analysis	✓	✓	☒	☒	☒	☒	☒	✓	☒	☒
Easy follow-up structure	✓	☒	✓	✓	✓	✓	✓	☒	✓	✓
Graphical representation of input data	✓	✓	✓	✓	✓	☒	☒	✓	☒	☒
Easy learnability and short learning curve period	☒	✓	✓	✓	✓	✓	✓	☒	☒	☒
USABILTIY & GRAPHICAL VISULAISATION OF THE TOOL (%)	87%	85%	85%	85%	85%	70%	70%	50%	35%	35%

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* Note: reprinted from “Building Performance Simulation Tools: Selection Criteria and User Survey” by: S. Attia , retrived from: https://www.researchgate.net/publication/339273591_Building_Performance_Simulation_Tools_Selection_Criteria_and_User_Survey

"Part II - Integration of KNOWLEDGE-BASE"

Question 1: "Indicate how important you think each of the following objectives is, concerning Integration of Knowledge-Base"

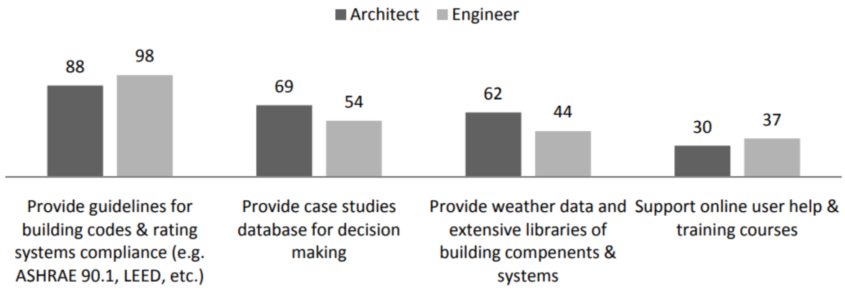


Figure 2.11 Ranking criteria concerning the integration of Knowledge-base systems in BPS tools

An agreement between architects and engineers is depicted in Figure 2.11*. The ability to offer guidelines for compliance with building codes and rating systems was cited by both groups as the most crucial component of BPS tools. The capacity to provide a database of case studies for decision-making came in second. The outcome is not unexpected, and both disciplines share an understanding of how to integrate knowledge bases.

Question 2: "Which tool(s) fulfil the following criteria?"

Table 2-3 Ranking criteria concerning the capabilities of the BPSTs the integration of Knowledge-base systems in BPS tools

	HEED	IES VE	eQUEST	Green Building Studio	Energy 10	Design Builder	Energy +	ECOTECT	Energy + SketchUp	DOE-2
Provide guidelines for building codes & rating systems compliance	✓	✓	✓	☒	☒	☒	☒	☒	☒	☒
Provide case studies database for decision making	✓	☒	☒	☒	☒	☒	☒	☒	☒	☒
Provide weather data and extensive libraries of building compenents & systems	☒	✓	✓	✓	✓	✓	✓	✓	✓	☒
Support online user help & training courses	✓	✓	✓	✓	✓	✓	✓	✓	☒	✓
INTEGRATION OF KNOWLEDGE-BASE (%)	75%	72%	72%	37%	37%	37%	37%	37%	25%	12%

* Note: reprinted from "Building Performance Simulation Tools: Selection Criteria and User Survey" by: S. Attia , retrived from: https://www.researchgate.net/publication/339273591_Building_Performance_Simulation_Tools_Selection_Criteria_and_User_Survey

“Part III – ACCURACY of the tools”

Question 1: “Indicate how important you think each of the following objectives is, concerning tools ACCURACY”

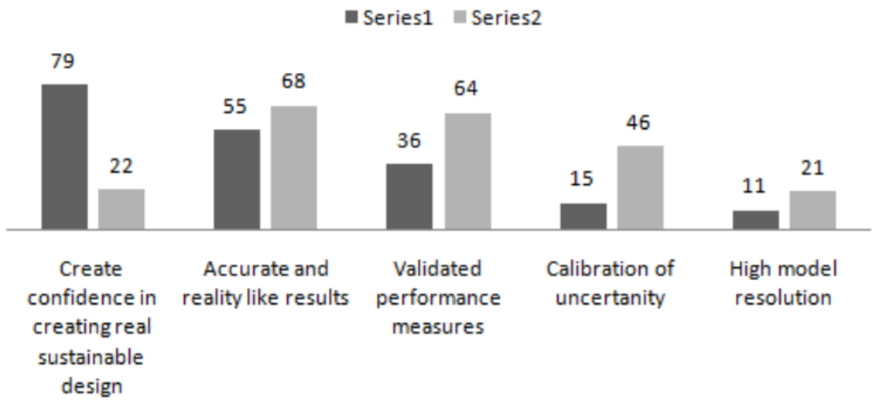


Figure 2.12 Ranking criteria concerning tools accuracy

Figure 2.12* demonstrates the priorities for every group. The ability to produce genuine sustainable design was architects' top preference (40%) in this category. On the other hand, the majority of engineers (31%) concurred that accurate and realistic results are the most crucial aspect of tools’ accuracy.

Question 2: “Which tool(s) fulfil the following criteria?”

Table 2-4 Ranking criteria concerning the capapbilities of the BPSTs tools accuracy

	eQUEST	Design Builder	Energy +	IES VE	Energy + SketchUp	DOE-2	HEED	ECOTECT	Green Building Studio	Energy 10
Confidence in creating real sustainable design	✓	✓	✓	✓	✓	✓	☒	☒	☒	☒
Accurate and reality like results	✓	✓	✓	✓	✓	✓	☒	☒	☒	☒
Validated performance measures	✓	✓	✓	✓	✓	✓	☒	☒	☒	☒
Calibration of uncertanity	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒
High model resolution	✓	✓	✓	☒	✓	✓	☒	☒	☒	☒
ACCURACY AND RELIABILITY (%)	80%	80%	80%	60%	80%	80%	12%	12%	12%	12%

* Note: reprinted from “Building Performance Simulation Tools: Selection Criteria and User Survey” by: S. Attia , retrived from: https://www.researchgate.net/publication/339273591_Building_Performance_Simulation_Tools_Selection_Criteria_and_User_Survey

"Part IV - INTEROPERABILITY of Building Model"

Question 1: "Indicate how important you think each of the following objectives is, concerning INTEROPERABILITY OF THE BUILDING MODEL"

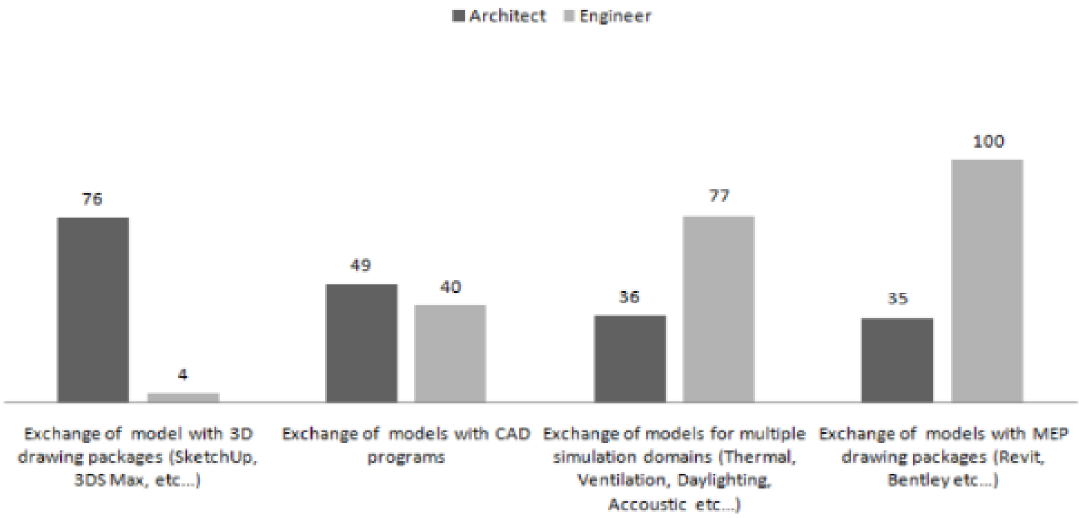


Figure 2.13 Interoperability sub criteria

Figure 2.13[*] illustrates the primary distinction between the needs and priorities of architects and engineers. Architects ranked the ability to exchange models with 3D drawing programs like SketchUp and 3DS Max first (39%). Engineers, on the other hand, prioritized various sub-criteria. The ability to exchange models with MEP drawing packages like Revit and Bentley products was the most crucial sub-criteria (45%).

Question 2: "Which tool(s) fulfil the following criteria?"

Table 2-5 Ranking criteria concerning the capabilities of the BPSTs tools interoperability

	IES VE	Design Builder	Energy + SketchUp	ECOTECT	Green Building Studio	Energy +	Energy 10	eQUEST	DOE-2	HEED
Exchange of building models for multiple simulation domains	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒
Exchange of building models with CAD programs	✓	✓	✓	✓	✓	☒	☒	☒	☒	☒
Exchange of building model with SketchUp	✓	✓	✓	✓	☒	✓	☒	☒	☒	☒
Exchange of building models with Revit	✓	☒	☒	☒	✓	✓	☒	☒	☒	☒
INTEROPERABILITY OF MODELS (%)	65%	53%	53%	53%	40%	37%	0%	0%	0%	0%

[*] Note: reprinted from "Building Performance Simulation Tools: Selection Criteria and User Survey" by: S. Attia , retrived from: https://www.researchgate.net/publication/339273591_Building_Performance_Simulation_Tools_Selection_Criteria_and_User_Survey

"Part V - MOST IMPORTANT features of a simulation tool"

Question 1: "What are the MOST IMPORTANT features of a simulation tool?"

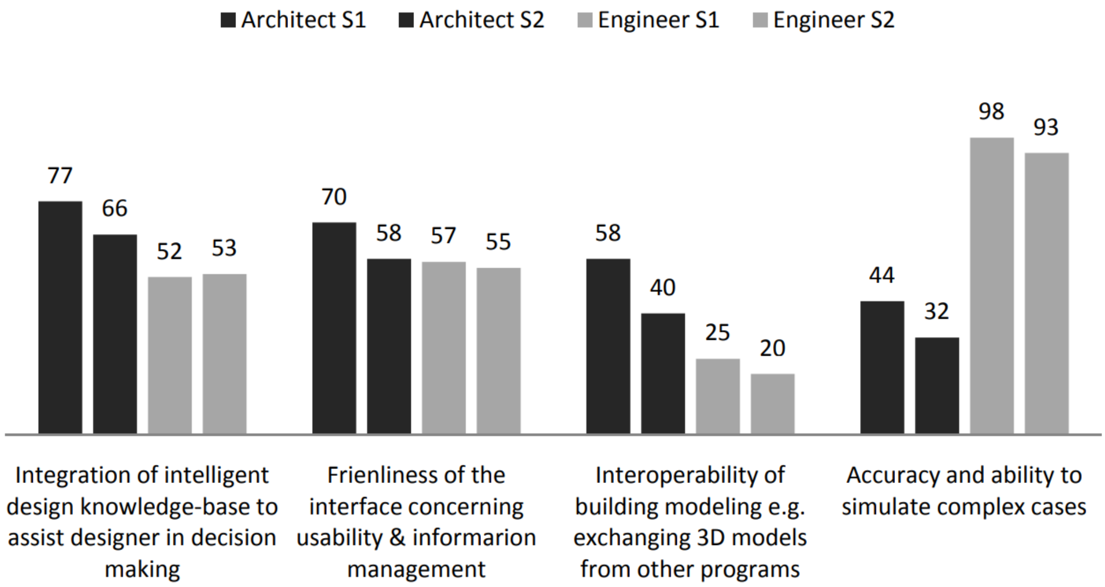


Figure 2.14 Ranking the most important features of a simulation tool

On Figure 2.14* the results from the fifth category can be seen, regarding which are the most important features of the tools used. The ability of the tool to integrate intelligent design knowledge-base to aid designers in decision-making was the most crucial factor for architects (31% and 34%). Surprisingly, this was more significant (28% and 30%) in terms of usability and information management than the friendliness of the interface.

Engineers, on the other hand, were ranked differently. The samples from both engineers agreed with one another. The accuracy of tools and the capacity to simulate complex elements were ranked first by engineers (42% and 42%). The friendliness of the interface with regard to usability and information management was the second most crucial factor (25 and 24%), followed by the tool's capacity to incorporate intelligent design knowledge-base to support designers in decision-making (22 and 24%).

* Note: reprinted from "Building Performance Simulation Tools: Selection Criteria and User Survey" by: S. Attia , retrived from: https://www.researchgate.net/publication/339273591_Building_Performance_Simulation_Tools_Selection_Criteria_and_User_Survey

Even though this survey is not written in recent years, it paints a clear picture of what the tools have to offer the users. The mentioned BPSTs have evolved over the years, offering the usera a wider viriety of option when it comes to predicting and analysing the building performance. Even though, these tools offer a much needed aid to the users, it is important to mention that they do not offer 100% accuracy in the results.

2.4. Building Information Modelling (BIM)

Building information modeling or building information management are both referred to as BIM. Thanks to this highly collaborative process that involves architects, engineers, real estate developers, contractors, manufacturers, and other construction experts, a structure or building can be planned, designed, and built within a single 3D model. To create complex digital renderings that are managed in an open cloud environment for real-time collaboration, BIM combines data from various disciplines. For AEC projects, using BIM enhances decision-making, provides more environmentally friendly options, and lowers costs. Traditional building design mainly utilized two-dimensional technical drawings (plans, elevations, sections, etc). Building information modeling (BIM), which also includes data on time, cost, asset management, sustainability, and other topics, extends the three fundamental spatial dimensions—width, height, and depth. BIM therefore extends beyond geometry. It also covers spatial relationships, geospatial information, quantities, and properties of building components (for example, manufacturers' details), enabling a variety of collaborative processes relating to the built asset from initial planning through to construction and then throughout its operational life.

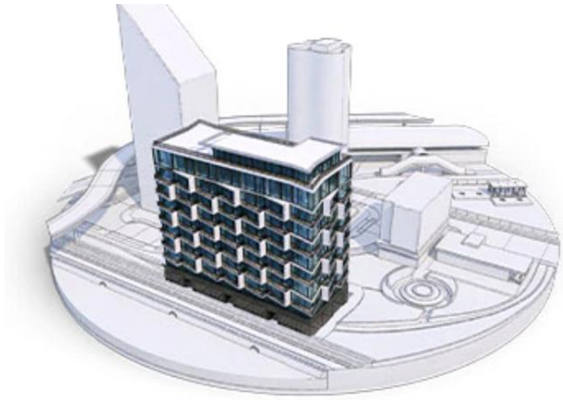
BIM enables the creation of multidimensional models that account for constraints on resources such as time, money, and materials as well as design and manufacturing data and aesthetic preferences. Even information-based real-time collaboration is supported. This information can be used to supply other cutting-edge technologies like city-sized models, augmented reality tools for use on construction sites, radio-frequency identification (RFID) tags to track components from manufacture to site, and even the use of 3D printers. BIM has a lot of benefits. One is that "collisions," or design elements that are incompatible and at odds with one another, can be found using BIM tools (Autodesk, 2022).

Plan [*]

In order to create context models of the current built and natural environments, reality capture and real-world data are combined.

Design

Conceptual design, analysis, detailing, and documentation are carried out during this phase. Scheduling and logistics are influenced by BIM data as the preconstruction phase gets underway.



Build

Fabrication using BIM specifications starts during this stage. To ensure the best timing and efficiency, project construction logistics are shared with tradespeople and contractors.

Operate

Operations and maintenance of finished assets use BIM data. Future cost-effective renovation or efficient deconstruction projects can also make use of BIM data.

Figure 2.15 The process of Building Information Modelling (BIM) [*]

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[*] Note: reprinted from “What are the benefits of BIM?” by: Autodesk official site
Retrived from: https://www.autodesk.com/industry/aec/bim/benefits-of-bim#:~:text=BIM%20integrates%20multi%2Ddisciplinary%20data,cost%2Dsavings%20on%20AEC%20projects.

There is currently no clear definition of what BIM is and is not. It is also difficult to predict what it might convert into.

BIM maturity is the transition from one level of BIM usage to another. There are already some traditional categories called "Levels" (Barnes, 2019). The following are these levels:

Level 0 - BIM is not actually being used at all. Only 2D CAD files are used for design and production data.

Level 1 - It represents design using 3D data. This level is also referred to as BIM alone. There may be many designers, but they don't work together. They are all working independently and only using their own models. There are some common data structures and formats used. Also available are some standalone financial and cost management software programs. However, they are never included in the main BIM model.

Level 2 - At this level, BIM benefits are applied. Managed 3D format is stored with data in separate BIM discipline software tools. Utilizing COBie (Construction Operations Building Information Exchange) is another important trait. The creation of guidelines for data sharing and party cooperation is required by this information exchange. It might also make the first steps toward cost or sequencing data for construction.

Level 3 - Real-time project models at are said to be fully integrated and collaborative. Web services are likely to make this model easier. BuildingSMART Data Dictionary/emerging Industry Foundation Classes (IFC) standards will be followed. At this level, software interoperability will be required. Additionally, infrastructure and legal barriers will exist for BIM. The development of standardized object data libraries, which will include manufacturer information, will be the driving force behind BIM models at this level, which will make use of construction sequencing, cost information, project life cycle, and other management information (Barnes, 2019).

2.4.1. List of BIM software programs used by the AEC industry

- **Document Management**

Autodesk BIM 360

- **Planning & Design**

Autodesk Revit Architecture
Graphisoft ArchiCAD
Nemetschek Allplan Architecture
Nemetschek Vectorworks Architect
Gehry Technologies – Digital Project Designer
Bentley Architecture
4MSA IDEA Architectural Design (IntelliCAD)
CADSoft Envisioneer
Softtech Spirit
RhinoBIM

- **Sustainability**

Autodesk Ecotect Analysis
Autodesk Green Building Studio
Graphisoft EcoDesigner
IES Solutions Virtual Environment VE-Pro
Bentley Tas Simulator
Bentley Hevacomp
DesignBuilder

- **Facility Management**

Bentley Facilities
FM:Systems FM:Interact
Vintocon ArchiFM (For ArchiCAD)
Onuma System
EcoDomus

- **Structures**

Autodesk Revit Structure
Bentley Structural Modeler
Bentley RAM, STAAD and ProSteel
Tekla Structures
CypeCAD
Graytec Advance Design
StructureSoft Metal Wood Framer
Nemetschek Scia
4MSA Strad and Steel
Autodesk Robot Structural Analysis

- **Mechanical, Electrical, and Plumbing (MEP)**

Autodesk Revit MEP
Bentley Hevacomp Mechanical Designer
4MSA FineHVAC + FineLIFT + FineELEC + FineSANI
Gehry Technologies – Digital Project MEP Systems Routing
CADMEP (CADduct / CADmech)

- **Construction (Simulation, Estimating and Construction Analysis)**

Autodesk Navisworks
Solibri Model Checker
Vico Office Suite
Vela Field BIM
Bentley ConstructSim
Tekla BIMSight
Synchro Professional
Innovaya

Figure 2.16 List of BIM software programs used by the AEC industry

In Figure 2.16 a list of the available BIM software programs on the market can be seen, and they are categorized by their capabilities and what they offer for the architecture, engineering and construction sectors (Brito, 2018).

2.5.Building Energy Model (BEM)

BEM is software that simulates building energy use based on physics. A BEM program accepts input information about a building's geometry, building materials, lighting, HVAC, refrigeration, and water heating system configurations, as well as component efficiencies and control methods. It also collects details about how the building is used, such as occupancy schedules, lighting requirements, plug loads, and thermostat settings. The thermal loads, system response to those loads, and resulting energy use, along with related metrics like occupant comfort and energy costs, are calculated by a BEM program using these inputs and local weather data. BEM programs execute calculations on an hourly or shorter basis for an entire year. They also consider system interactions, such as those between heating and cooling and lighting (Office of Energy Efficiency and Renewable Energy, 2020). Applications for BEM make use of its capacity to respond to inquiries that are difficult to resolve through other channels. The following are significant use cases:

1. Design of Buildings: BEM is used by architects to create energy-efficient structures, specifically to inform quantitative trade-offs between initial construction costs and ongoing energy costs. BEM can frequently lower both energy costs and initial construction costs.
2. HVAC operations: Commercial building HVAC systems can be big and complex in terms of design and operation. BEM aids mechanical engineers in creating HVAC systems that effectively meet building thermal loads. It aids in the development and evaluation of control strategies for these systems.
3. Building Performance Rating: BEM can be used to evaluate a building's inherent performance while accounting for its intended use and mode of operation.
Processes like code compliance, green certification, and financial incentives are all based on inherent performance rating.

Building Stock Analysis: BEM analysis on prototype models aids in the development of energy codes and standards and aids in the development of large-scale energy-efficiency initiatives by utilities and local governments. Two of the most popular types of BEM software programs can be divided into 2 types: the first one using the calculation developed by the US Department of Energy (DOE-2) and the ones that use their own calculation engine.

Since the 1970s, DOE has encouraged the study, creation, and application of BEM and has also actively used it. The Building Technologies Office (BTO), a division of DOE, creates two important BEM software programs. EnergyPlus is a BEM engine which can model low-enegry building designs and HVAC systems and OpenStudio engine which is a software development kit (SDK) that simplifies the use of EnergyPlus, including a graphical interface (Office of Energy Efficiency and Renewable Energy, 2020).

2.5.1. Energy Analysis Model (EAM)

Before using any type of BEM software programs, a Energy Analysis Model (EAM) is created. There are many different types of BIM and BEM tools, however, no matter which tools are used for modelling, analysis and simulations, getting a valid Energy Analysis Model (EAM) is crucial. An Energy Analysis Model (EAM) is essentially an abstraction of a building's general shape and layout into a "computational network" that is capable of accurately capturing all the major paths and processes of heat transfer throughout the building. This phase, which is the one that follows the modelling methodology, is more concerned with energy issues and the export of those issues to the development of a real energy model (BEM). It demonstrates how the flow changes in the case of a simplified model planning, moving from the creation of the energy model to its export after first examining the dependability of the relevant data. The term "EAM," or "energy analysis model," refers to an abstraction of a building's form and structure in a "computational network" that is capable of fully encapsulating all the primary paths and processes of heat transfer inside the building. In essence, the EAM can be thought of as a bridge between the parametric BIM model created in Revit and the energy model (BEM) created later with an energy analysis tool (Molloy, 2013). In Figure 2.17, the connection from BIM to BEM can be seen throughout EAM.

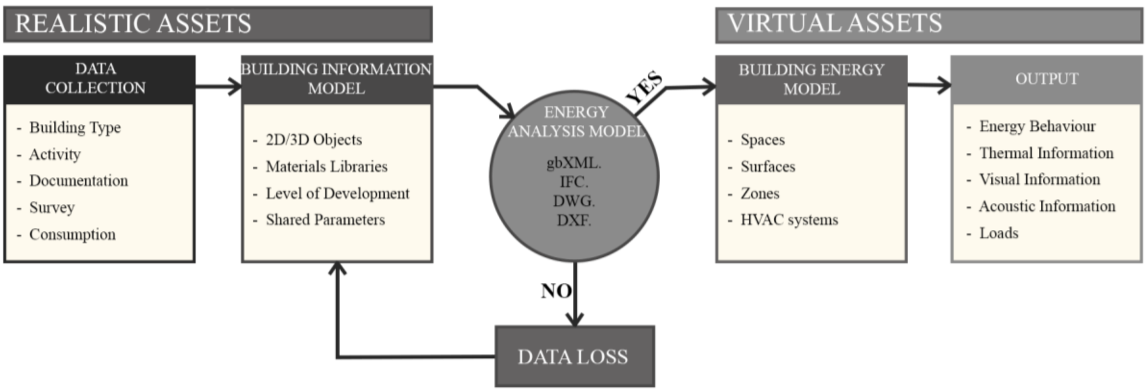

Figure 2.17 Workflow from BIM to BEM

A building's general shape and layout are essentially abstracted into an "energy analysis model" (EAM), which is able to precisely represent all of the main paths and processes of heat transfer throughout the building. Zones, surfaces, and spaces make up the three different types of components that make up general geometry. Spaces are distinct air volumes (really, masses) that exchange heat with other Spaces, the outside environment, as well as go through internal processes like occupants, lighting, equipment, and HVAC that cause heat gain or loss. For the transfer of heat into or out of each Space, including between interior spaces and the outside world, surfaces serve as conduits. Finally, Zones are groups of Spaces that are used to specify some shared characteristics, such as the same orientation, shared function, or shared HVAC system. EAMs are not inherently complex systems. They follow a particular set of fundamental principles and have a small number of parts and characteristics. The main challenge with EAMs has always been producing them consistently and reliably enough (Molloy, 2013) .

2.5.2. Capabilities of the BEM programs

BEM can be used at different points in the building lifecycle to enhance energy efficiency (Kim, 2013). Design experts can use BEM simulations during the design phase to evaluate the energy performance of various design options and choose the most effective design (Kim, 2013).

The capabilities, inputs, outputs, and applicability of current BEM tools are varied across the building lifecycle. The recommendations made by this study are intended to help prospective BEM users evaluate and choose the best BEM tool for the application they intend to use it for. In Figure 2.18*, it is shown what are the capabilities of the most used BEM software programs (Reeves, 2015). The list is constructed of various surveys done over the years, one of them is also the suer survey by S. Attia, mentioned previously (Attia, 2010).

* Note: reprinted from: "Guidelines for Using Building Information Modeling for Energy Analysis of Buildings" (2015)

Category	Phase	Item	eQuest	Green Building Studio	Design Builder	EnergyPlus	IES VE
Recommended required inputs	Conceptual Design	Building geometry	■	■	■	□	■
		Building orientation	■	■	■	■	■
		Weather file	■	■	■	■	■
		Building envelope constructions	■	■	■	■	■
		HVAC type	■	■	■	■	■
		Building type/ function	■	■	■	■	■
	Design Developement	Glazing type	■	■	■	■	■
		Lighting power density	■	■	■	■	■
		Equipment power density	■	■	■	■	■
		Ocupancy schedule	■	□	■	■	■
		Lighting schedule	■	□	■	■	■
		Equipment schedule	■	□	■	■	■
		Fuel type	■	□	□	■	■
		Operable windows	■	□	■	■	■
		Operable window schedule	■	□	■	■	■
		System energy efficiency	■	□	□	■	■
		Roof reflectance	■	□	□	■	■
	Construction Documents	User- defined glazing specifications	□	□	■	■	■
		User- defined envelope construction layers/ properties	■	□	■	■	■
	Construction and Contracting	MEP BIM model	□	□	□	□	■
		Water efficient fixtures	■	□	□	□	■
		HVAC component sizing	□	□	□	■	■
	Facilities Management	Costomizable occupancy schedule	■	□	□	■	■
		Costomizable lighting schedule	■	□	□	■	■
		Costomizable equipment schedule	■	□	□	■	■
		Plant data	□	□	□	■	■
		HVAC fan power	■	■	□	■	■
		Required interior design temperatures	■	□	□	■	■
		Energy costs	■	■	□	■	■
Outputs		Energy analysis	■	■	■	■	■
		Daylight analysis	■	■	■	■	■
		Natural ventilation analysis	■	■	■	■	■
		Passive energy potential	■	□	□	■	■
		LEED credit assistance	□	■	■	□	■
		Design alternatives	□	■	□	□	□
		Carbon emissions	■	■	■	■	■
		Resource management	□	■	□	□	■
		Thermal analysis	■	□	■	■	■
		Heeting/ cooling load breakdown	■	■	■	■	■
		Solar analysis	■	□	■	■	■
		Electric lighting design	□	□	□	□	■
		Lifecycle cost analysis	■	■	□	■	■
		Water usage	■	■	□	■	□

Figure 2.18 Guidelines for BEM tool evaluation and selection

2.6.BIM and BEM interoperability

The use of the computer to foresee building performance has increased, and BIM is one method for supplying both geometric data and other properties of the virtual building. Even though BIM is now frequently used in architecture firms for the 3D modelling of buildings and creation of construction documents, the transfer of the 3D data to other software programs is not always simple or complete. As a result, there is a disconnect between the design development and the energy analysis of various design choices. As an outcome, the architect's early selection of energy-conscious design strategies might not be utilized to their fullest extent. BIM is particularly helpful because architecture firms frequently have access to a digital building that they can use. It can also be later given to consultants as a starting point for more intricate energy calculations (Hijazi, 2015).

The ability of software applications to communicate, exchange, and use data is known as interoperability, but achieving it between BIM and BEM is not an easy task. Between BIM authoring tools (Revit, ArchiCAD, etc.) and the building performance simulation (BPS) tools (IES-VE, EnergyPlus, etc.), data exchange schema may serve as the intermediary (Abanda, 2016).

2.6.1. Data conversion methods

The industry foundation class (IFC) and the green building extensible markup language are two widely used schemas (gbXML). In the context of the entire AEC industry, IFC aims to facilitate information sharing and process improvement throughout the entire building life cycle (Dong, 2007). Despite being extensive and detailed, it is difficult to use. There is still a lot of redundant information for energy simulation, both geometrically and semantically, even though it may take the form of different phases, levels of details, or definitions of model views. On the other hand, gbXML was primarily created to make the conversion of data from BIM to BEM easier. Both its geometric and semantic data structures are compliant with the specifications of the simulation engine. As seen on Figure 2.19* and Figure 2.20, in contrast to gbXML, which only accepts surfaces represented by boundary loops and thus does not contribute to B-rep spaces, IFC supports sweep volume, constructive solid geometry, and boundary representation (B-rep).

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* Note: reprinted from "A gbXML Reconstruction Workflow and Tool Development to Improve the Geometric Interoperability between BIM and BEM" by: Y. Yang, Y. Pan, F. Zeng, C. Li, (2022)
Retrived from: https://www.mdpi.com/2075-5309/12/2/221#

There are two gbXML modeling conventions: one without gaps that follows the manual modeling convention and chooses the wall center line as the boundary for thermal zones; the other with gaps between spaces that comes from BIM, which already has the surface-matching data stored (Figure 2.24) *. Mathematical models using these two conventions are identical, apart from the bias in the surface area (Donkers, 2013).

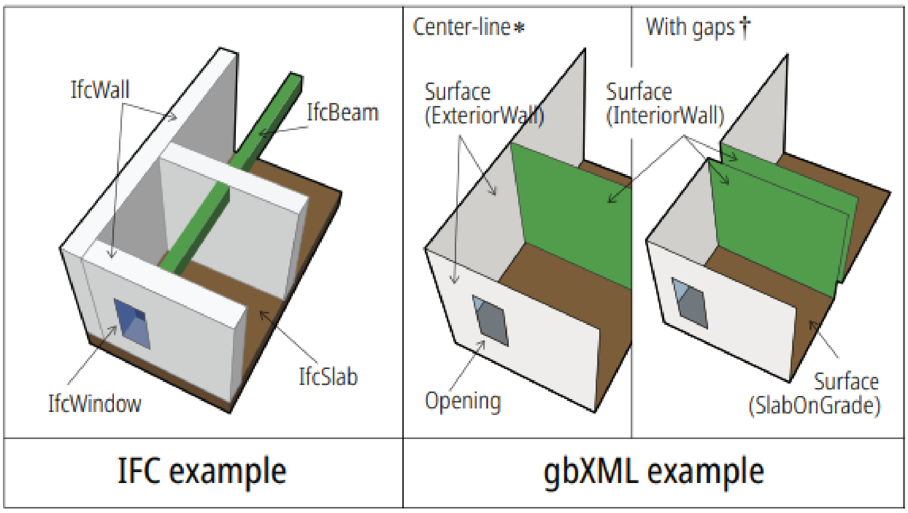

Figure 2.19 Different geometry representations by IFC and gbXML, an example. (*) Modelled by wall centre line (without gaps). (†) Modelled by wall faces (with gaps)

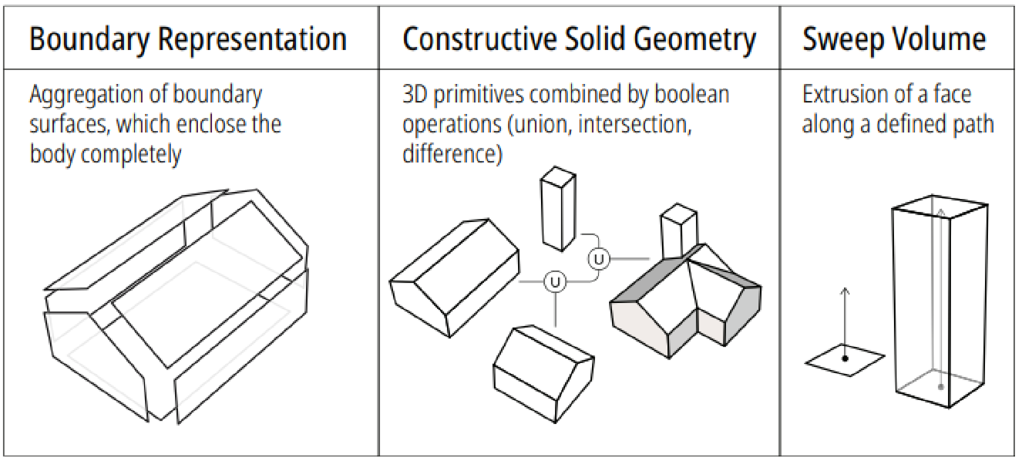

Figure 2.20 Three types of geometry representation in IFC

* Note: reprinted from "A gbXML Reconstruction Workflow and Tool Development to Improve the Geometric Interoperability between BIM and BEM" by: Y. Yang, Y. Pan, F. Zeng, C. Li, (2022)
Retrived from: https://www.mdpi.com/2075-5309/12/2/221#

Over many years, software from both academic and commercial sources as well as common data exchange schemas like IFC and gbXML have supported interoperability. The exchange schema serves as the foundation for BIM and BEM authoring tools. This schema-centered system requires that all software explicitly exchange its data with a single BIM document. This architecture is applicable to conventional BEM authoring tools, the majority of which have their own simulation engine and combine modeling and simulation on the same platform. Thus, the degree to which the BIM is accepted and documented (by the BIM authoring tool) determines the geometry interoperability (by the BEM authoring tool). The modeler must iteratively revise the geometry before exporting it to BEM for verification when the transformation error coming from either BIM export or BEM import is unknown. Another ecosystem built around specific computer-aided design (CAD) software has grown in popularity as a means of easing the iterative manual fix on geometry models. Even without IFC or gbXML, the logic of geometry exchange remains the same, albeit more implicitly. A good illustration is Autodesk Revit, which incorporates GBS (based on DOE-2) and Insight as two cloud services on BPS (based on EnergyPlus) (Autodesk, 2021).

2.6.2. Possible workflows

After the literature review regarding BIM and BEM software programs, in the previous chapters, it can be understood that specific programs accept either IFC or gbXML file format. Furthermore, some of the optional workflows that are constructed are:

1. Revit → Make analytical model → Export as .IFC / .gbXML → Design Builder, Green Building Studio, IES VE, EDSL - TAS
2. Revit → Make analytical model → Export as .gbXML → Import to Green Building Studio and convert to .inp → eQuest
3. Revit → Make analytical model → Export as .gbXML/ .IFC (through BIM server) → Open Studio

2.6.3. Data loss

This issue is in detail described by Gabriela Bastos Porsani , Kattalin Del Valle de Lersundi, Ana Sánchez-Ostiz Gutiérrez and Carlos Fernández Bandera in the article "Interoperability between Building Information Modelling (BIM) and Building Energy Model (BEM)", where case studies were constructed in order to analyse the interoperability between Revit as a BIM software program and Green Building XML, Design Builder, Open Studio and CYPETHERM HE as BEM software programs.

The lack of BIM-BEM interoperability is one of the current gaps between digitalization and the construction industry. As the basis for energy performance certificates (EPCs), which are required to uphold investors' confidence in the energy efficiency sector, BEMs should provide accurate results. It was found that the workflow between BIM and BEM is partially automated. In order to export gbXML and IFC files, some Revit parameters must first be activated. Second, the BEM tool's settings for the building typology, ideal loads, occupation schedule, and weather file must be accurate in order to import model schema data. However, since many of the problems with the BEM softwares were caused on by errors made when transferring the data from the BIM authoring tool to the gbXML and IFC files, their configuration was insufficient to ensure adequate interoperability. The energy models produced with gbXML and IFC cannot be used as a reference point for the BIM as they presented thermal properties and geometry values that differed from the baseline model. The simulation outcomes as a result were distinct and inaccurate. Additionally, not all building types can use BIM-BEM interoperability. It has been demonstrated that the bigger and more complicated the building is, the less reliable the data transfer is and the more difficult it is to build the model in the BEM software. The energy simulations were rendered impossible by the fatal errors caused by these geometry problems (Bastos Porsani, 2021).

2.7. Visual Programming Language software programs (VPL)

Any programming language that allows users to create programs by manipulating program elements graphically rather than by specifying them textually is known as a visual programming language (visual programming system, VPL, or VPS) in the field of computing (Jost, 2014). Programming with visual expressions, spatial arrangements of text and graphic symbols, and secondary notation are all possible with a visual programming language (VPL). For instance, the concept of "boxes and arrows" is the foundation of many VPLs (also known as dataflow or diagrammatic programming), where boxes or other screen objects are treated as entities and connected by arrows, lines, or arcs that represent relations (Bragg, 1994).

Icon-based languages, form-based languages, and diagram languages are additional categories that can be used to categorize VPLs based on the type and extent of visual expression used. Visual programming environments offer graphic or iconic elements that can be interactively modified by users in accordance with a particular spatial grammar for program creation. The main purpose of VPLs is to support programmers at three different levels and to make programming more approachable for beginners (Repenning, 2017). Numerous studies demonstrate that visual programming languages, as opposed to conventional programming languages, are simpler for novice programmers or non-programmers to understand (Asl, 2014). For designers using Rhino or Revit, Grasshopper and Dynamo are based on the visual programming language "Python", and they offer numerous opportunities.

2.7.1. Introduction to Dynamo

The program Dynamo is available for free download and can be used either standalone or as a plug-in for Revit. It's a visual programming tool designed to be user-friendly for both programmers and non-programmers. It enables users to define custom logic, visually script behaviour, and script in a variety of text-based programming languages. Users can create custom algorithms and process data using Virtual Programming after installing Dynamo. By connecting code blocks that are programmed to carry out a task assigned to them, users can easily create geometries and manipulate models in Revit or within Dynamo itself.

One of the differences between Dynamo and Grasshopper is that in Grasshopper the glow of the work goes from left to right, but in Dynamo, it can go both ways. On Figure 2.21*, a typical Dynamo workflow can be seen (Mengana, 2016).

* Note: reprinted from "Parametric BIM: Energy Performance Analysis Using Dynamo for Revit" by: T. Mousiadis and S. Mengana, (2016)
Retrived from: https://www.diva-portal.org/smash/get/diva2:1064171/FULLTEXT01.pdf

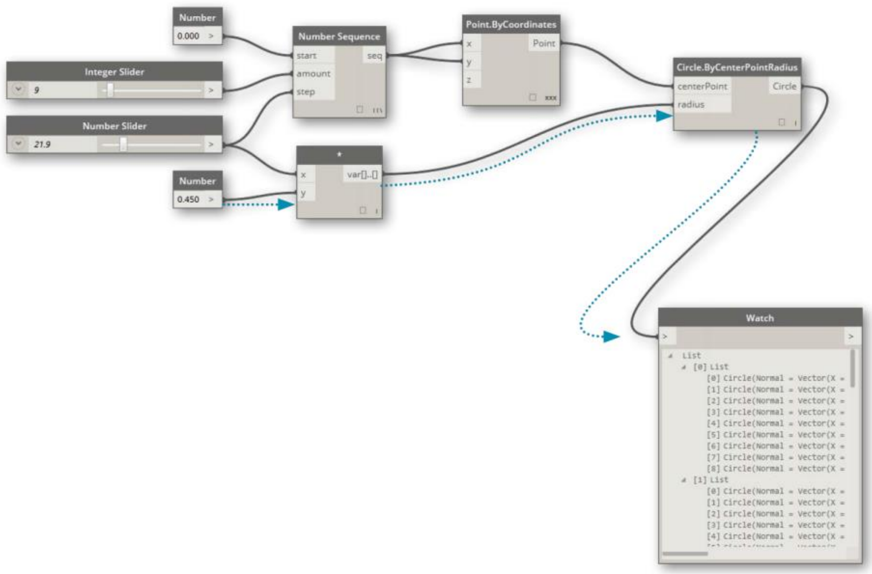

Figure 2.22 Program flow in Dynamo

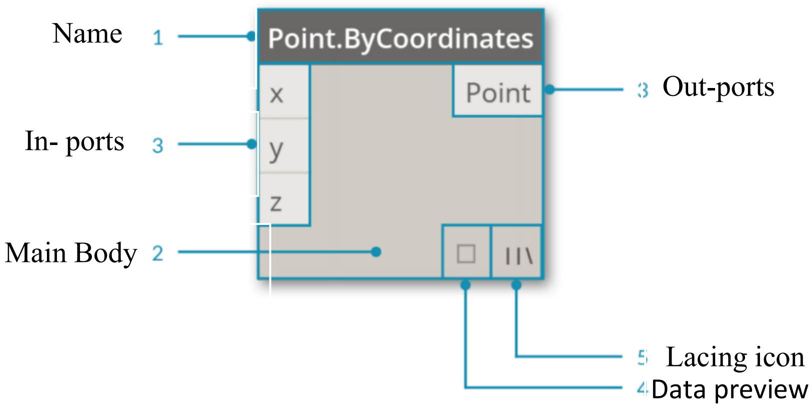

Figure 2.21 Node components on Dynamo

The nodes are made up of scripts that have been given tasks. It could be something as straightforward as adding a number to a list or as complex as making complex geometry. Python is the language used to script the codes. With a few exceptions, most nodes consist of the following five components as seen on Figure 2.22*. Nodes can be connected to one another very easily by simply clicking on the out-port from one node and connecting to the in-port on another port. The type of nodes and the direction of the workflow determine the input and output. Data is transported over the wires connecting the nodes (Mengana, 2016).

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* Note: reprinted from "Parametric BIM: Energy Performance Analysis Using Dynamo for Revit" by: T. Mousiadis and S. Mengana, (2016)
Retrived from: https://www.diva-portal.org/smash/get/diva2:1064171/FULLTEXT01.pdf

2.7.2. Introduction to Grasshopper

Grasshopper is a visual programming language and environment that runs within the Rhinoceros 3D computer-aided design (CAD) application. Components are dropped onto a canvas to form programs. The inputs of succeeding components are then coupled with the outputs of these components. The main purpose of Grasshopper is to create generative algorithms, such as those used in generative art (Ma, 2021). Many Grasshopper’s parts produce 3D geometry. Other types of algorithms, such as those for text, audio, video, and haptic applications, may also be found in programs. The main purpose of Grasshopper is to create generative algorithms, such as those used in generative art. Many of Grasshopper’s parts produce 3D geometry. Other types of algorithms, such as those for text, audio, video, and haptic applications, may also be found in programs (Tedeschi, 2011).

Grasshopper consists of many kinds of objects; however, the two mains are parameters and components. Parameters contain data, meaning that they store information and components contain actions. An example can be seen on Figure 2.23* .

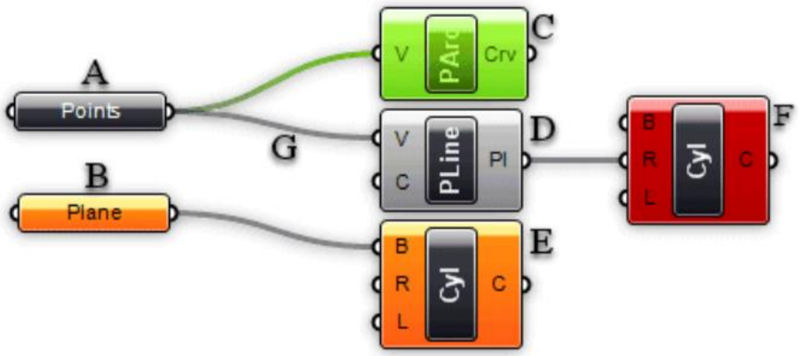


Figure 2.23 Nodes on grasshopper and the meaning of different colours

A. A data-contained parameter. The object does not inherit its data from somewhere else because there is no wire coming out of the left side of the object. The text in the thin, black blocks with horizontal spacing represents parameters that do not have errors or warnings.
B. A parameter that is empty of information. Any device that doesn't collect data is suspected in an explicit history definition because it seems to be a waste of time and

* Note: reprinted from “Grasshopper Primer” by: A. Payne & R. Issa, (2009)
Retrived from: http://www.liftarchitects.com/blog/2009/3/25/grasshopper-primer-english-edition

resources for everyone. Since no data is present in any of the parameters (when they are first added), they are all orange, indicating that they have no functional impact on the result of the History Solution. A parameter turns black once it inherits or defines data.

C. A chosen element. There is a green glow to each of the selected items.
D. A regular component.
E. An alerts component. A component may contain a variety of input and output parameters, so it is impossible to tell from just looking at the component which specific object issued the warning.
F. A component that contains an error. Similar to warnings, it is impossible to determine where in a component an error occurred. The warning bubble needs to be read by the user for a better understanding of the issue that has occurred.
G. A wire connector. An output and an input parameter are always connected. Any given parameter may contain an unlimited number of connections (Payne, 2009).

A component typically needs data to perform its functions, and it typically produces a result. Input and output parameters are terms used to refer to a set of nested parameters that are present in most components. Output parameters are located on the right side, while input parameters are located on the left and the name of the component is usually located in the middle of the node (Figure 2.24*).

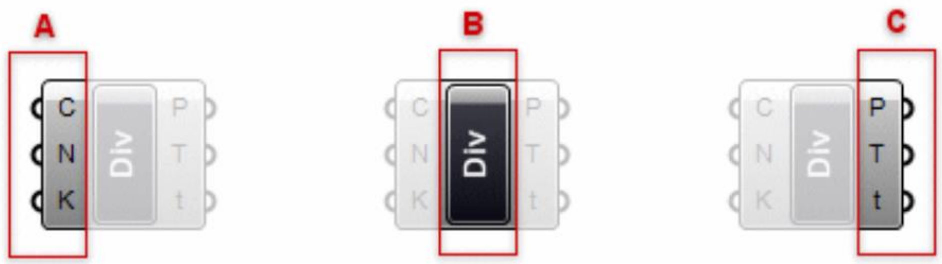


Figure 2.24 Grasshopper component anatomy

* Note: reprinted from "Grasshopper Primer" by: A. Payne & R. Issa, (2009)
Retrived from: http://www.liftarchitects.com/blog/2009/3/25/grasshopper-primer-english-edition

2.7.2.1. Grasshopper plug-ins

Grasshopper offers the users many options when it comes to parametric modelling but also any energy, acoustic, thermal comfort, daylight, LCA and other types of analysis. In this research, the fosus is to understand which Grasshopper components and also Grasshopper plug-ins can help the user achieve the desired results (Figure 2.25*).

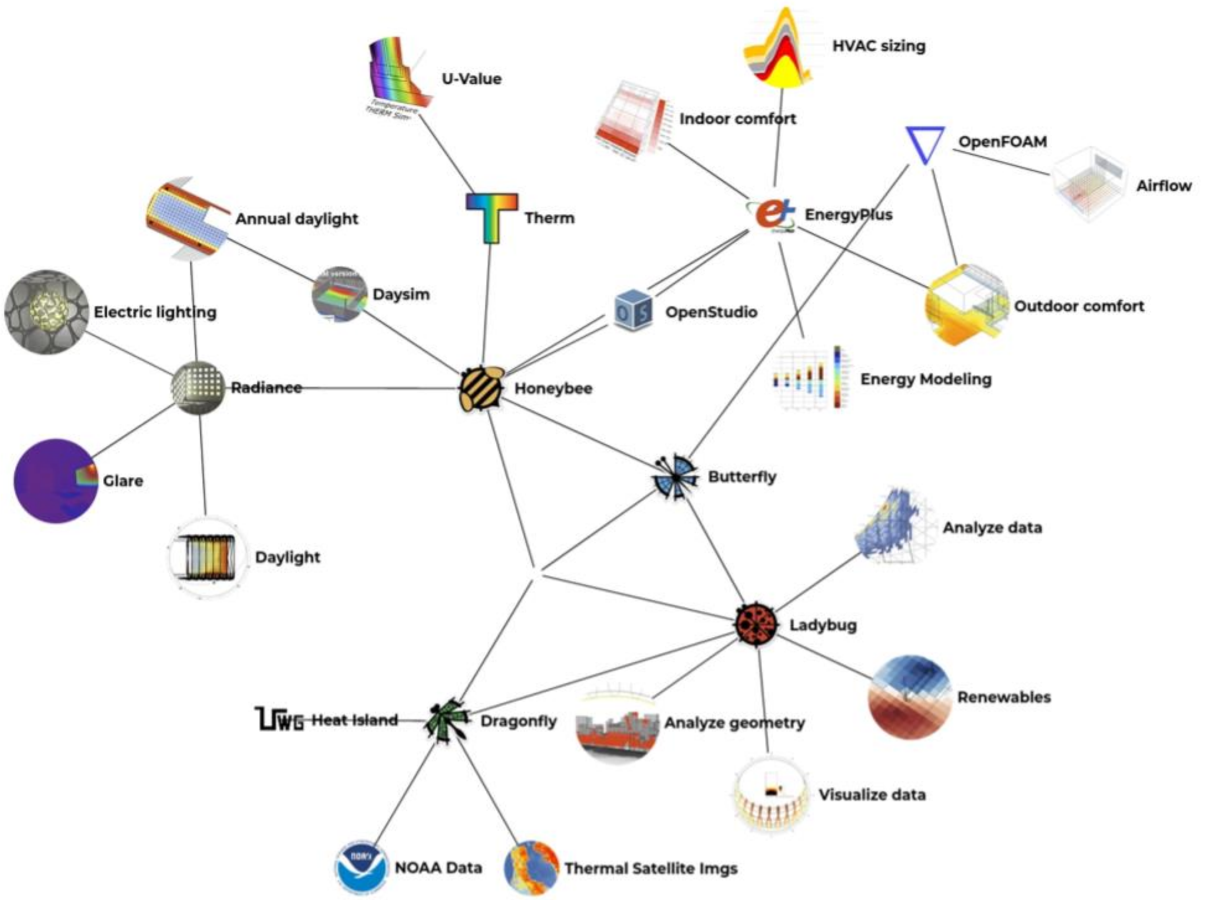


Figure 2.25 Grasshopper's plugins and their capabilities

2.7.2.1.1. Honeybee

In-depth daylighting and thermodynamic modelling, which are frequently most important in the middle and later stages of design, are supported by Honeybee. It specifically creates, runs, and displays the output of energy models using EnergyPlus/OpenStudio and radiation and daylight simulations using Radiance. It achieves this by integrating these engines with the Grasshopper/Rhino CAD environment. For these engines, it also functions as an object-oriented Software Development Kit (SDK) (Ladybug Tools, 2019).

* Note: retrived from: https://www.food4rhino.com/en/app/ladybug-tools?lang=it

2.7.2.1.2. Ladybug

Grasshopper can import common EnergyPlus Weather files (.EPW) through Ladybug. It offers a selection of interactive 2D and 3D climate graphics to aid in decision-making during the preliminary design stages. Through solar radiation studies, view analyses, sunlight-hours modeling, and other methods, Ladybug additionally aids in the assessment of preliminary design options. Integration with visual programming environments enables high levels of customization and instant feedback on design changes (Ladybug Tools, 2019).

2.7.3. BIM and VPL data conversion methods

The rules differ when a model is exported from a BIM software and then imported into another BIM interface. For instance, a Revit model is exported as a CAD file when being used to create a BIM model (DWG. or DXF.). The DWG and DXF vector image files were created by Autodesk. While DWGs are primarily used for drawing, DXF files are used for sharing. These are both essential drafting and engineering file types. Autodesk developed their own proprietary DWG file format to store 2D and 3D images. This adaptable image file type uses compact binary code to facilitate moving and storing DWG files. DXF, another creation by Autodesk, debuted around the same time as DWG. Drawing Exchange Format is exactly what its name denotes and what it is for. DXF connects Autodesk files to many more CAD and drafting programs, possibly hundreds. Compared to DXF files, DWG files are smaller and can store a wider variety of files. DWG files are written in binary code, a language that computers use to process zeros and ones. DXF files only contain text-based coding (ASCII). Due to the more condensed nature of binary code, DWG files typically measure about 25% less than DXF files. In DXF vector drawings, each element is "spelled out" in ASCII. DXF expands as a result, but it also improves its software compatibility. Some DXF files, especially those with numerous layers, can be hundreds of megabytes in size. In these circumstances, splitting up the large file, compressing it, or doing both is recommended (Adobe, 2020).

2.7.4. Introduction to Speckle

Speckle is an open-source digital infrastructure for anything 3D-designed. It deals with real-time collaboration, data management, versioning, automation, and software silo interoperability (Speckle, 2021). Speckle uses online streams which contain data that can be transferred on to the chosen BIM software program. There are various so-called “connectors” that can be downloaded as plug-ins for the BIM programs. Once the connectors are downloaded for the software that sends data and the software that receives it, the information is sent to the Speckle online stream and later can be accepted by other programs where the model is required. The variety of connectors is quite wide, so many of the most used BIM, VPL or BEM software programs could be able to use the connectors.

The main idea of Speckle is to fix the issue of interoperability and to simplify it, while minimizing the data loss. Important information about exportation with the Speckle stream is that all the information that is sent to the stream, can be accessed in anytime, without disappearing. This tool is relatively new on the market, and it is still in the process of development.

2.7.5. Possible workflows from BIM to VPL

From the literature review regarding BIM and VPL interoperability, the possible workflows constructed can be seen below.

1. Revit ↔ Dynamo (Honeybee, Ladybug, Energy Analysis for Dynamo)
2. Revit → Insight
3. Revit ↔ RhinoInside ↔ Grasshopper (Honeybee, Ladybug, Dragonfly, Bombyx, Pachiderm, OneClickLCA)
4. Revit → Export as .DXF/.DWG → Import to Rhino → Grasshopper (to analyze all component need to be specified)
5. Revit ↔ Revit Connector ↔ Import to Speckle Stream ↔ Open Speckle Web Account ↔ Copy the link ↔ Import as link connected to Grasshopper “Receive” node from Speckle Connector ↔ Define objects attributes ↔ further analysis on Grasshopper (Honeybee, Ladybug, Dragonfly, Bombyx, Pachiderm, OneClickLCA)

2.8. Pollination

Pollination is an ecosystem that links simulation and performance analysis services to design applications rather than being a centralized "one-stop-shop" simulation tool. And in doing so, it links the various project leaders—the architect, mechanical engineer, and energy modeler—to one another, enabling a quicker and more effective level of collaboration. Pollination is primarily a web-based hub for collaboration that houses analysis models. A collection of tools is included for previewing geometry, editing models, running various analyses—lighting simulations using Radiance, energy simulations using OpenStudio and

EnergyPlus, multi-building simulations using URBANopt, and (soon) CFD studies using OpenFOAM—as well as viewing and navigating the results. Users can run these simulations on the cloud with Pollination, but it is not a "cloud-only" service. By running simulations on their own computers and only utilizing cloud resources, when necessary, users can save money. This far, so typical. Even among BEM applications, web-based applications supported by cloud computing infrastructure are a common software configuration. Pollination stands out, though, thanks to a few important characteristics. In keeping with the company's origins, Ladybug Tools heavily relies on design plug-ins for software like Revit and Rhino3D that let designers access Pollination's features, such as results viewing and navigation, from within their preferred workflow. A high level of interoperability is needed to support numerous design applications and analysis engines, and Pollination provides this support using a new schema called HBJSON (short for Honeybee JSON). Building performance analysis is notoriously difficult because of the broken BIM-to-BEM pipeline. Ladybug Tools created HBJSON to address this issue (Office of Energy Efficiency and Renewable Energy, 2022). Pollination has been released this year (2022), and by its attributes it looks like a promising solution to the BIM and BEM users. However, pollination has not been used further in this research.

2.9.Key Performance Indicators

As architects we must keep in mind for whom we are designing a building and keep the occupant's health and comfort as our priority. In order to achieve that, a complex strategy is constructed that evaluates the primary environmental aspects of thermal comfort, air quality, acoustics and lighting. This study presents a collection the indicators for assessing the comfort and health of occupants in assessments of indoor environmental quality. Nowadays, everyone is aware of how important it is to have high-performance buildings in order to reduce both energy consumption and the environmental impact (CO2 emissions into the atmosphere). The current problem is to maintain low energy consumption while ensuring a high standard of indoor quality. Assessments of indoor environmental quality (IEQ), particularly regarding workplace environments, should consider all potential factors that might have a negative impact on health in addition to the perceived levels of comfort. More and more people are using new holistic methods where the indoor environmental conditions and building energy performance are combined. This study specifically focuses on better understanding the thermal comfort and energy consumption. Thermal comfort and energy use are closely related to each other, for example, when deciding the type of HVAC system in a building both factors are taken into consideration.

Table 2-6 Collection of KPIs

Aspects		Performance indicators	Target value	Reference	Design Impact Factors	Physical Variables
Visual Comfort	Daylight	• Daylight Factor (DF) • Daylight Autonomy (DA) • Useful Daylight Illuminance (UDI) • Continious Daylight Autonomy (cDA) • Spatial Daylight Autonomy (sDA) • Annual Sunlight Exposure (ASE)	• ≥ 2% - residential ≥ 3% - commercial • > 50% • $UDI_{100\text{-}3000\ lx}$ ≥ 80% • > 55% • $sDA_{300,50\%}$ ≥ 40% - sufficient $sDA_{300,50\%}$ ≥ 55% - preferable $sDA_{300,50\%}$ ≥ 75% - optimal • $ASE_{1000,250}$ ≤ 10% *(otherwise, identify how glare is addressed)*	• Italian Technical Standard UNI 10840:2007 • IES LM-83-12 • UK Education Funding Agency. Baseline designs and strategies for schools in the Priority School Building Program (PSBP). • IES LM-83-12 • IES LM-83-12 • LEED v4.1 |U.S. Green Building Council	• Transperent Surface Size • Exterior and interior shading devices • Type of glass • Surrounding environment • Position of reference point	• Incident illuminance • Reflection and refraction of the referenced surface
	Glare	• Glare Autonomy • Spatial Glare Autonomy • Daylight Glare Probability (DGP)	• $GA_{40\%}$ • $sGA_{40\%,5\%}$ • <20% - not validated 20% - 35% - imperceptible 35% - 40% - perceptible, but not disturbing 40% - 45% - disturbing > 45% - intolerable	• EN 17037 • EN 17037 • EN 17037:2018		
	View out	• Maximum view distance • Number of visual layers • Aesthetical scene quality	• ↑ • ↓ • ↑	• EN 14501:2021		
Thermal Comfort		• Predicted Percentage of Dissatisfied (PPD) • Predicted Mean Vote (PMV)	• < 20% • close to 0	• ASHRAE 55 and ISO 7730	• Building materials • Thickness of component • Total area • HVAC	• Mean radiant temperature • Operative temperature • Relative humidity • Activity level • Air velocity • Clothing
Energy		• Primary Energy Use	• ↓ (kWh)	• EPBD- 2010/31/EU	• Features of building enevelope • Type and size of building • HVAC • Equipment systems • Renewable Energy Source	• Opaque and transparent surfaces properties • Energy loads and zones • Occupancy schedule • Equipment schedule • Location
Acustic Comfort		• Reverberation time (RT) • Weighted Sound Reduction index	• RT_{60} < 1s - good for classrooms RT_{60} = 1s - good for speaking: articulation of speech is clear RT_{60} = 1.5s - 2.5s - a good compromise if the room is to be used for both speaking and music RT_{60} = 3.5s - better for music, but some loss of articulation. Would likely be difficult to understand speech RT_{60} = 8 s to 11 s: Large medieval cathedrals will have a very long RT_{60} • ↑	• ISO 3382-1 *(performance spaces)* ISO 3382-2 *(ordinary rooms)* ISO 3382-3 *(open-plan offices)* ASTM E2235 standard • ISO 16283-2:2020	• Building materials • Thickness of component • Windows and doors area • Total area • Surrounding environment	• Frequency and Amplitude of the incident sounds • Mass and Natural resonances Absorption, Transmittance and Reflection of sounds • Air tightness • Presence of people
Environmental Footprint-LCA		• Global Warming Potential (GWP) • Acidification Potential (AP) • Eutrophication Potential (EP) • Photochemical Ozone Creation Potential (POCP) • Ozone Depletion Potential (ODP) • Abiotic Depletion Potential (ADP) minerals, metals and fossil resources • Water Deprivation Potential (WDP) • Embodied/ Operational impact	• ↓ • ↓ • ↓ • ↓ • ↓ • ↓ • ↓ • ↓	• EN 15804 • EN 15804 • EN 15804 • EN 15804 • EN 15804 • EN 15804 • ISO 14046 • EN 15978	• Type of material • HVAC • Renewable/ Non-renewable Energy Source • Geometry	• The absorption of infrared radiation by a given gas • The time horizon of interest (integration period) • The atmospheric lifetime of the gas • Atmospheric pollution from SO_2 or NH_3 • VOCs • Water demand • Embodied/ Operational energy • Reuse and recycle
Air Quality		• Ventilation Rate • CO2 • PM10 (Particulate matter) • Indoor Air Quality Index (IAQ)	• > 7.5 L/s^{-1} PP • 1080 $mg\ m^{-3}$ • 0.05 $mg\ m^{-3}$ • < 100	• WHO AQGs	• Building materials • Thickness of component • Windows and doors area • Total area • HVAC • Surrounding environment	• Airflow • Humidity • Presence of people

2.9.1. Predicted Mean Vote (PMV)

A seven-point thermal sensation scale is used in the PMV index, which attempts to predict the mean value of votes cast by a group of occupants. When an occupant's internal heat production and heat loss are equal, thermal equilibrium is reached. Levels of physical activity, clothing insulation, and the specifics of the thermal environment can all affect a person's body heat balance. For instance, when occupants of a space have control over indoor temperature (i.e., natural ventilation through opening or closing windows), thermal sensation is typically perceived as better. This helps to reduce high occupant thermal expectations on a mechanical ventilation system. In terms of the PMV index, +3 corresponds to too much heat, while -3 corresponds to too much cold (Fanger, 1970).

2.9.2. Predicted Percentage of Dissatisfied (PPD)

The PPD, or index, which establishes a quantitative prediction of the percentage of thermally dissatisfied occupants (i.e., too hot or cold), can be calculated after the PMV has been calculated. PPD essentially indicates the proportion of people who are expected to feel localized discomfort. Unwanted body cooling or heating of an occupant is the main cause of local discomfort. Drafts, unusually high vertical temperature differences between the ankles and the head, and/or floor temperature are common causes (Liu, 2020).

2.9.3. Primary Energy Use (PEU)

Primary energy (PE) is a type of energy that can be found in nature that hasn't undergone any artificially engineered conversion procedures. It is the energy that is present in unprocessed fuels and other energy sources, such as waste, that are introduced into a system. Renewable or non-renewable sources can be used for primary energy. In cases where the term "primary energy" is used to describe fossil fuels, the embodied energy of the fuel is available as thermal energy, with an average conversion loss of about 70%. Solar and wind energy both suffer a similar 60–80% conversion loss when converted to electricity, but according to current UN conventions on energy statistics, the electricity generated by these sources is the primary energy. An international debate over how to count primary energy from wind and solar has resulted from one effect of this counting method, which is that the contribution of wind and solar energy is underreported when compared to fossil fuel energy sources (Sauar, 2018).

$$\text{Primary energy factor}(\text{PEF}) = \frac{\text{Total primary energy consumed in the delivery}}{\text{Total energy delivered for end use}}$$

The calculation for deriving the primary energy used is from the energy loads that are divided by the specific efficiency factor (EF) per system and th multiplied by the primary energy factor (PEF). For the future research, the primary energy factors used are 1.05 for natural gas and 2.42 for electric energy (15A05198, 2015).

2.9.4. Sound Reduction Index (SRI)

A sheet of material positioned in the paths used for sound transmission serves as the simplest insulator. A pressure wave is the form in which sound energy travels to the surface. A portion of the energy enters the partition, while the remainder is reflected. A partition's ability to partially absorb and transform energy into heat. When using a simple partition, this is probably very small. The remaining energy will then displace molecules and pass through the barrier as sound in a manner like how sound travels through air. This can then travel to the partition's edge and be reradiated as sound from other building components. Transmission flanking is the term for this. By causing the partition to vibrate in sympathy with the incident sound and reradiating the sound onto the opposite side, a thin partition allows the greatest amount of energy to pass through it. The ratio of incident energy to transmitted energy serves as a proxy for sound transmission through a partition. This quantity is referred to as the sound-reduction index when expressed in decibels (SRI) (Snow, 2001).

$$\mathbf{R = L1 - L2 + 10\log (S/A)}$$

- R = Sound Reduction Index
- L1 = average sound pressure level in the source room
- L2 = average sound pressure level in the receiving room
- S = area of the test specimen (m^2)
- A = equivalent sound absorption area of the receiving room (m^2)

2.9.5. Conventional Reverberation Time (CRT)

When sound is produced in a space, it will repeatedly reflect off surfaces like the ceiling, walls, floors, windows, and tables while gradually losing energy. The phenomenon known as reverberation is produced when these reflections combine. Reverberation time is a measurement of how long it takes for sound that is reflected in an enclosed space to "fade away" after the source of the sound has stopped. In determining how a room will react to acoustic sound, it is crucial (NTI, 2017). The ISO 3382-1 (ISO, 2009) standard for performance spaces, the ISO 3382-2 (ISO, 2008) standard for regular rooms, and the ASTM E2235 (ASTM, 2020) standard all defines the reverberation time measurement. When a sound source is abruptly turned off, the amount of time it takes for the sound pressure level to drop by 60 dB is known as the reverberation time. Reverberation time is frequently referred to by the abbreviations T or RT60. Positions within a room have different Reverberation Time values. As a result, a reading that represents the space being measured is typically taken.

$$\mathbf{RT_{60} = 0.161V_m / S\ \alpha}$$

- RT_{60} = reverberation time (s)
- V_m = volume of room (m^3)
- S = total surface area of room (m^2)
- α = average absorption coefficient of room surfaces (sabin)

2.10. Linking Grasshopper to the KPIs

Table 2-7 Software engines that calculate specific KPIs

Aspects		Performance indicators	Honeybee	Ladybug	Butterfly	Pachyderm	Bombyx	OneClickLCA	Engines
Visual Comfort	Daylight	• Daylight Factor (DF) • Daylight Autonomy (DA) • Useful Daylight Illuminance (UDI) • Continious Daylight Autonomy (cDA) • Spatial Daylight Autonomy (sDA) • Annual Sunlight Exposure (ASE)	✓						RADIANCE
	Glare	• Unified Glare Rating (UGR) • Daylight Glare Probability (DGP)	✓						
	View out	• Maximum view distance • Number of visual layers • Aesthetical scene quality	✓	✓					
Thermal Comfort		• Predicted Percentage of Dissatisfied (PPD) • Predicted Mean Vote (PMV)	✓	✓	✓				THERM ENERGY +
Energy		• Primary Energy Use	✓						ENERGY+
Acustic Comfort		• Reverberation time (RT) • Weighted Sound Reduction index				✓			PACHYDERM
Environmental Footprint-LCA		• Global Warming Potential (GWP) • Acidification Potential (AP) • Eutrophication Potential (EP) • Photochemical Ozone Creation Potential (POCP) • Ozone Depletion Potential (ODP) • Abiotic Depletion Potential (ADP) minerals, metals and fossil resources • Water Deprivation Potential (WDP) • Embodied/ Operational impact					✓	✓	
Air Quality		• Ventilation Rate • CO2 • PM10 (Particulate matter) • Indoor Air Quality Index (IAQ)	✓						ENERGY+

3. Methodology

In this research, the focus was to find the connection between the software programs so that the KPIs mentioned in the previous chapter could be analyzed. The priority was to find the appropriate workflow so that the information flow could be as smooth as possible. The literature review led to the understanding which are the appropriate tools for such analysis. At the end the decision that was made, was to use a Revit as BIM program and Grasshopper from Rhino as a VPL program with the Ladybug and Honeybee plugins. In the further chapter there is a detailed explanation of the workflows used on two different case studies. The conceptual methodology can be seen on Figure 3.1.

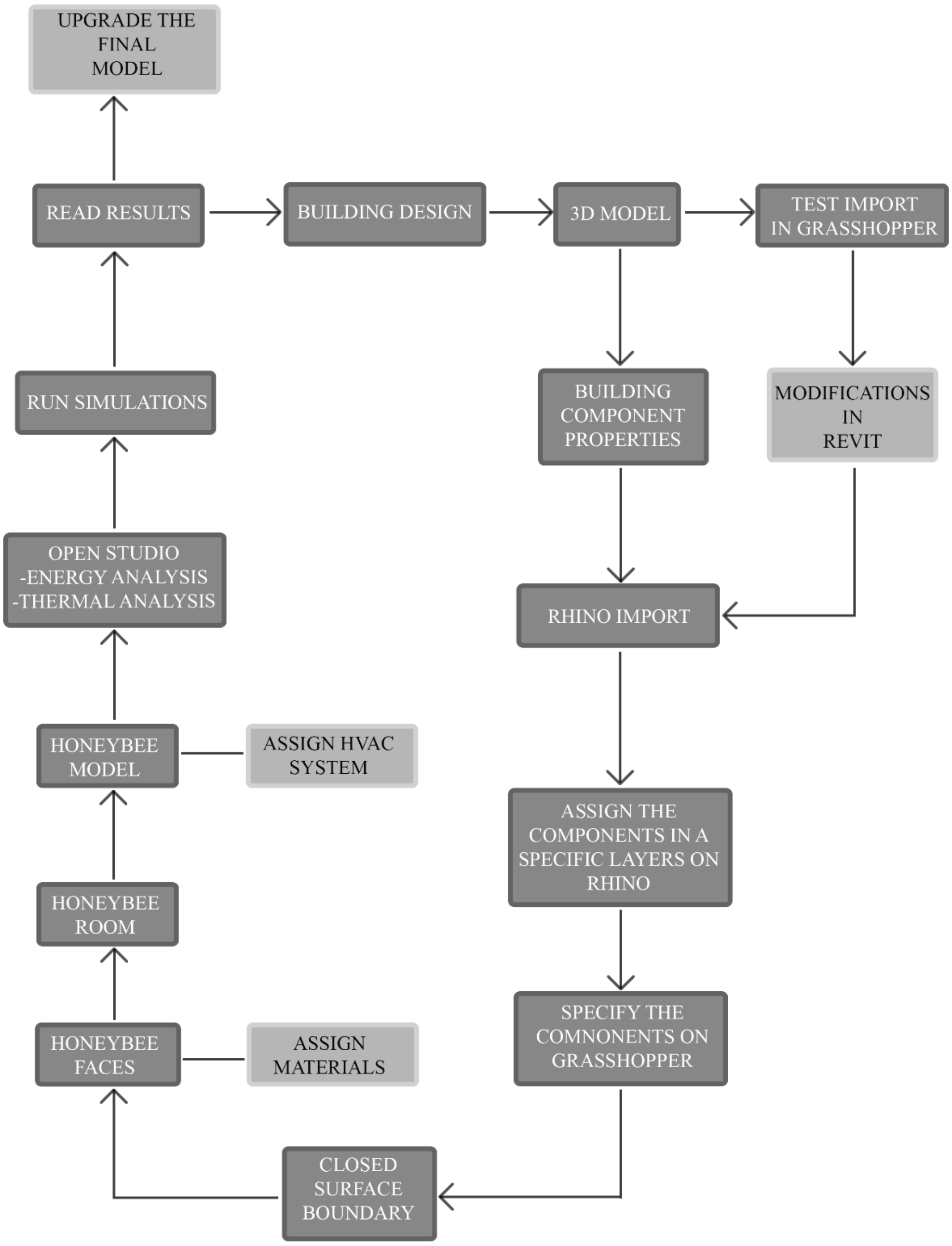


Figure 3.1 Conceptual methodology for the research workflow

In the further research, the 4 main questions will be explained, and they will lead the way to have a clearer picture of what the specific tools have to offer and how to be used:

1. What is the smoothest workflow when converting the model from BIM to VPL with the least percentage of data loss?
2. What are the common issues when using the software programs and how can they be resolved?
3. How do parametric simulation tools help the design process and decision-making process?
4. What are the capabilities of the simulation tools and in which stages of the design can they be used?

3.1. Description of research method

In this research the main point is to understand the interoperability of the software programs in order to have a smooth transition in information when analyzing thermal comfort and energy consumption. Since Revit is the most used BIM software by architects and engineers, it was chosen to model the building geometry for the case studies, which will be explained in the next chapters.

Firstly, the specific types of case studies were decided. The next step was modeling the geometry. Revit allows the users to implement information about the specific components of the program, which later can be used in further analysis.

The next process was deciding which specific program would be used to run the analysis. After the literature review, I came to the decision to work on Rhino using Grasshopper, which is a VPL type of program. The Grasshopper interface consists of various components that connect to various input data, to give results for specific issues. It gives the user freedom to control the simulations with the desired parameters. In the Grasshopper environment, there are many plug-ins that can help the user achieve the desired analysis. Such plug-ins are Honeybee and Ladybug, which were used in the simulation of energy and thermal simulations.

There are multiple options when exporting the model from Revit, and even though most of the options might seem similar, they have many differences when the model is imported in Rhino. In further case studies, two types of exportation methods were used: exportation directly from Revit using a .DWG file and the other one is exporting the model using the Speckle stream (which will be explained later). Once the model is imported on the Rhino interface, then it can be used on Grasshopper, where all the components and the surfaces can be specified.

Finally, when the model is imported in the Grasshopper environment, other properties are specified: detailed specification of the materials, HVAC system, weather file etc.

3.2. Design of the case-studies

In order to test the strengths and limitations of the programs used to analyse the performance of the building, two case studies were constructed. Each of the case studies has a different level of complexity. The first case study is a so called "shoe-box" type of model. This means that the model is simplified to its most basic building attributes. The reason behind the selection and design of the model is to test the opportunities that the programs offer. Its simple design helps the research to build a workflow for analysing the thermal and energy KPI mentioned in chapter 2.9.

The second one is a multizone model, representing an office building, with a more detailed component layers, different sizes and types of window openings and it contains a curved wall. The reasoning behind the design of the second case study is to understand the strengths and limitation of the simulation tools when it comes to a building where more than one zone or room must be analysed, in fact the whole construction. This model contains a geometry such as two curved walls, offices with different sizes, window opening with different sizes and more detailed layered components. With this information, it was important to see if the same workflow as the single zone model can be implemented to run the simulation on the multizone model.

3.2.1. Workflow I

The first workflow that was used in this research was the traditional method, which is exporting the BIM model from Revit and importing it on the Rhino interface. It represents an exportation process using a .DWG file format. This workflow was used for the exportation process of the single zone model.

3.2.1.1. Exporting the Revit model as a .DWG file format

For the exportation process for the first case study, two methods were tried before making the final decision about which format of exportation it is going to be used; firstly, the model was exported as .DXF format and secondly exporting the model as. DWF format. This was done to understand whether both formats were recognized and supported by Rhino. This led to the realization that in both cases the model was recognized and could be used in further analysis (with some adaptations on Grasshopper later).

Firstly, when the model was exported, (both as .DWG and as .DXF) the geometry was accepted by Rhino as mesh (a mesh is a group of polygons and vertices that determines how a polyhedral object will be shaped; Rhino meshes are made up of triangles and quadrilaterals). Once the model is on the Rhino interface, it can be modified so that Grasshopper will recognize the surfaces for the analyses. One command that is helpful in this case is “quadrangulate mesh”, which transforms all the triangular meshes into rectangularly shaped meshes. This step is important since Grasshopper does not recognize the surfaces which contain more than one plane surface. However, there is a solution on Rhino for this issue. When exporting the file, there is an option to modify the exportation setup, where the properties of the model can be modified depending on the needs of the user. In this menu, there is an option in the toolbar called “solids” where it can be chosen for the model to be exported as “ACIS solids” (Figure 3.2). This later simplifies the surface selection on Grasshopper.

When exporting the model in the .DWG file format, there is an option to open the file in AutoCAD 3D where some modification of the geometry could be done if there is a need for a simple correction.

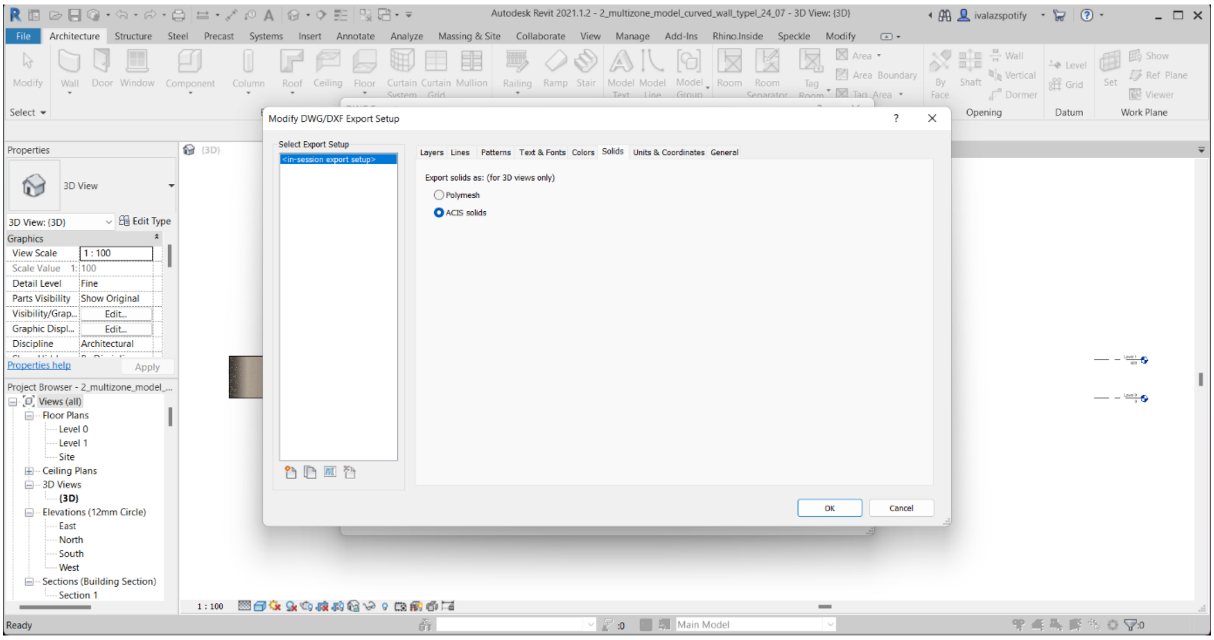


Figure 3.2 Revit “Modify DWG/DXF Export Setup” to export the components as solids

3.2.2. Workflow II

For the second type of exportation, a tool called "Speckle" was tested. "Speckle" is an open-sourced digital platform which acts as a connector between various CAD or BIM software programs. It can be downloaded as a plug-in for many software programs, and it helps handle the problem with interoperability between them. In order to be connected with Grasshopper, the same plug-in also has to be installed for the Grasshopper interface. This workflow was tested on the second case study, the multizone model.

3.2.2.1. Exporting the model using the Speckle stream

Once the geometry is modeled on Revit, the Speckle connector is opened where the components can be sent to the on-line stream. In the connector, there is the option to either send the complete geometry or to choose specific components that the user wants to further use on another platform. Since all the model components have specific properties, it recognizes them depending on the category they were modeled in (ex. walls, floors, roofs, construction elements, windows, etc.).

When the elements are sent to the on-line stream, they are visualized for the user to have a clearer picture of what the stream consists of. Also, there is a complete list of all the items on the stream, named by their category. Components can be added or removed from the stream without the need to open a new one. Figure 3.3 shows the Speckle connector on Revit.

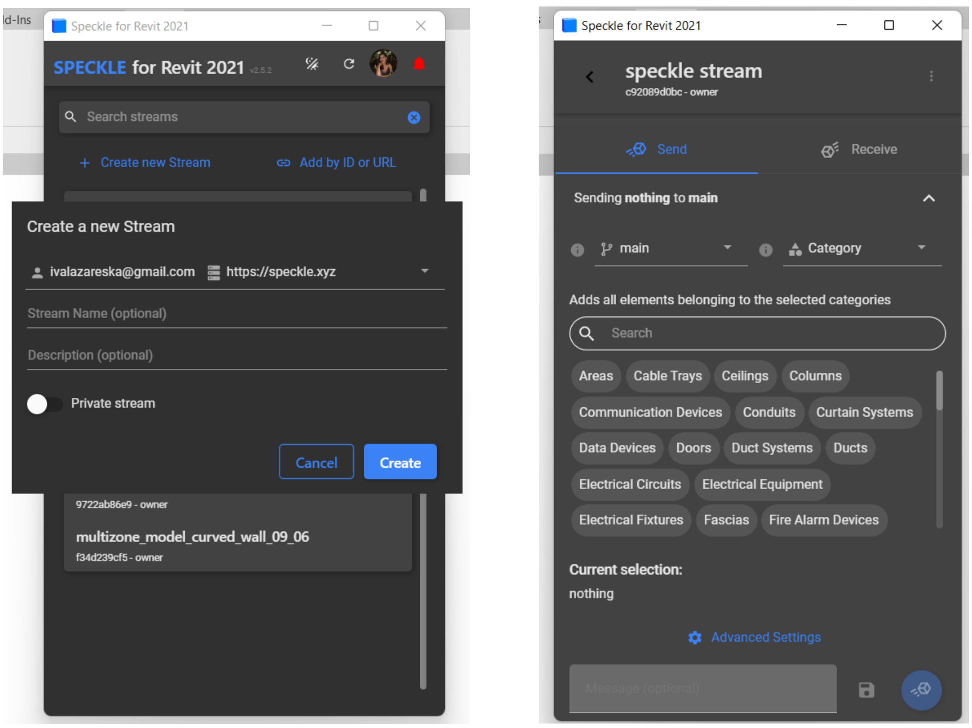
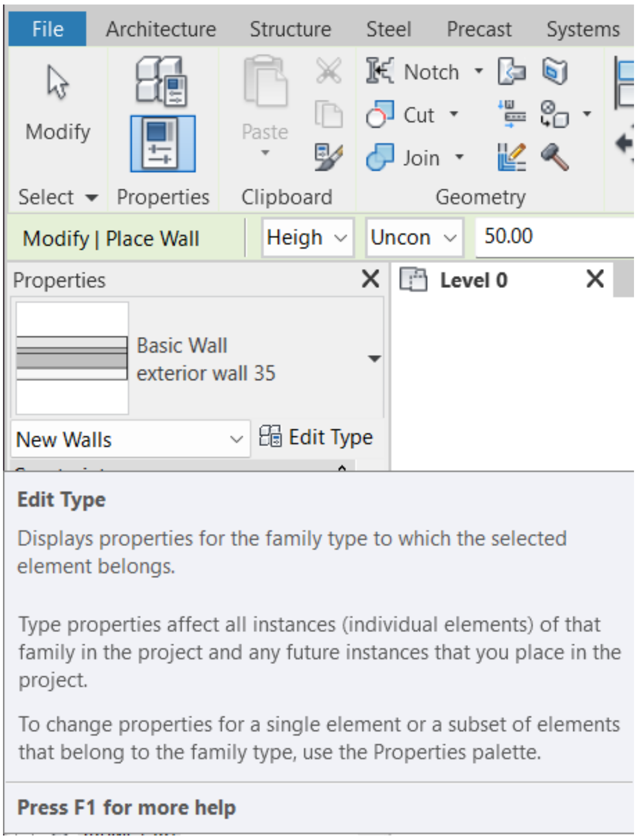


Figure 3.3 Sending geometry to the Speckle stream

3.3.Revit modelling process

The first step of the research was to decide the types of case studies on which the simulations will be done. The process began with modeling the geometry on Revit. In this process, all the general properties of the geometry were decided. The components were all modeled using Revit families. To the specific components (walls, floors, roofs, doors, windows) materials were assigned in the family editor. In “Edit Type”, all the properties of of the component can be edited (Figure 3.4).



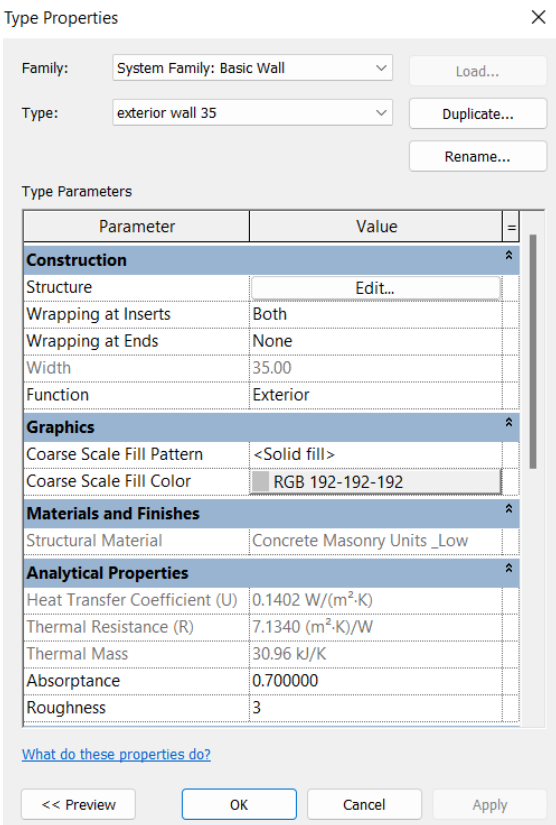


Figure 3.4 Description of "Edit Type" option in Revit for component modification

Figure 3.5 "Edit Type" menu on the Revit interface

When “Edit Type” is opened, there are categories in which the user wants to make a changes to the component such as construction (where the structurre and function of the component can be edited), graphics (how does the component visualy appear on the interface), material finishes, analytical properties (such as thermal mass, heat transfer coeficient, absoptance, roughness etc. can be modified) and identity data (Figure 3.5). The categories vary depending on the type of component that is being modified.

3.3.1. Common modelling errors and their solutions

An important thing to keep in mind when working on Revit for further analysis is how geometry is modelled. All the components must be joined; however, they cannot intersect each other (ex. the walls must be joined using the “wall join” tool on Revit, with the command “mitter” so that the walls will be connected diagonally instead of the “butt” join which is the default setting on the program, (Figure 3.6). For further use, it is important to understand which types of analysis will be done, and on which specific surfaces or components they will be done. In this specific case, the analysis done were regarding thermal comfort and energy consumption, so it was important to have an enclosed space using the internal surfaces of the components.

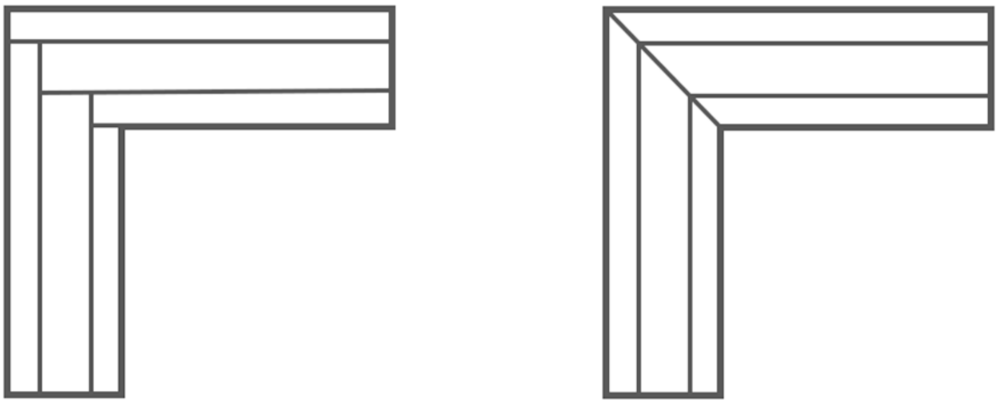


Figure 3.4 Types of wall-joins on Revit 1. BUTT 2. MITTER

In order to have a closed envelope in Grasshopper, it is important that the surfaces don’t intersect. Keeping this in mind, the next important model adaptation in Revit is the position of the floor and roof components. The option for the solution is to make the adaptation on Revit, since it is much easier to manipulate the elements there, instead of making the adjustments on Grasshopper. When constructing a roof element in Revit by default it is modelled to lay on top of the wall elements. However, this later becomes a problem since for the analytical model it is obligatory to have a closed boundary surface, meaning that all of the element’s edges should be connected and not exceed the border of one another. Once the roof component is modelled, in the option “Edit Footprint” it can be modified. When flipping the model lines, the borders of the roof element connect to the interior wall borders (Figure 3.7).

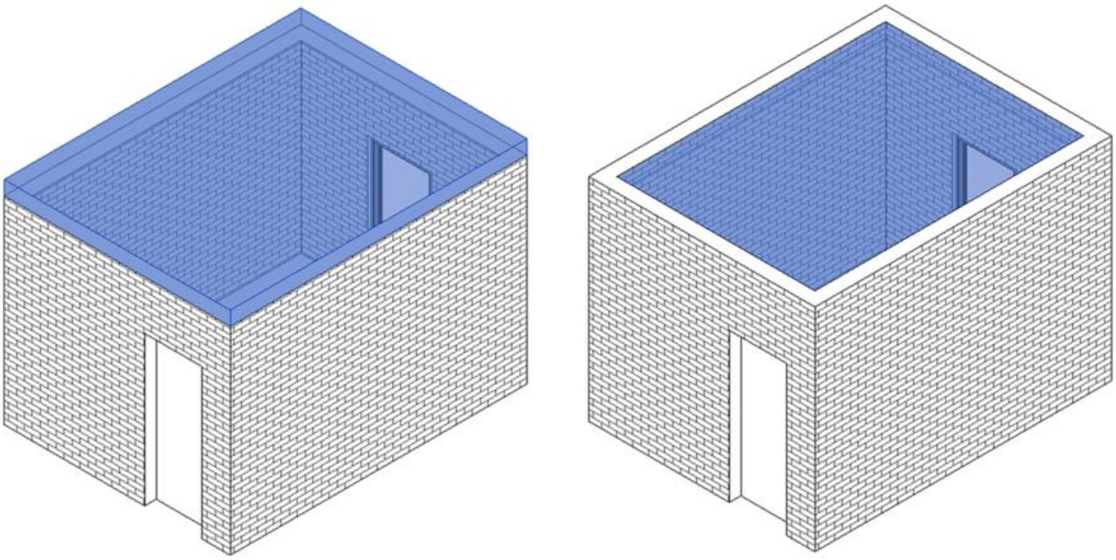


Figure 3.5 Modified inverted roof extrusion, inside the interior wall surface borders

The problem with the roof element can be spotted then the floor component is constructed. It is also modelled by default connected with the exterior wall borders and it is extruded downwards. The solution for this issue is like the floor adjustment, **w**hen the floor element is constructed, it can be also modified in the "Edit Footprint" tool in the commands tab menu. The model lines are flipped, and the floor borders are connected than with the interior wall edges. Also the extrusion is reversed, meaning the lower edges of the floor are connected to the starting edges of the walls.

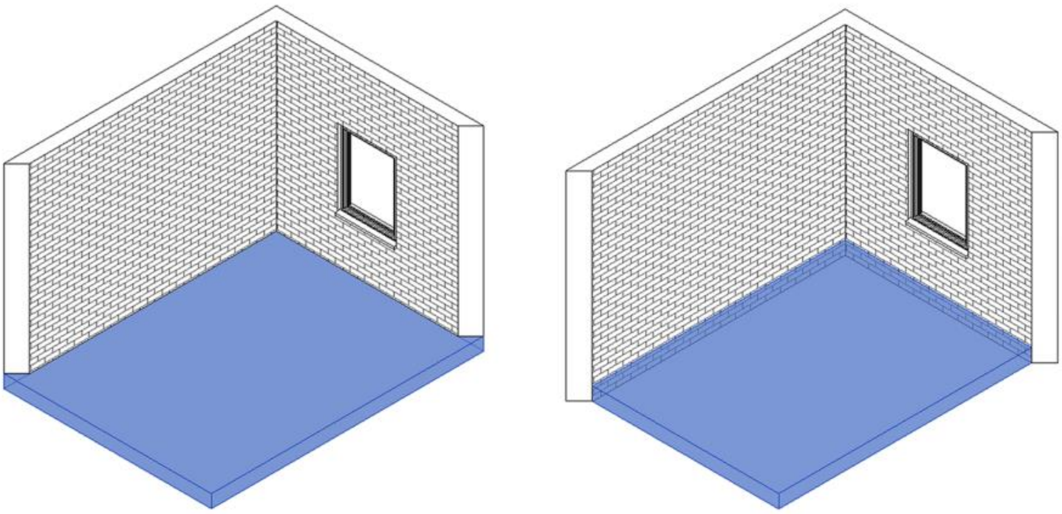


Figure 3.6 Modified inverted floor extrusion, inside the interior wall surface borders

3.4. Case Study I – Single zone model

The first case study was done on a simple "shoe box" type of model. The model represents a small office. The purpose of the simple model was to understand how the connection between the two software programs works. In this scenario, it was important to use simplified geometry in order to see what the capabilities of the programs are. It was of great significance to realize which information can be transferred and used for analysis and achieving smooth transfer of data. The other issue that was investigated was understanding which steps should be followed when modeling geometry so that is accepted by the other programs.

3.4.1. Model description

The geometry was modelled as a one zone office. Turin, Italy was assigned as the location for the analysis. The total floor area of the office is 11 m^2 with dimensions L: 4.2m, D: 3.2m and H: 3m. On the south-west facade there is a window opening with dimensions 1.2m x 0.9m. On the north-east facade a door was modelled with the dimensions 2.1m x 0.8m, however, the door opening was not taken into consideration when the thermal comfort and energy consumption simulations were done (Figure 3.7).

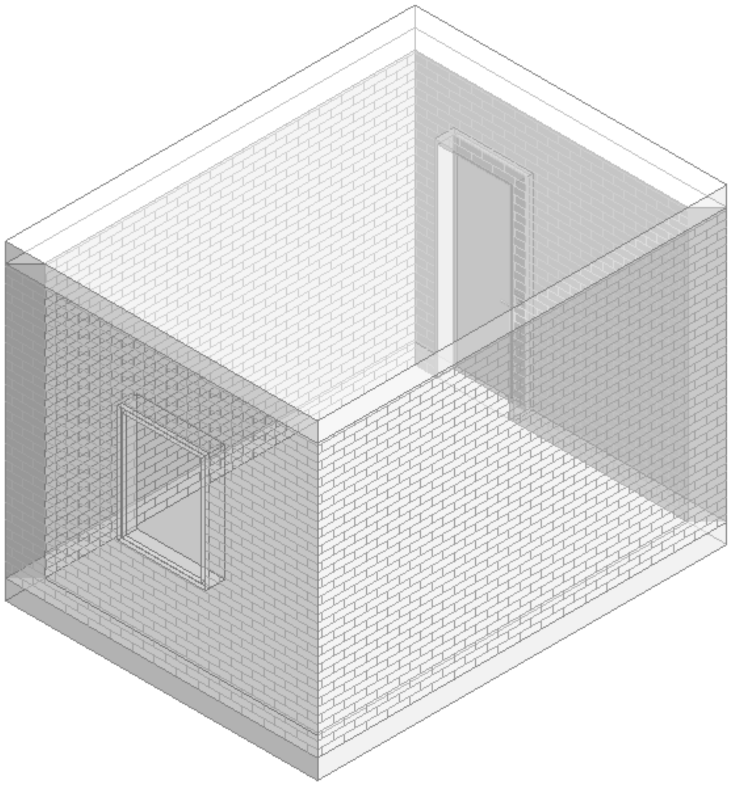


Figure 3.7 Graphical representation of the single-zone model

Since geometry is simple, it was also important that the layers of the components are also simple, meaning, the materials for each element are composed of one layer. The reason for this was to understand firstly, if and how the materials can be transferred and implemented in the simulation. In Figure 3.10, the material editor can be seen with the specific properties of each building element. The thermal transfer coefficient (U value) for all the opaque components is 5.23 W/m²K which is very high for a standard construction, but since the importance of the first case study was to understand what the possibilities of the programs are, it was important to keep the model simple, with only one material layer.

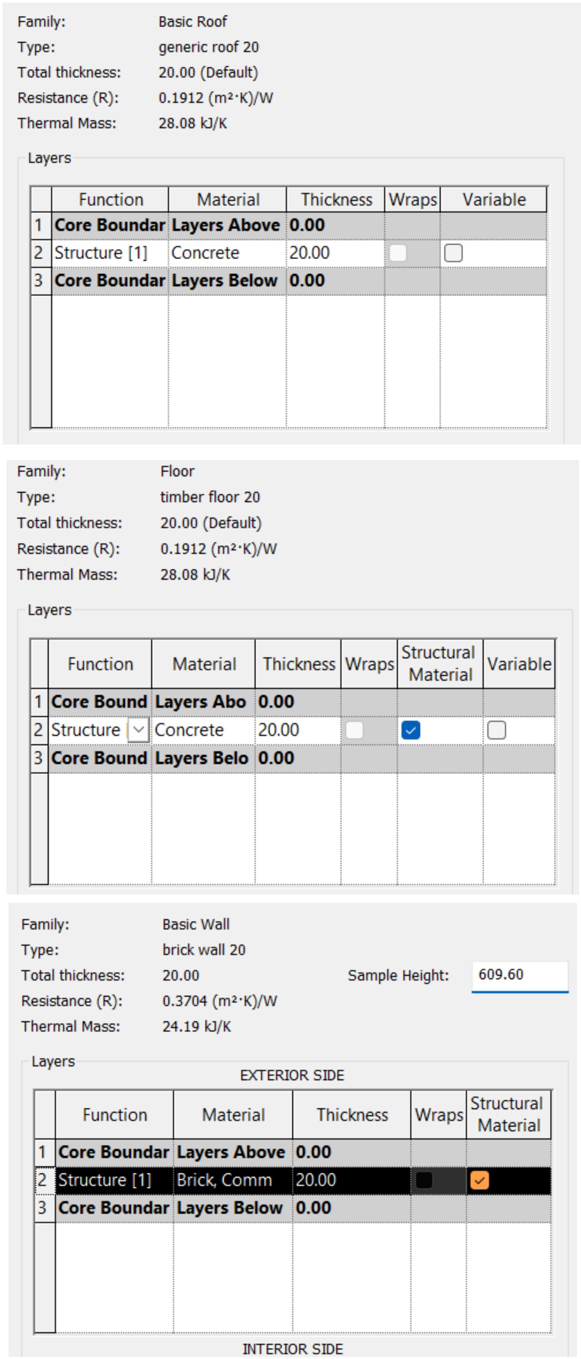


Figure 3.8 "Edit Type" menu where the construction can be edited for the elements on Revit, with the material properties

3.4.2. Importing process using .DWG file format

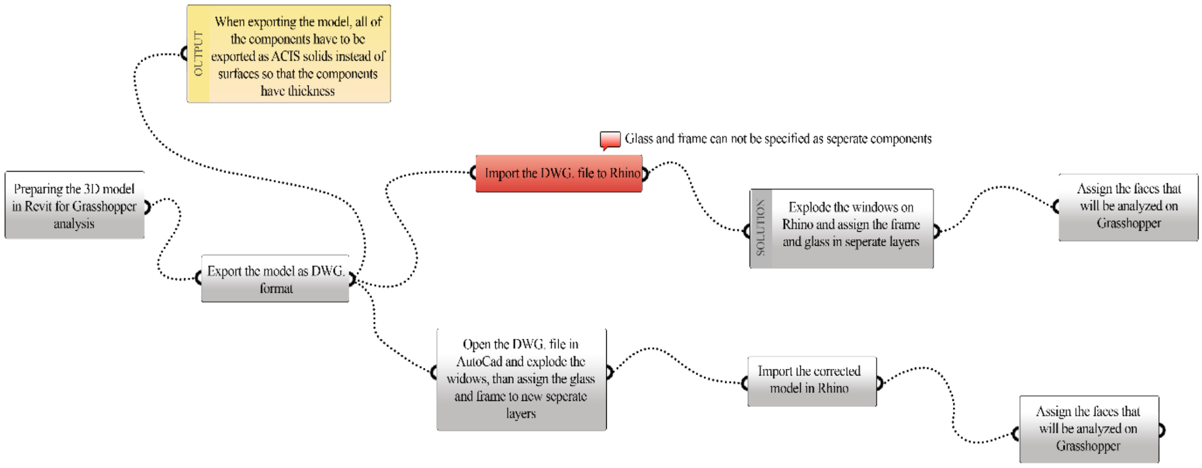


Figure 3.9 Graphical representation of the workflow using .DWG exportation

The next step was to import the model on Rhino. This is done by clicking on the “file” menu in the top bar on Rhino and then “import”. Furthermore, the model units are specified depending on the corresponding metrics of the ones in Revit. Once the model is opened on the Rhino interface, an important step in this process is to assign all the different elements in specific layers. This helps to simplify the process on Grasshopper when all the surfaces are selected for the analysis.

One thing that came up as an issue, was the window geometry. Since Revit uses a model family for the windows, the glazing surface and the frame are all recognized as one component. This is solved by exploding the window model on Rhino and assigning the elements to separate layers.

Furthermore, all the separate elements of the model were assigned on Grasshopper. This process started with the component “geometry” where all the separate elements like walls, floor, roof, and window (where the glass and frame were assigned in a separate geometry component) were selected by right clicking on the node and choosing “select one geometry”. The geometry is selected by clicking on the specific element on the Rhino interface.

3.4.3. Data loss when exporting as a .DWG file format

Even though this process is quite simple to use and understand, it has some issues. One of the biggest problems is the loss of data when the model is exported. The exportation of geometry is without flaws, if the correct approach is taken. However, the one thing that this process does not handle is the exportation of the component layers from Revit. One thing that in Revit is very useful for architects and engineers, is that the materials can be specified for each of the components in the material editor. All the specific materials can be assigned according to the user's needs and design ideas, but this information is not included in the export. The materials can be transferred by other methods, which are handled manually.

3.4.4. Geometry adaptation on Grasshopper

When the geometry is assigned on Grasshopper, the next step is to choose the desired surface so that the building envelope is a completely closed volume. In this specific case, the interior surfaces were picked for the simulations to be done on. The adaptations done on this model were quite simple. It was necessary to close all the surfaces where there is an opening and to assign the glazing on the closed surface. The rezoning behind this is that Honeybee does not accept any types of openings on the surface, even if there is another surface that closes this opening, it is still not accepted by the software. The solution is to have one completely closed surface, and then to add another one laying directly on it (ex. wall and window). There are multiple ways in order to do this. Firstly, the interior surface of the wall with the void is chosen (the surface is picked with a "Deconstruct Brep" component, that is connected to the output of the "Geometry" node, than "List Item" is plugged in with a number slider that allows the user to select the item from the list index), than the plane is closed with either choosing the end points of the surface or the edges (another "Deconstruct Brep" component is plugged in with a "List Item" where the vertices or the edges can be selected, than a two components can be assigned depending on the previous selection, either "4point Surface" (Figure 3.10) or "Boundary Surface").

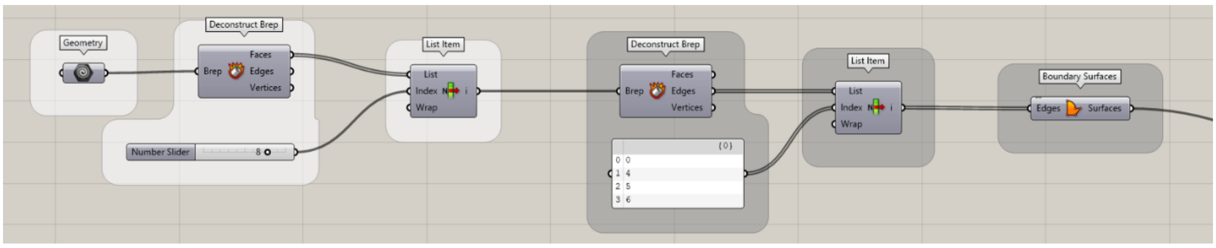


Figure 3.10 Grasshopper workflow of closing the window opening on the south-west facade

In the figure below (Figure 3.12) the outcome of the algorithm that is used is shown how it is visualized on the Rhino interface.

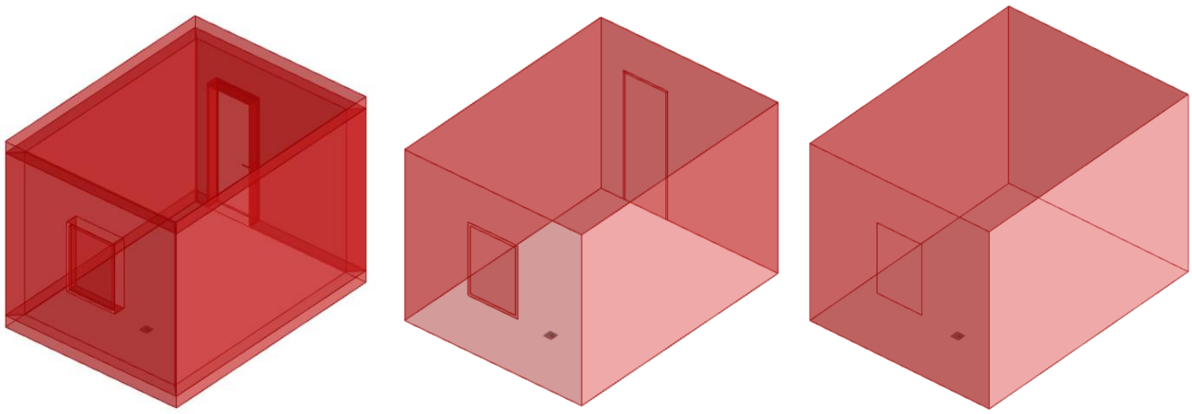


Figure 3.11 Visualized analytical model on Rhino: 1. Imported geometry; 2. Selected surfaces for the analytical model with window and door opening; 3. Closed boundary

3.4.5. Constructing a Honeybee model

Sequentially, the model must be converted into Honeybee model. In this process there are a couple of steps that must be taken in order to get the model ready for the next part.

3.4.5.1. Assigning surfaces as Honeybee faces

Firstly, Honeybee faces are created. Here all the previously chosen surfaces are added. The elements are assigned as categories (separate for each category ex. walls, floor, roof etc.). In the “Honeybee Face” component, are assigned all the material properties for each of the element’s layers. In the input “_geo” of the “HB Face” node, all the elements of the same category are assigned, that have the same material properties.

3.4.5.2. Opaque components with material properties

The opaque elements in this case studies are: four exterior walls, floor and roof. The “HB Face” component has multiple inputs where the type of element is specified as seen on Figure 3.12, Figure 3.13, Figure 3.14 and Figure 15. The input “_bc” specifies the boundary condition of the surface. It is used to specify the nature of heat exchange in energy simulations. The façade wall where the aperture is situated is set to “outdoors” but the other walls are set to “adiabatic”. The floor’s boundary condition is set to “ground” and the roof is set to “outdoors”. The input “_type” specifies what is the kind of geometry and it states how the layers of the materials are going to be generated (horizontally (for roofs, ceilings, roofs) or vertically (for walls or separators)). The properties of the materials are edited using the node “HB Opaque Construction”. There, the name of the component material is stated, and it is connected to a component called “HB Opaque Material”. In that component, all the detailed material properties, such as thickness, conductivity, density, specific heat, roughness, thermal absorbance, solar absorbance and visual absorbance.

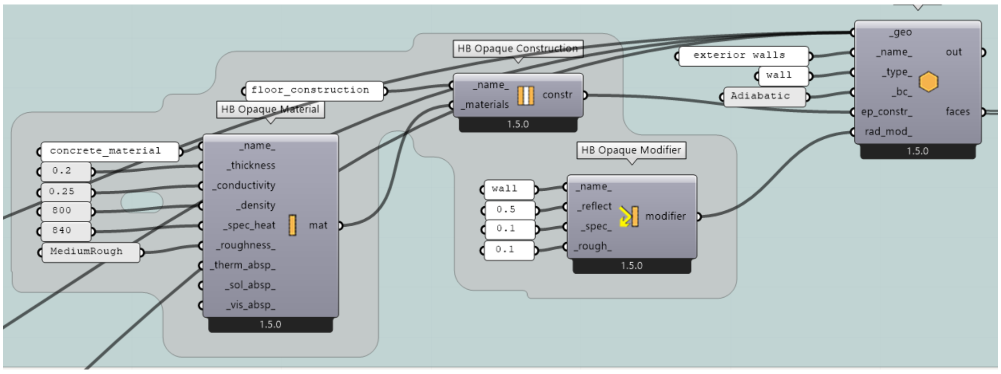


Figure 3.15 “HB Face” algorithm with construction modifier for opaque component- adiabatic walls

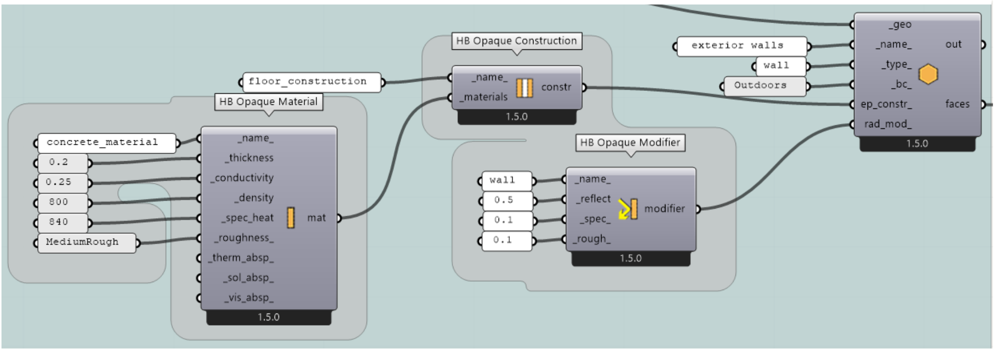


Figure 3.12 “HB Face” algorithm with construction modifier for opaque component- outdoors walls

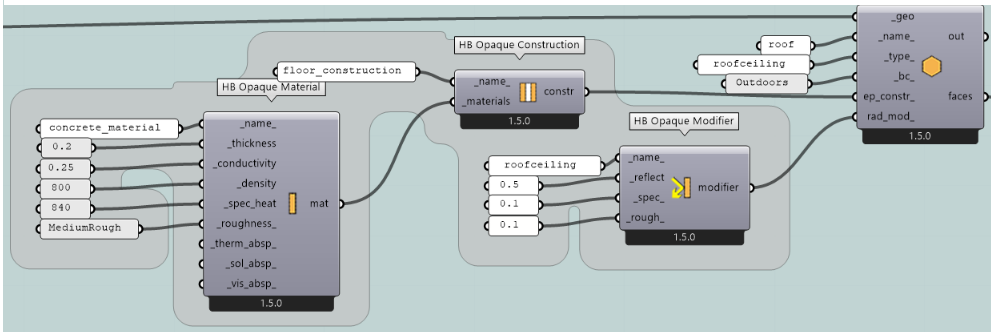


Figure 3.13 “HB Face” algorithm with construction modifier for opaque component- roof

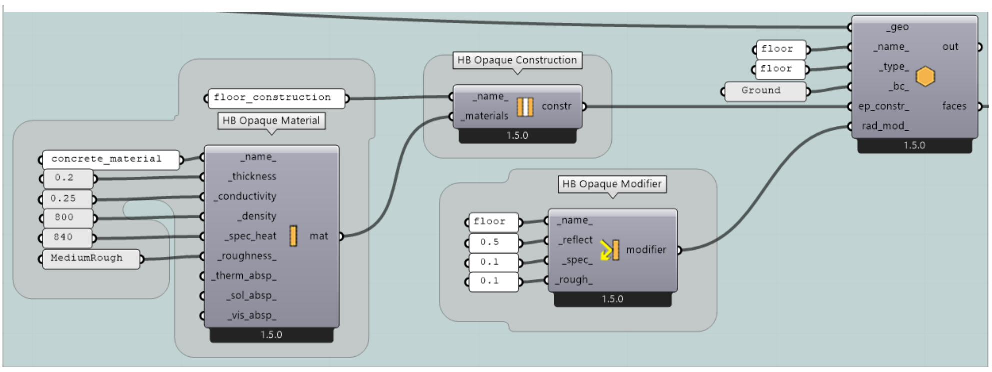


Figure 3.14 “HB Face” algorithm with construction modifier for opaque component- floor

3.4.5.3. Transparent components with material properties

When it comes to the glazing element, a different component is used, and the connection is slightly different. In this case “HB Aperture” is used. As a surface, only the glazing plane is used for analysis, without the window frame (since the window frame is an opaque component, it is taken as a part of the wall area). The material of the glass is assigned the same way as it is for the “HB Face” case. A “Boolean Toggle” is used in order to set the window as operable. This type of window is a single glass model without a gap as can be seen in Figure 3.16. The properties of the glass were calculated on the “GlassAdvisor” site [2]. The thermal transmittance (u) value of the glass is 5.8 W/m²K which is very high, and the solar factor (g) value is 86%. The window-to-wall ratio is 14.8%.

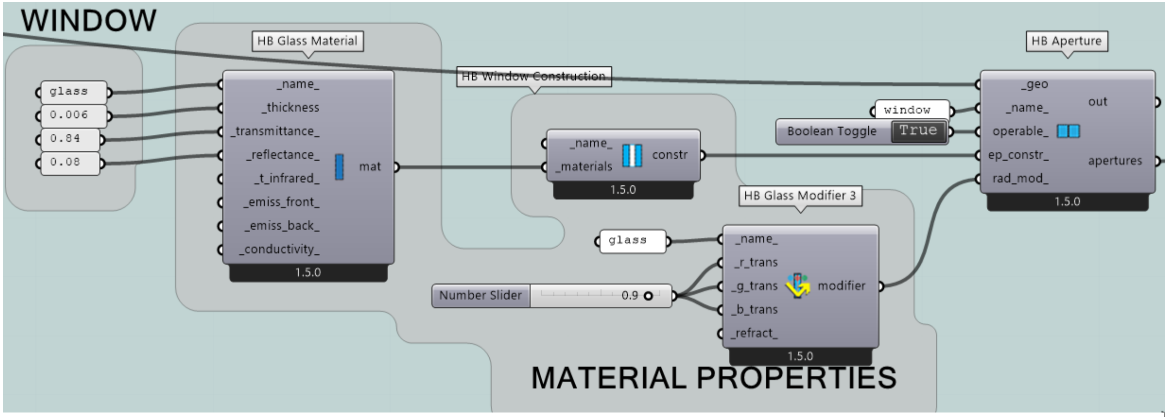


Figure 3.16 “HB Aperture” algorithm with construction modifier for transparent component

3.4.5.4. Constructing Honeybee Room

When all the faces are assigned with the appropriate constructions, they are connected to the component “HB Room” (Figure 17). It is important to have a closed volume here, to have a correct analytical room and for the component to work. Another thing that is set as input is whether the room is conditioned or not. In this case, a “Boolean Toggle” is connected that is set to TRUE, meaning that the office is indeed conditioned.

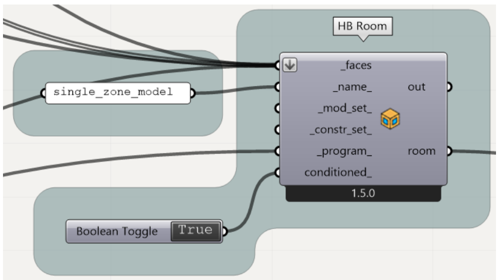


Figure 3.17 Creating a “HB” room algorithm

[2] https://www.glassadvisor.com/

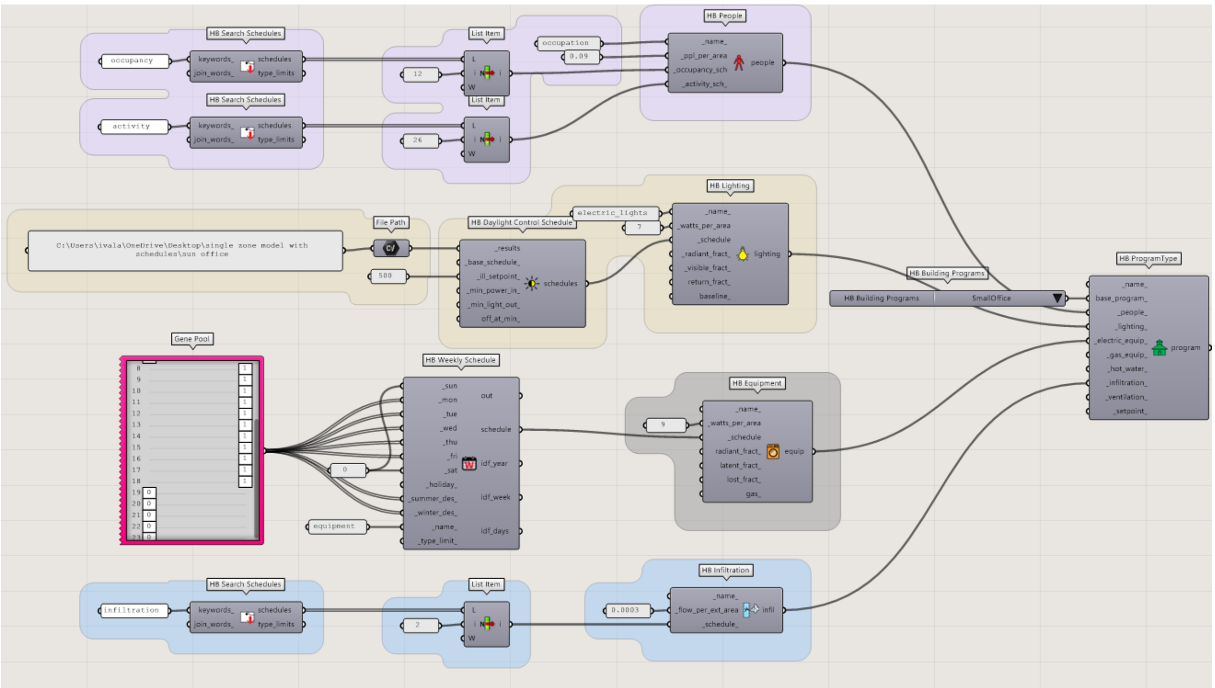


Figure 3.18 Creating a program type using the component "HB ProgramType"

In "HB Room" the building program is set as input "HB ProgramType" where the schedules and other important information regarding occupancy, electric lighting, electric equipment and infiltration are assigned. Firstly, regarding the occupancy, the office was designed for a single occupant, which in this case we input the value of 0.09 (number of occupants divided by area), then the power density for lighting is set to 7 Watts per m^2. Regarding the lighting schedule, a component called "HB Daylight Control Schedule" is assigned, where the illuminance set point is assigned to 500 lux. In the same component, in the input "_results" data from a daylight glare probability simulation is assigned. For the electric equipment, a schedule is assigned that states the working hours of the week and implies that the electric equipment is not used during the weekends, holidays and after the working hours. The power density for electric equipment is set at 9 Watts per $m^{2.}$ Next, regarding the infiltration loads, the input for the intensity of infiltration is set 0.0003 m^3 per second, which is an average value for an average building leakage. Lastly, since the model is a simple office, the program is set as Small Office (Figure 3.18).

3.4.5.5. Assigning a shading component to apertures

The process of assigning the aperture is slightly different. After all HB faces are assigned to the HB Room component, and there is a closed envelope, the node “HB Add Subface” is used, where the output of the HB Room is connected to “_hb_obj” and the “HB Aperture” is plugged in “_sub_faces”.

Furthermore, for the purpose of the research, it was important to find a way to generate a shading device on the apertures. The first type of shades that were assigned to the model were louver shades. The shades were added to the exterior surface on the window, using the “HB Louver Shades” components. The aperture geometry is connected through “HB Add Subface” in the “_hb_objs” input node in the shade component. What this does, it generates the shades on the assigned surface. Here, various parameters can be manipulated such as the angle of rotation, panel count, surface offset, distance between panels, whether they are set vertically or horizontally etc.

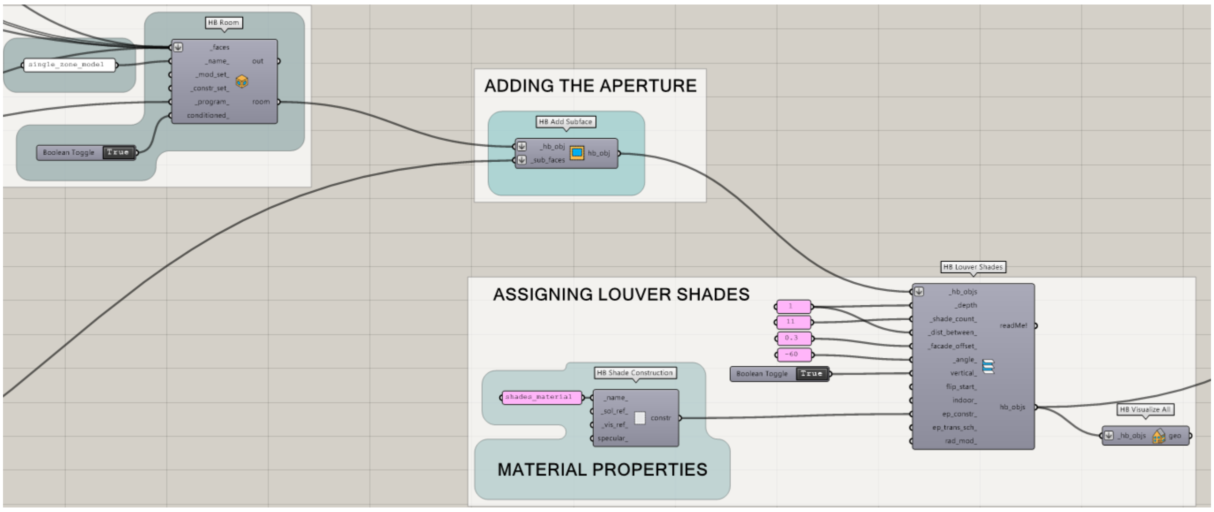


Figure 3.19 Assigning "HB Louver Shades" to the "HB Room" algorithm

Another topic of research was whether the shades could be generated and if they could work as dynamic shading system and two approaches were undertaken.

Primarily, it was researched whether there is a possibility to assign a schedule to control the rotation of the shade panels according to a DGP annual simulation. The results were divided into two types of “HB Day Schedules” one for a summer day and another for a winter day where the glare is the highest. The result was converted into an approximate angular rotation of the panels corresponding to the result. The angles for the shades started from -90° (completely closed) to 0° (completely opened).

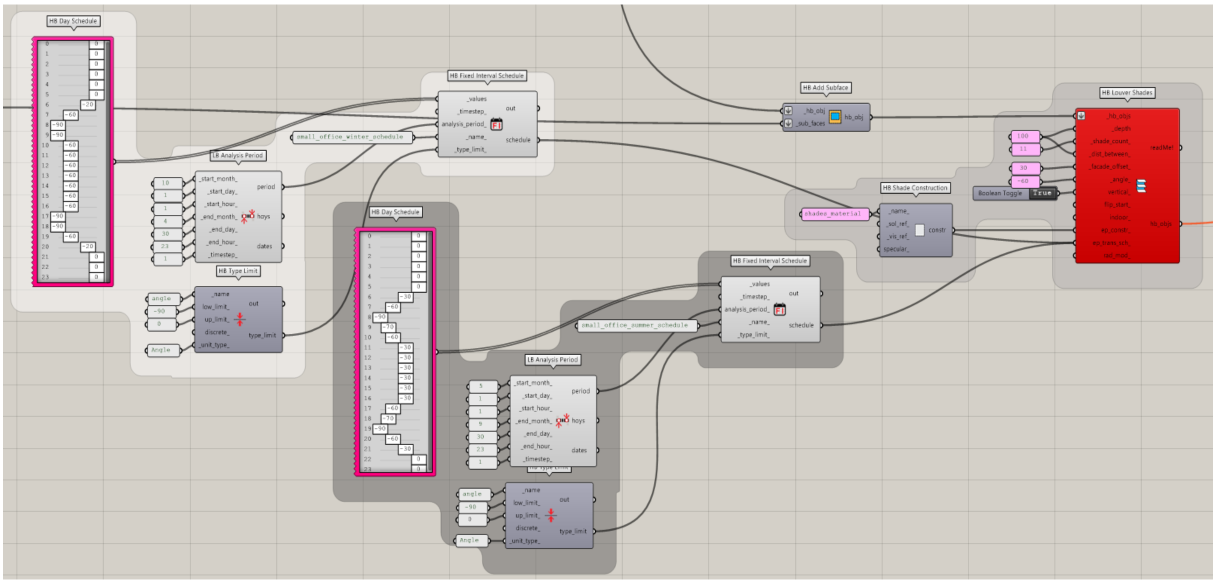


Figure 3.20 Adding seasonal schedules to the louver shades for dynamic rotation

With this process, it is not possible to make the shading system dynamic, since the schedule type is not supported by the “HB Louver Shades”. An error pops up which says that schedule should be fractional (dimensionless) and the information that the component got is not recognized. There is a component by the developers of Honeybee that to this day it is in the process of development. The result of the first trial led to the second method. This time static louver shades were used. The reason behind this was to understand whether the shades make any type of changes in the energy consumption and thermal comfort simulations. The simulations were done once without the louver shades and once with, in order to see what kind of impact they will have on the indoor environment thermal conditions and regarding that, what will be the energy consumption result.

3.4.5.6. Assigning a HVAC system

Next on, an HVAC system is added to the Honeybee room so that the indoor temperature can be controlled regarding the occupants needs. The desired temperature is set from 20°C to 26°C. These parameters were set regarding the PMV results, where the metabolic rate of the occupants was set to 1.1 met, which means that the people are sitting and typing. The clothing insulation was predicted by assigning a component which controls the clo by the outdoors conditions. The thermostat of the “Ideal Air” was tested to see in which conditions the predicted mean vote was most neutral and the percentage of dissatisfied is the lowest. The schedule for the HVAC system is regulating when heating or cooling is activated. This is done by assigning a designed weekly schedule for the summer and winter seasonal schedules. The schedule states the working hours of the week and implies that the electric equipment is not used during the weekends, holidays and after the working hours (Figure 3.21).

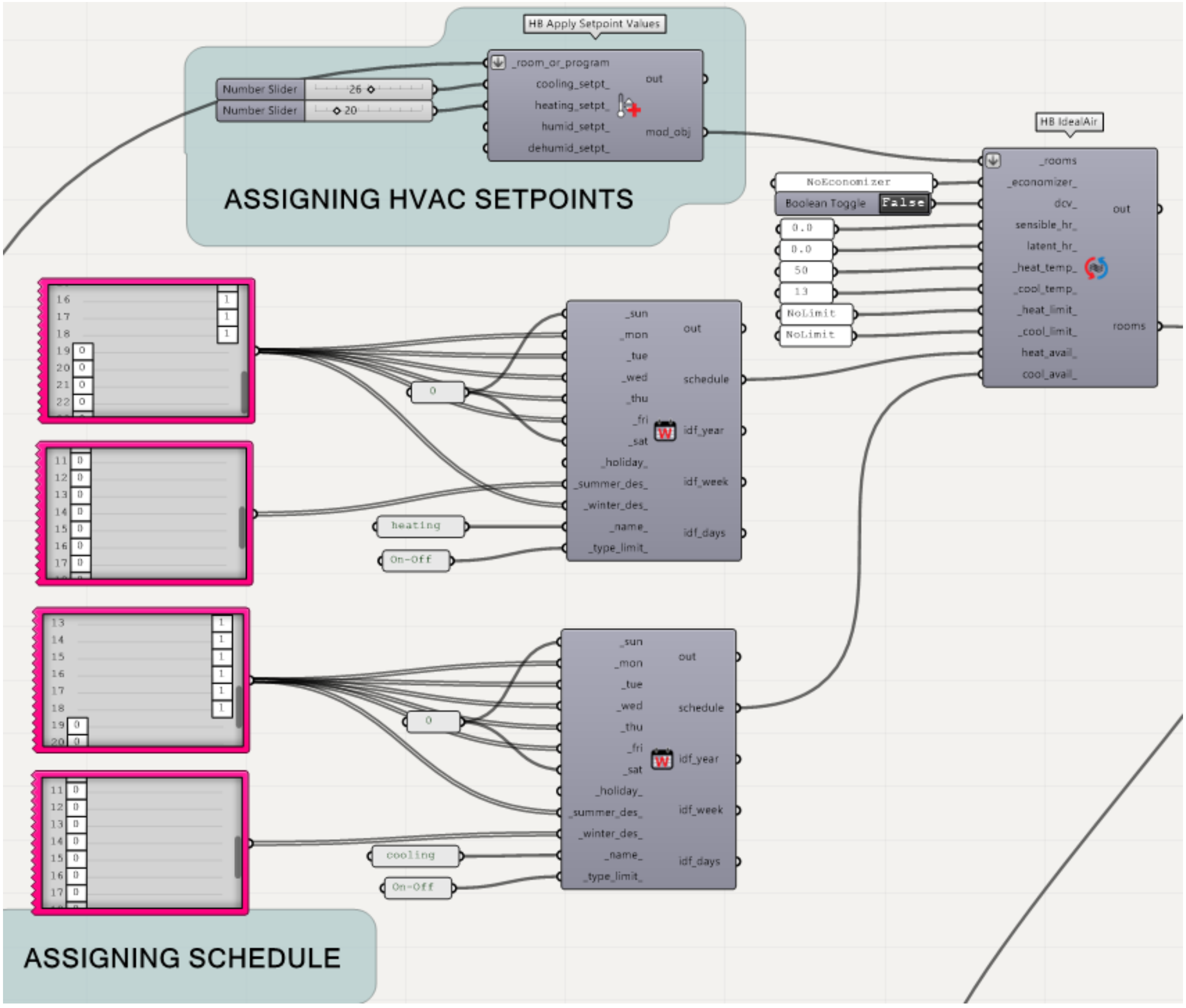


Figure 3.21 Assigning HVAC system with the component "HB Ideal Air"

Lastly, a window opening control component is assigned that controls the ventilation of the building. In order for this component to work (figure 3.22) the apertures have to be assigned as operable before, when assigning the "HB Aperture" component.

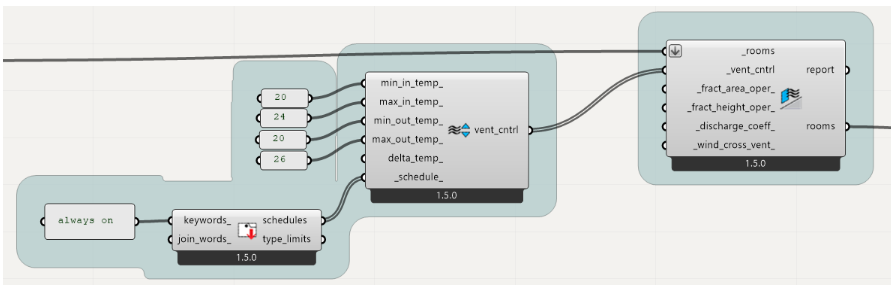


Figure 3.22 Assigning a window control component "HB Window Opening" to apertures

3.4.6. Simulation model inputs

The simulations that were done in this research are about energy consumption and thermal comfort. OpenStudio was used as a cross-platform, using the engine Energy Plus. The simulations were done for a period of one year. The location assigned was Turin, Italy. The epw. file was downloaded from the website from Energy Plus weather data, which gave the information about all the information about the natural conditions on the specific location.
The component used to set these inputs is “HB Simulation Parameters” where, firstly, “HB Simulation Outputs” is plugged in. There the user can create a simulation output object by selecting sets of commonly requested output variables. In this case the zone energy use is set to true to add output for zone energy use when “Ideal Air” systems are assigned. This includes heating, cooling, lighting and electric equipment. Next, a “Boolean Toggle” set to true is also connected to “gains_and_losses_”, where it gives information about the zone gains and losses. This gives output for various parameters such as: people gains or losses, solar gains or losses, infiltration gains or losses etc. The “comfort_metrics_” gives an output for the zone thermal comfort analysis, such as: mean radiant temperature, air humidity, relative humidity, operative temperature etc. Output parameters are also taken into consideration “surface_temperature_” (that it adds outputs for indoor and outdoor surface temperatures) and “surface_energy_flow_” (which adds outputs for energy flow across all surfaces). Finally, the last input in this component is in “load_type_”, where a panel is connected stating “All”, meaning that all energy use is taken into consideration, including heat loss from the zone.

Next on, the analysis period is set with the component “LB Analysis Period”. The parameters are set for the whole year, for 24 hours a day. The “HB Simulation Control (SimControl” command creates simulation controls with instructions for which types of EnergyPlus calculations to be done. Here, all the inputs are set to false, except the “_for_run_period”.

Furthermore, the “HB Shadow Calculator” is assigned and it is set to do a full interior and exterior simulation. It simulates the model with a direct sun. It takes into consideration the surrounding geometry and it generates the solar rays within that consideration. Finally, a “HB Sizing Parameter” is assigned. Here the weather file is connected as an .ddy file. This file contains information about the design days that are used for the sizing of the HVAC system. Figure 3.23 shows all these inputs plugged in the e “HB Simulation Parameters” component. Together with the complete HB Model and an .epw file, these complete all the inputs needed to run the simulations via OpenStudio.

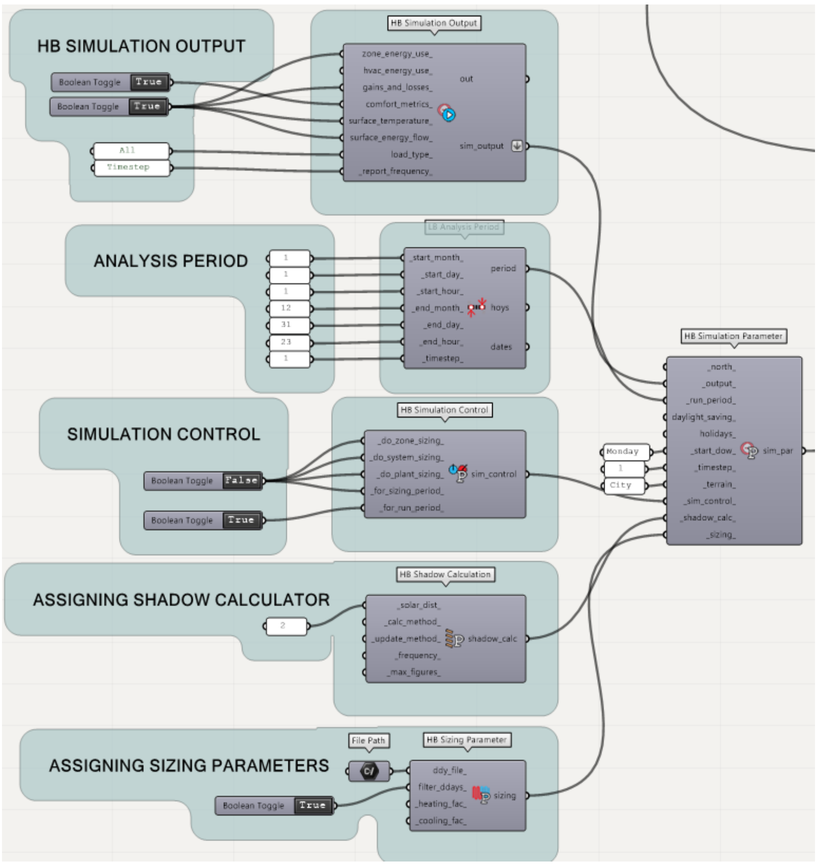


Figure 3.23 Simulation model inputs

In order to read the desired custom results, in this case, the desired outputs had to be added as a string to the OpenStudio component. The string is written in the format "*Output:Variable,*,Variable_name,report_frequency;*". Together with the complete HB Model and an .epw file, these complete all the inputs needed to run the simulations via OpenStudio (Figure 3.24).

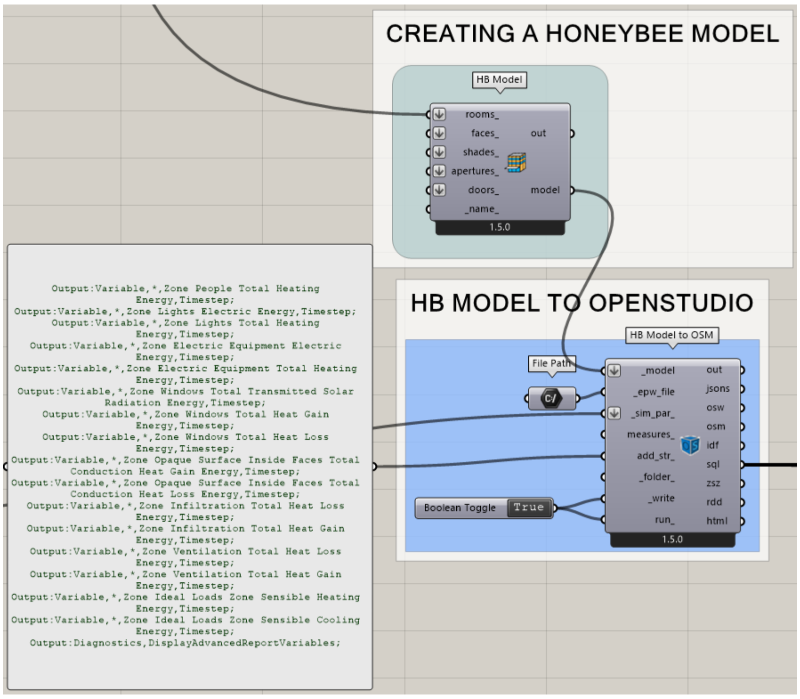


Figure 3.24 Requesting the desired outputs and running the simulations

3.4.7. Energy Simulations Visualization

The last part of the energy simulations is the reading and visualization of the results. Primary, an algorithm was assigned to calculate the energy balance results. The balance outputs represent the energy gains and losses. In order to read the previously assigned strings as outputs, a component that is called "HB Read Custom Result" is connected to the "_sql" output that is located on the OpenStudio component that runs the simulation. In the component that reads the custom results, the output name is assigned regarding the output that is desired to be analysed. The requested results that were derived in this case were: Zone People Total Heating Energy, Zone Lights Total Heating Energy, Zone Electric Equipment Total Heating Energy, Zone Windows Total Transmitted Solar Radiation Energy, Zone Windows Total Heat Gain Energy, Zone Opaque Surface Inside Faces Total Conduction Heat Gain Energy, Zone Infiltration Total Heat Gain Energy, Zone Ventilation Total Heat Gain Energy, Zone Windows Total Heat Loss Energy, Zone Opaque Surface Inside Faces Total Conduction Heat Loss Energy, Zone Infiltration Total Heat Loss Energy and Zone Ventilation Total Heat Loss Energy. An important thing to note here is that for the energy losses to be presented as negative values on the chart, the values were multiplied by -1 (Figure 3.25 and Figure 3.26). Also, the metric units must be checked, since the data might be in joules and the values might have to be converted in kWh. Lastly, Ladybug offers the opportunity for visualisation of the data with the component "LB Monthly Chart", however, in this case the data was extracted from Grasshopper and the visualization of the charts was done on Excel which offers the option for wider variety of chart types.

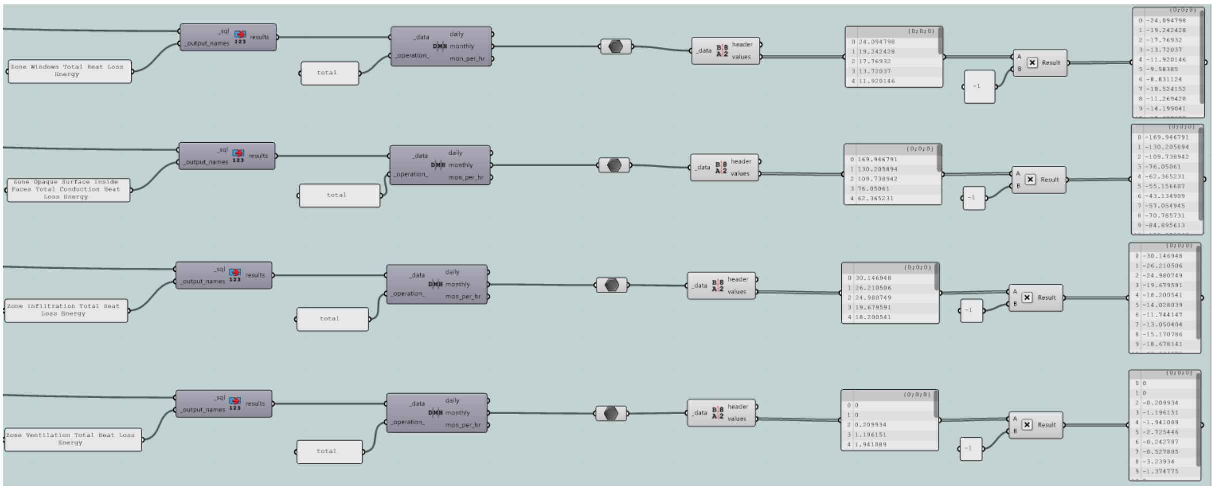


Figure 3.25 "HB Read Custom Results" requesting results for energy losses

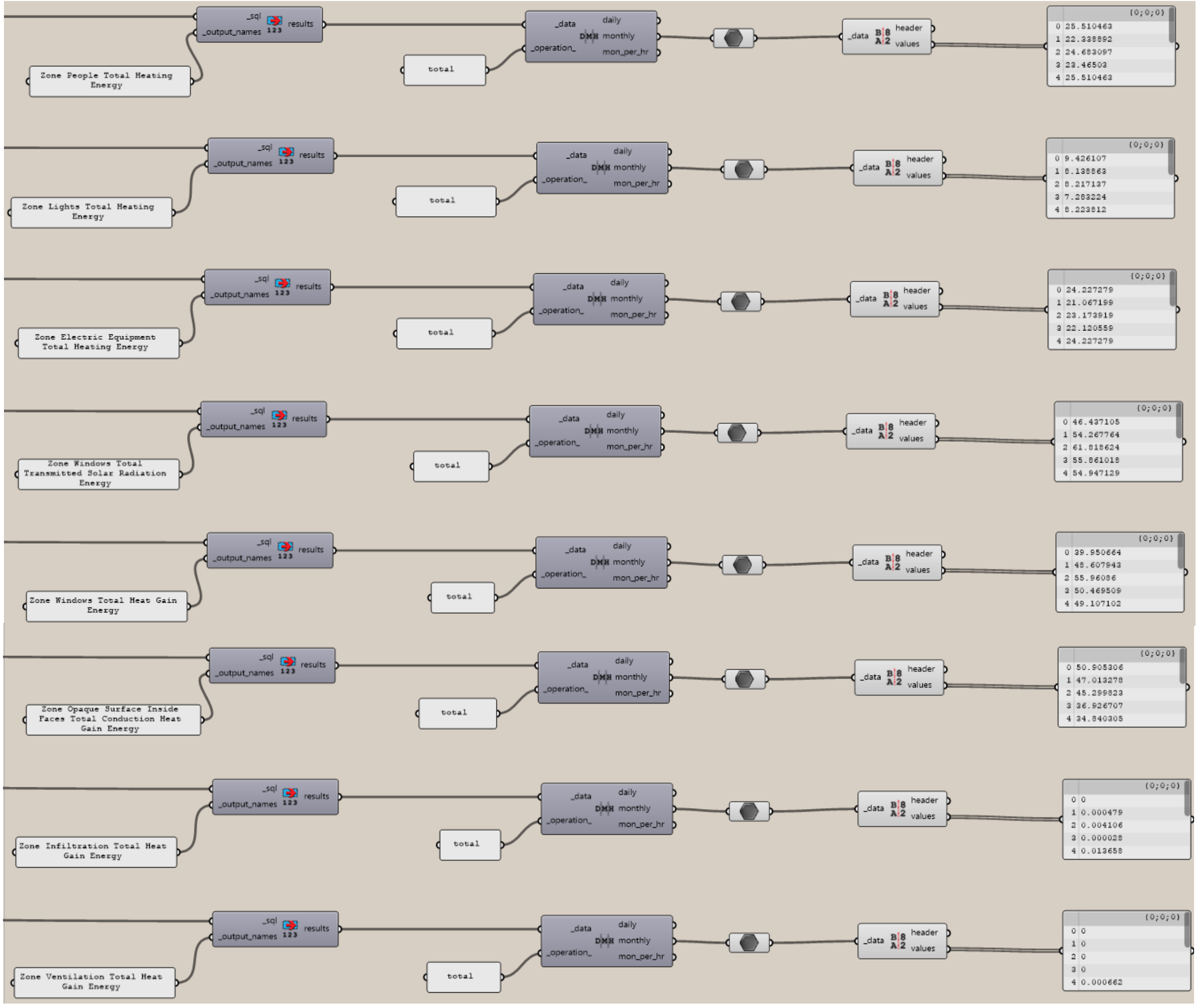


Figure 3.26 "HB Read Custom Results" requesting results for energy gains

Next the primary energy use was calculated. Using the component "HB Read Custom Results" that allows the users to see the specific energy results for all the components in the building that the simulations are done on. The results that were derived from this component were the energy loads. In order to convert the results to primary energy use, firstly they were divided by the specific efficiency factors (heating 0.85, cooling 3.2, electric lighting 1 and electric equipment 1) and multiplied by the specific primary energy factors (natural gas 1.05 and electricity 2.42) and lastly, the results are divided by the total area of the zone on which the analysis are done. Here the impact of the systems can be seen and how they correspond with the geometry that they are assigned to. A monthly or an hourly chart can be done for a graphical representation with the components "LB Monthly Chart" and "LB Hourly Chart". This process can be seen on Figure 3.27.

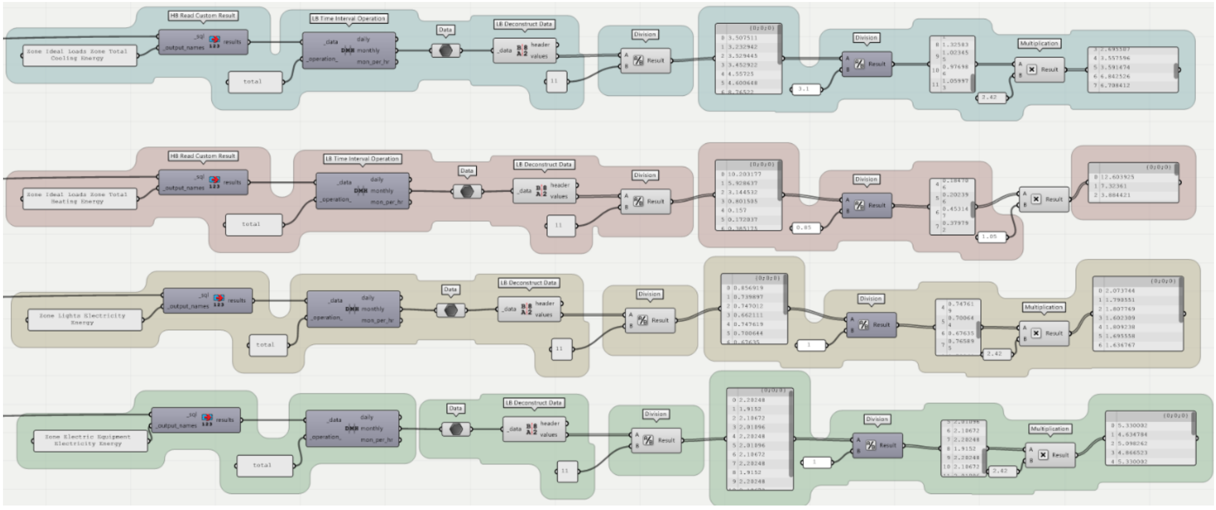


Figure 3.27"HB Read Custom Results" requesting results for energy uses and converting it to primary energy used

3.4.8. Thermal Comfort Simulations Visualization

The final part of the thermal comfort simulations is the visualization of the results. Once all the needed inputs are added to the OpenStudio component, from the "sql" output is connected to the component "HB Read Room Comfort Result" in order to visualize the thermal results. Then the outputs for operative temperature, mean radiant temperature and air temperature are represented with a heat map with the component "LB Hourly Plot" (Figure 3.28).

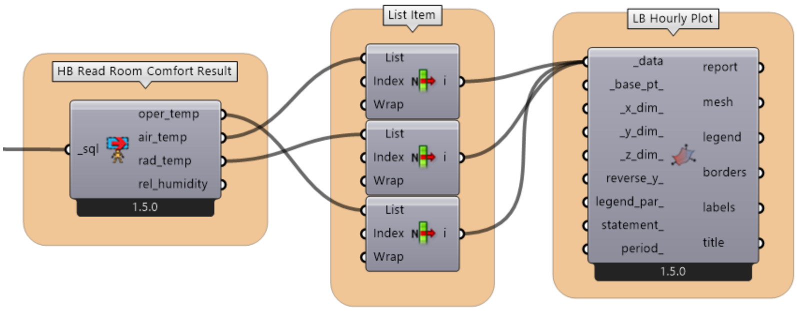


Figure 3.28 "HB Read Room Comfort Results" algorithm for thermal comfort visualization

The last analysis that is visualized is the PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied). This is achieved with the component "LB PMV Comfort" which can later visualize the charts for PMV and PPD. The values for the metabolic rate of the occupants were set to 1.1 met, which means that the people are sitting and typing. The clothing insulation was predicted by assigning the "LB Clothing by Temperature" component which controls the clo by the outdoors conditions. The full algorithm of the process is shown on Figure 3.29.

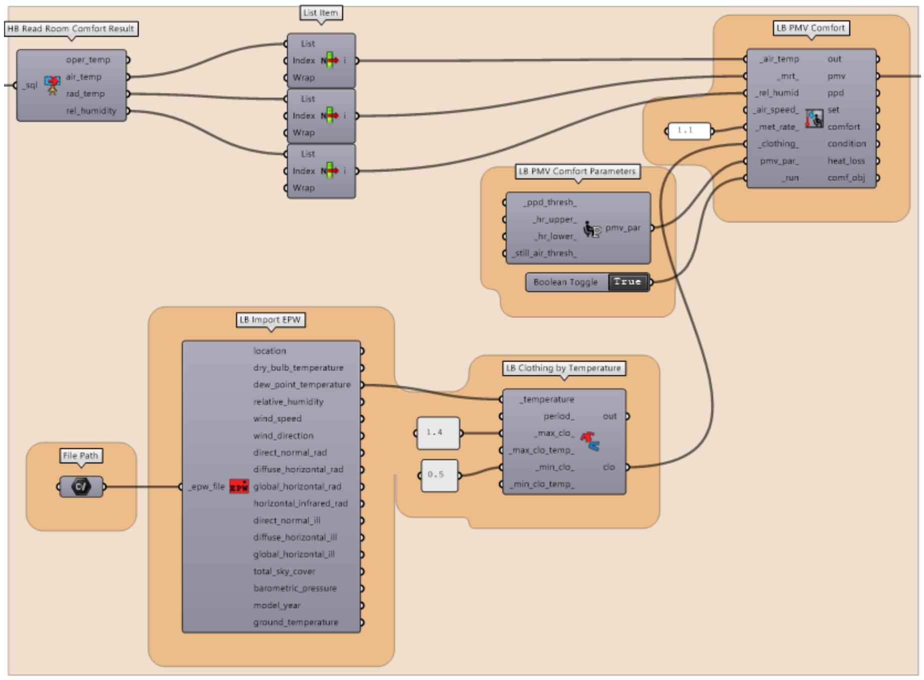


Figure 3.29 PMV analysis algorithm

3.5.Case study II – Multi zone model

The second case study is a multizone model, representing an office building, with a more detailed component layers, different sizes and types of window openings and it contains a curved wall. The reasoning behind the design of the second case study is to understand the strengths and limitation of the simulation tools when it comes to a building where more than one zone or room must be analysed, in fact the whole construction. With this information, it was important to see if the same workflow as the single zone model can be implemented to run the simulation on the multizone model.

3.5.1. Model description

The geometry is modelled as a multi zone, office building. The location for the second case study, as well as the first one, was taken Turin, Italy. The gross floor area of the construction is 128 m2. The hight of the construction is 4.5m. The entrance of the building is situated on the north façade The door was not taken into consideration when the thermal and energy simulations were done. On the south façade, there is a curtain wall, where the conference room is situated. In the building there are six offices that have different sizes, one toilet, one utility room, a conference office and finally a hall with an entrance. Each of the rooms have different window shapes and sizes (Figures 3.30 and 3.31).

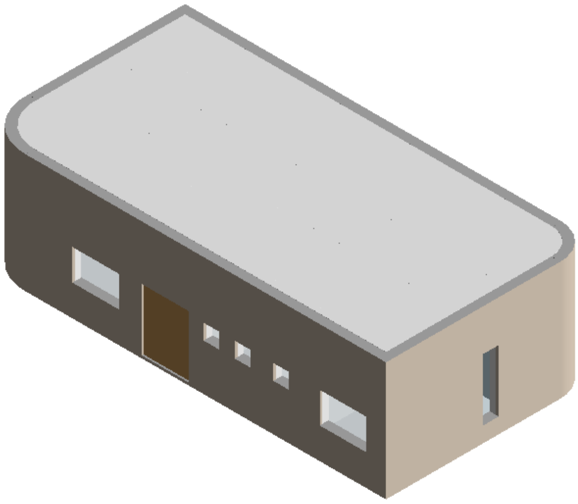


Figure 3.31 North-west facade of the multizone model

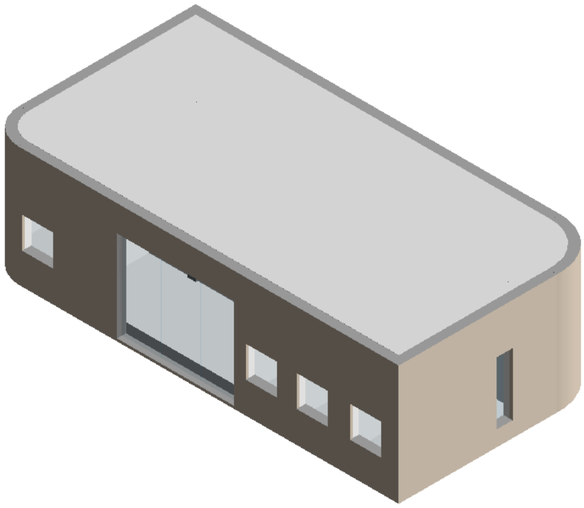


Figure 3.30 South-east facade of the multizone model

Table 3-1 Window to wall ratio (multi-zone model)

Room type	Wall Area [m^2]	Glazing Area [m^2]	WWR [%]
Office 1	11	2.2	20.0
Utility 2	6.6	0.4	6.1
WC 3	9	0.8	8.9
Corridor 4	9	1.4	16.0
Office 5	16.6	2.2	13.3
Office 6	13.2	2.4	18.2
Office 7	7.4	2.4	32.4
Office 8	7.8	2.4	30.8
Conference Room 9	6.6	16.2	245.5
Office 10	25.8	2.4	9.3
All Rooms	113	32.8	29.1

3.5.2. Material properties on Revit

In comparison to the first case study, where layers of the components are simple, meaning, the materials for each element are composed of one layer, for the second case study, each of the components have a collection of material layers. The reason for this was to understand firstly if and how the materials can be transferred and implemented in the simulation but also, to have the information regarding the properties and performance of the materials. Figure 3.32, the complete list of materials that are assigned to each of the families in Revit can be seen. This can be done in the "Edit Type" menu in the "Properties" Revit menu.

The thermal transmitance (u value) of the components are: external wall 0.21 W/m²K, interrior 0.34 W/m²K, floor 0.18 W/m²K and 0.22 W/m²K for the roof.

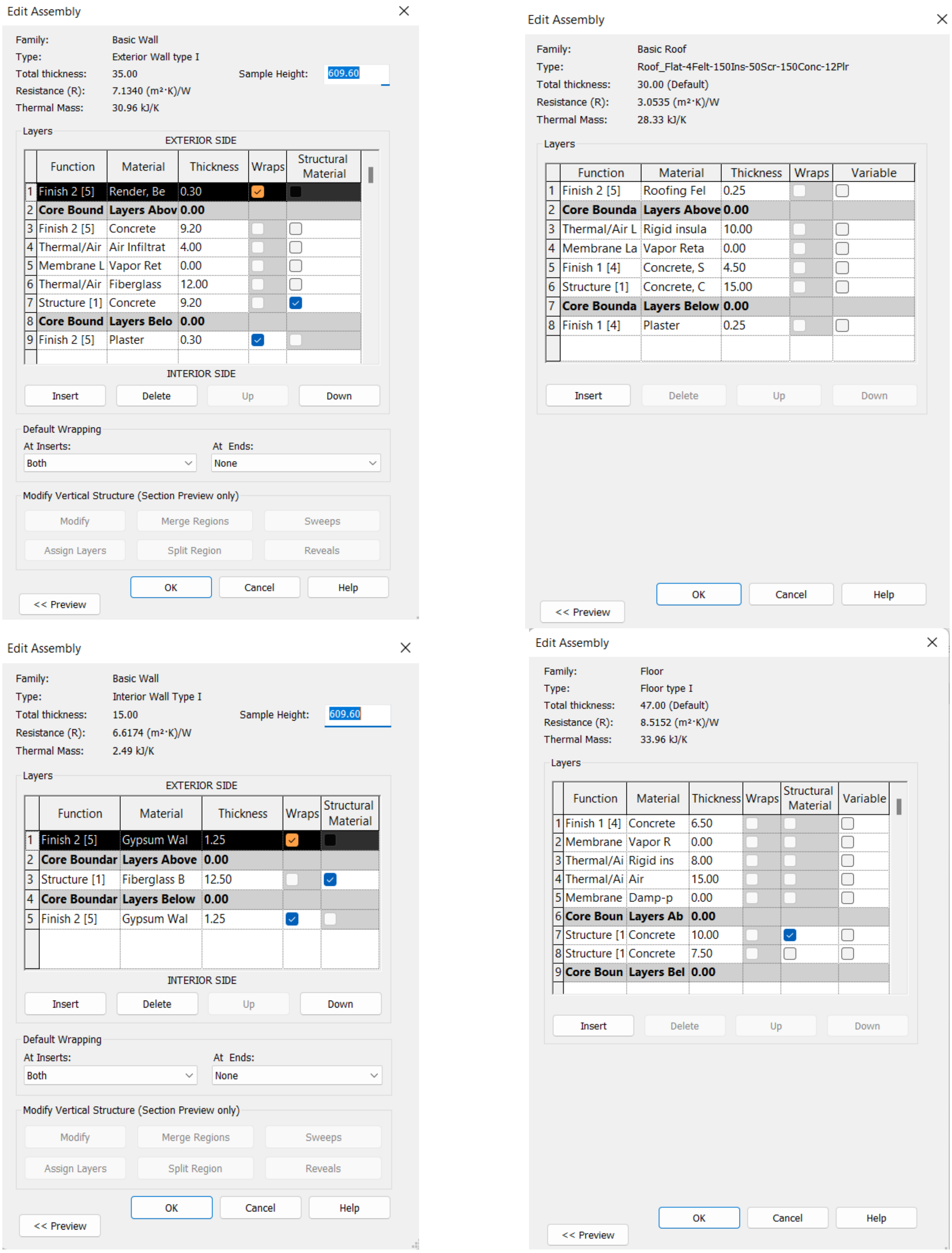


Figure 3.32 “Edit Type” menu where the construction can be edited for the elements on Revit, with the material properties for the multizone model

3.5.3. Assigning rooms on Revit

In order to have an easier data transfer when exporting the model, for this case study a different approach was taken. Firstly, all the zones were defined in Revit as rooms. This can be done with the command called "Rooms" in the architecture tab. This command creates rooms from boundary elements such as walls, floors, ceilings and other separators. The room boundaries are automatically assigned; however, they can be edited regarding the needs of the user. In Figure 3.33, the floorplan of the multizone model can be seen, with the assigned room programs and the area.

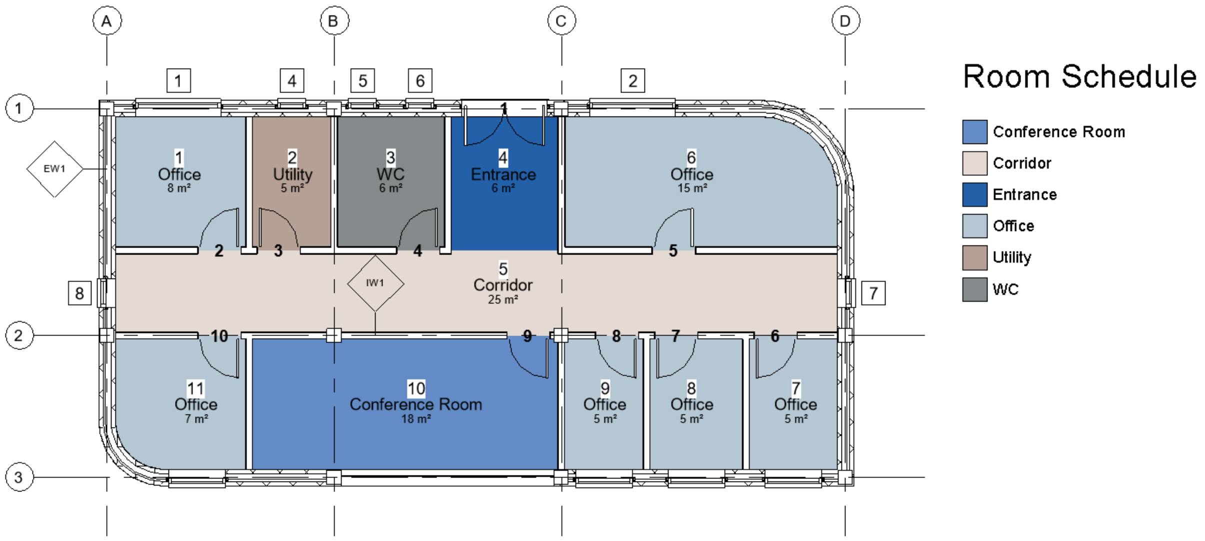


Figure 3.33 Floor plan of the multizone model with room programs

3.5.4. Exportation process using Speckle stream

Once the model geometry is finished with the materials assigned and the room programs, it can be exported. For the second case study, a different workflow was tested. This method was with the Speckle stream. Since Speckle is quite new on the market, the only information and instructions regarding the use of it, were found on the official website[3].

Once the appropriate connectors are installed for the Revit and Grasshopper, the process of the exportation can begin. The Speckle command is found in the "Speckle" tab on Revit. On the Speckle stream, various data can be transferred. In this case, only the room geometry could be transferred. By clicking on the command "Revit Connector", the stream window is opened. There is a library with past Speckle streams that the user has created in the past, or there is also

[3] https://speckle.systems/

an option of creating a new stream. There is an option to choose which elements the user wishes to transfer to the cloud whether by category (family) or the whole geometry on the Revit interface. In this case, the whole geometry of the interface was transferred. Once the geometry that should be transferred is chosen, it is sent to the cloud by clicking the blue button on the right bottom corner (Figure 3.34). The user can open the link that leads the user to the online cloud, this link can be found in the window of the stream. On the cloud, the geometry is visualized, and in the drop menu on the left side, the list of elements by category can be found (Figure 3.35).

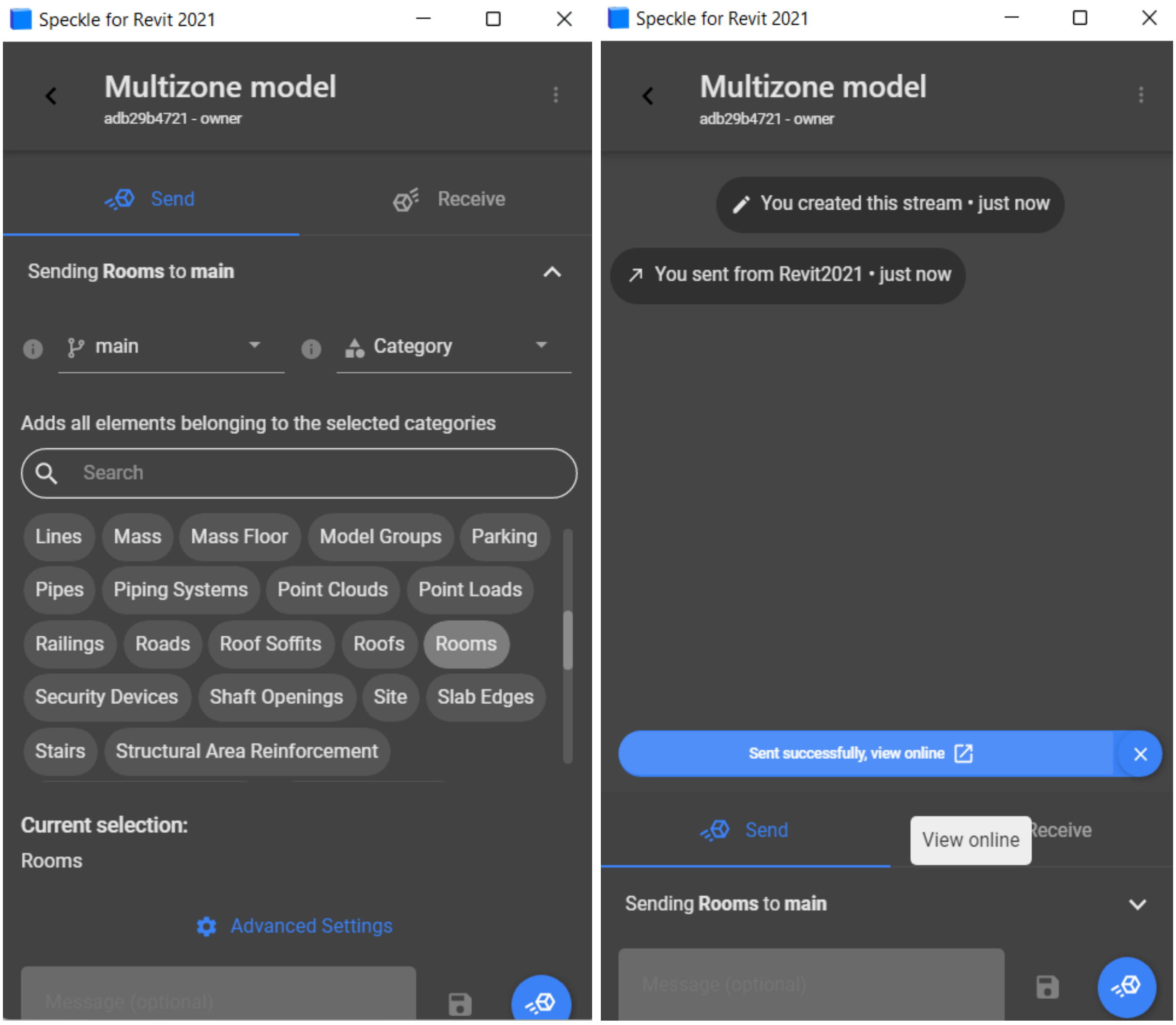


Figure 3.34 1. Choosing the geometry on Revit that will be transferred using the Speckle stream; 2. Speckle stream window that contains the link to the online Speckle cloud

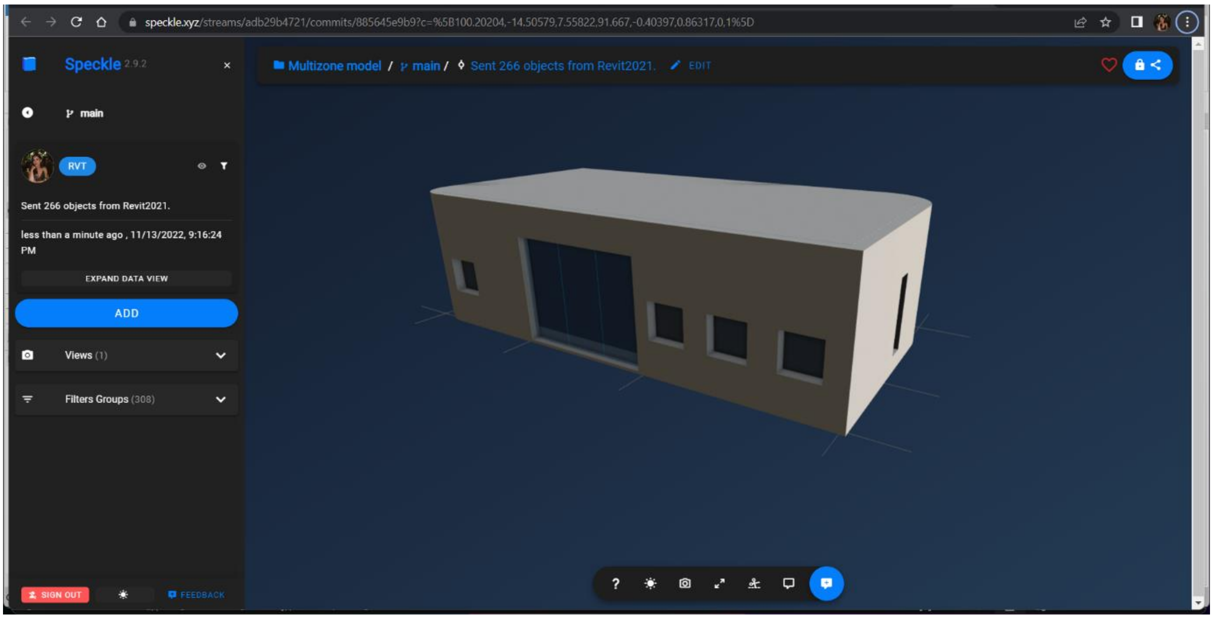


Figure 3.35 Visualization of the geometry that was received on the Speckle cloud

3.5.5. Data loss when exporting via Speckle

The exportation procedure used for the first case study encounters the same type of problem as this procedure. Data loss when the model is exported is one of the biggest issues. If the right strategy is used, geometry exportation is flawless. The exportation of the component layers from Revit is the only thing that this procedure cannot handle. According to the user's requirements and design preferences, all the specific materials can be assigned, but this information is not included in the export. Other manual handling techniques can be used to transfer the materials.

3.5.6. Receiving the model on Grasshopper

When Grasshopper is opened, and after the Speckle connector for Grasshopper is installed, in the Speckle 2 tab, the component "Receive" can be found. With this component, the model that was previously sent to the Speckle cloud can be imported onto the Grasshopper and Rhino interface. This is done by connecting the component input to a panel where the link of the online stream is inserted. Then a list of the components by category is opened, where the user can choose which elements are needed for future use. In this case, the room geometry with windows was chosen. Next, the geometry is baked so that the specific rooms later can be used separately. In order for easier manipulation of the geometry, the Speckle object was baked.

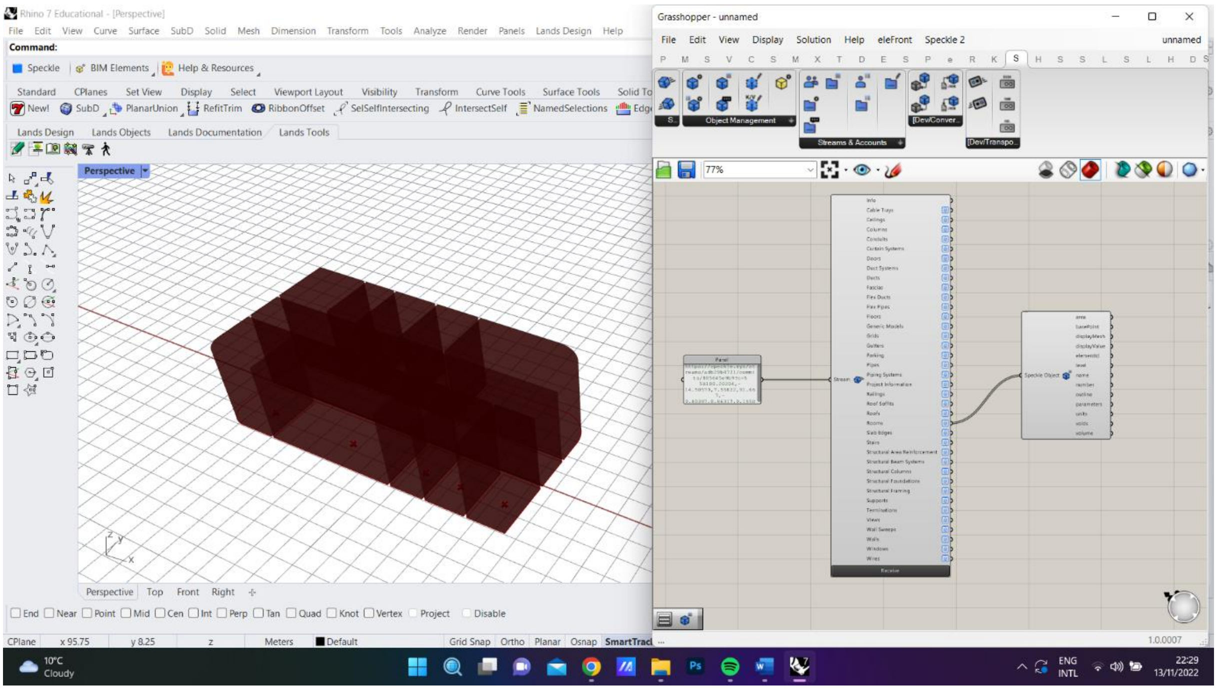


Figure 3.36 Receiving the geometry on Grasshopper using the Speckle stream

3.5.7. Geometry adaptation on Grasshopper

For the geometry adaptation, this time since the geometry was exported as rooms, there was no need to close the surfaces where the window openings are, however, another issue resurfaces, that is the curved wall geometry. Honeybee does not support curved objects, so the wall, floor and roof components to which this applied had to be modified. The solution was to divide the surfaces into segments. In Figure 3.37 the process of constructing the segments from the curved wall can be seen. The endpoints on the top and bottom are chosen to create rectangular segments using the component "4Point Surface". This is repeated for each of the segments. Later on, in order for the floor and roof to be connected to the wall to create a closed envelope. For the floors and roofs the same process is done.

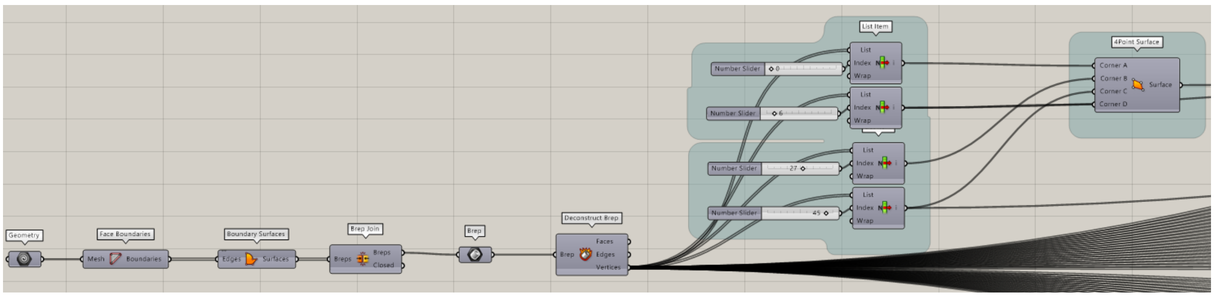


Figure 3.37 Constructing segments from the curved wall

The next modification that is done is the positioning of the glazing surface to the appropriate wall surface. This is acieved with the component "Move To Plane" where under "Geometry" the glazing surface is connected and under "Plane" the specific wall surface is attached Figure 3.38).

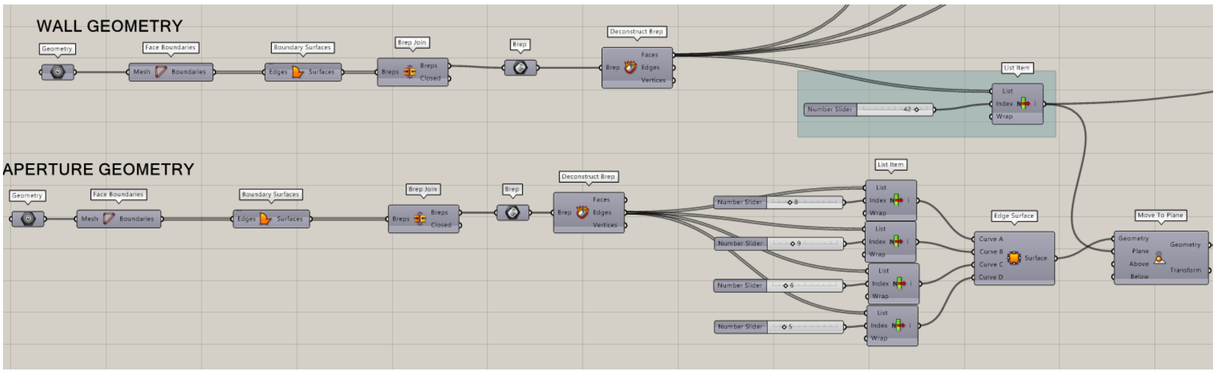


Figure 3.38 Attaching the glazing surface to the appropriate wall

Once these steps are done, the surfaces are ready for further use. On Figure 3.39 and 3.40 the result from these actions can be seen for office room 6. Another room that followed the same procedure for geometry adaptation was office 11.

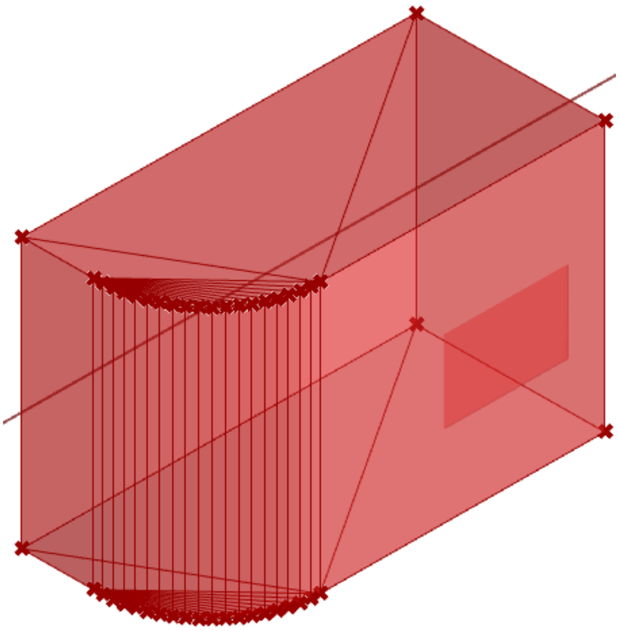


Figure 3.40 Visualization of the imported geometry for office 6

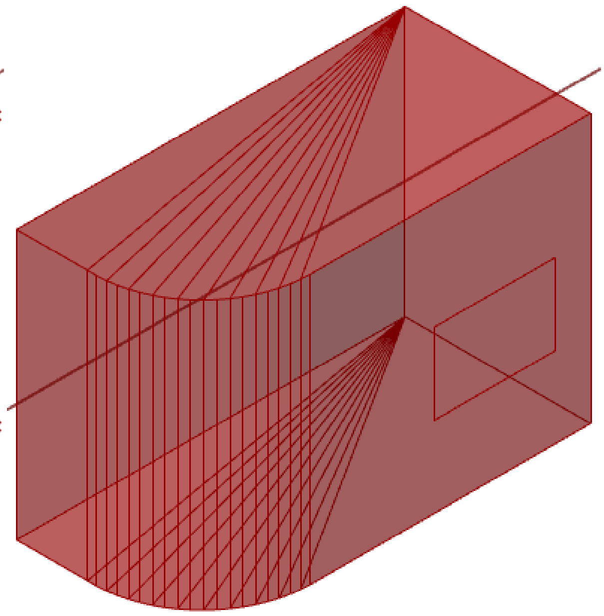


Figure 3.39 Visualization of the adapted geometry for office 6

Another case where geometry adaptation was done, was the corridor. The corridor surfaces were divided into irregular polygons. The surfaces are reconstructed using the component “4Point Surface” using the enpoints of the poligons. In this case, two surfaces were constructed, on where the enrance is situated and another one where the corridor is.

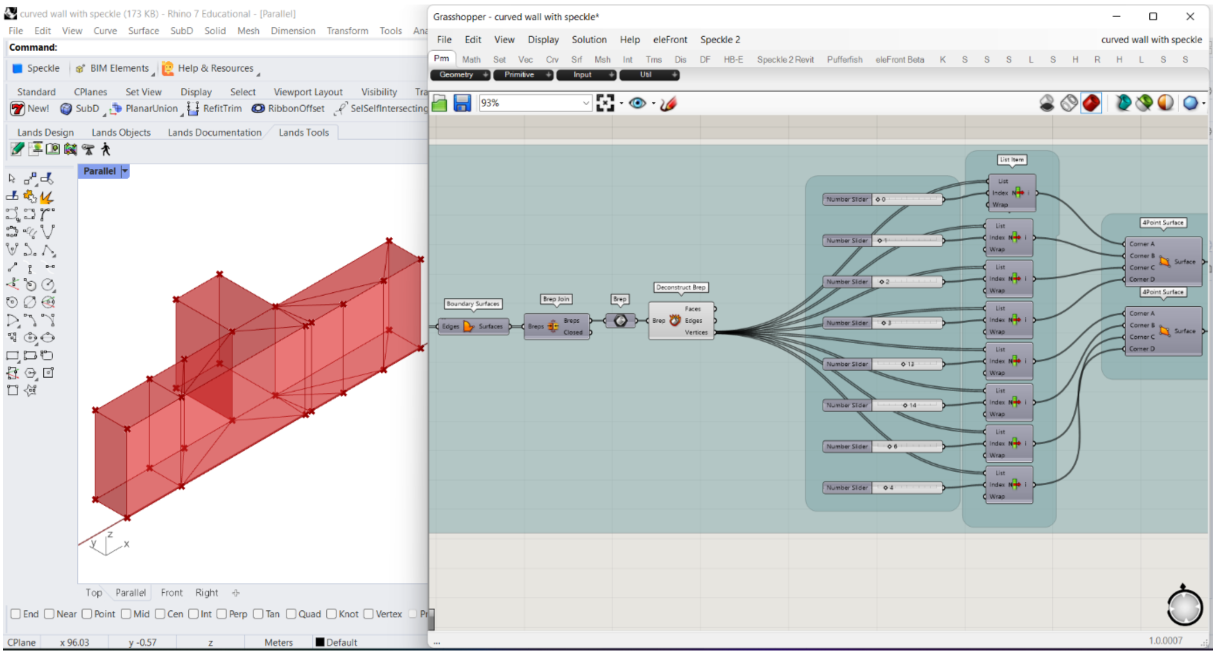


Figure 3.42 Visualization of the imported geometry for the corridor geometry

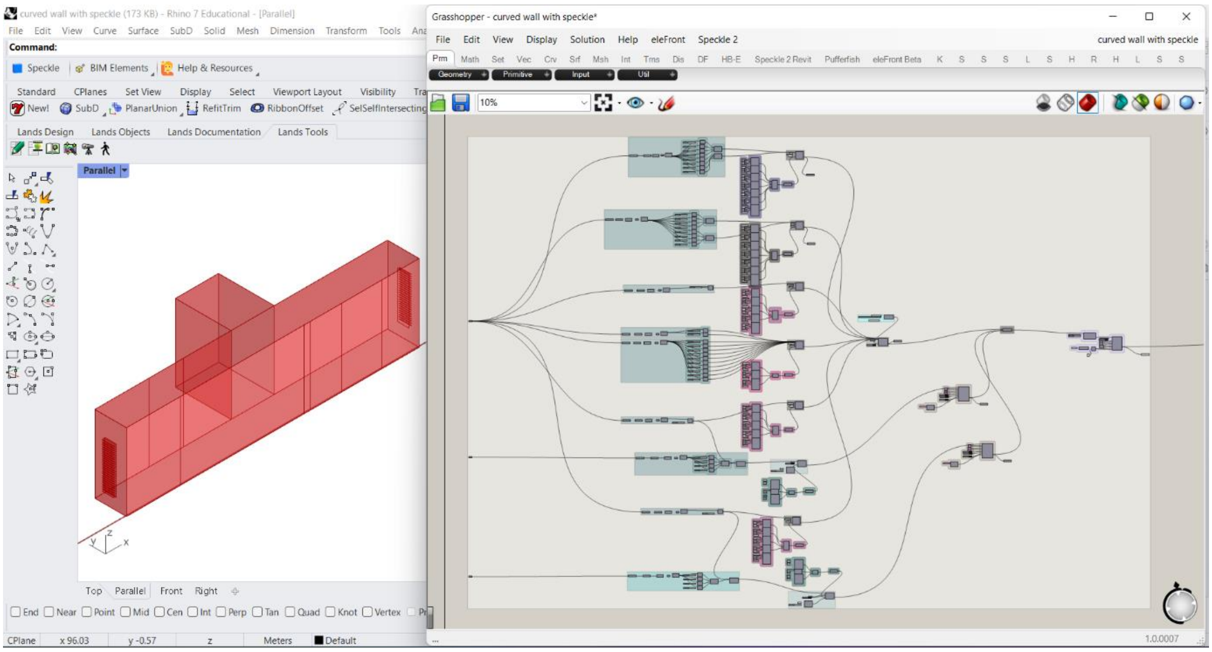


Figure 3.41 Visualization of the adapted geometry for the corridor geometry

The last room that required modification was the conference room. The reason behind this is that on the Revit model the glazing element is modelled as a curtain wall. This element was not recognized by the Speckle component that received the geometry data on the Grasshopper interface. The wall where the curtain wall component was situated, was transferred as a component with just the window opening but not the glazing element. This issue was resolved by constructing a surface with the end points (vertices) of the opening of the wall surface. The components used to deconstruct the geometry were “Deconstruct Bep” and with connecting the node “List Item” to the vertices output. The selection of the points was connected to the input “Index” of the component. Once the points were chosen “4PointSurface” was used to construct a glazing plane. Finally, after the surface has been constructed, it is relocated and placed on the wall surface that is chosen for further analysis.

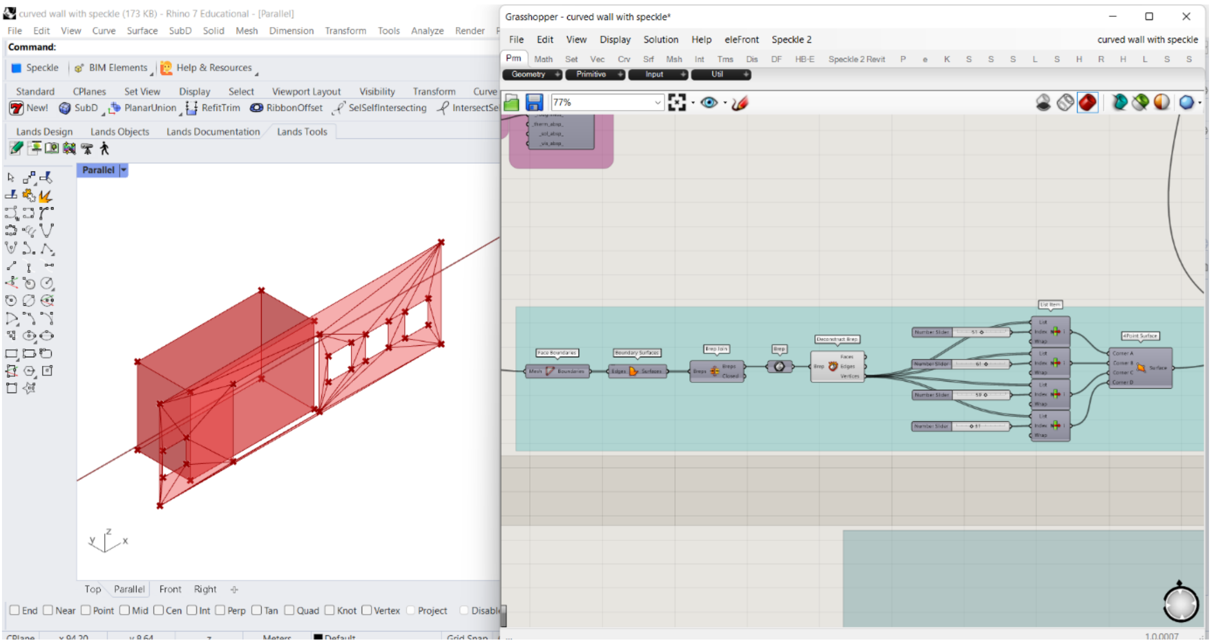


Figure 3.44 Visualization of the imported geometry for the conference room geometry

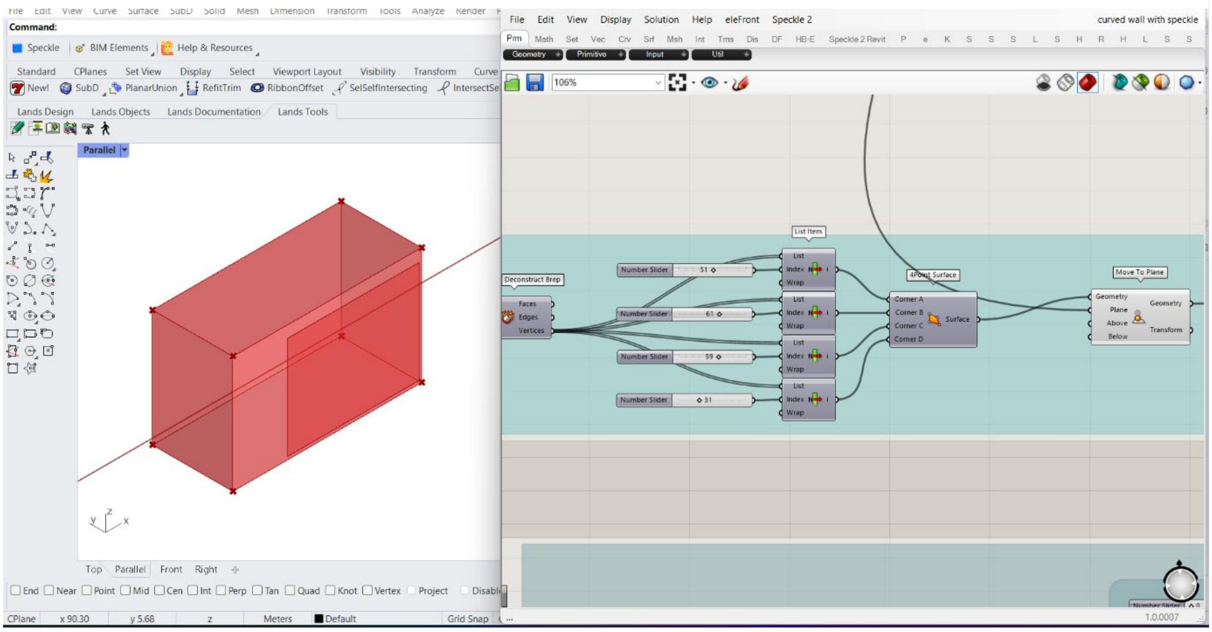


Figure 3.43 Visualization of the adapted geometry for the conference room geometry

3.5.8. Constructing a Honeybee model

Further more, the model needs to be transformed into a honeybee model. There are a few steps in this process that must be completed in order to prepare the model for the following stage.

3.5.8.1. Assigning surfaces as Honeybee faces

To begin with, honeybee faces are made. All of the previously selected surfaces are combined here. The components are given category categorizations (separate for each category ex. walls, floor, roof etc.). All the material properties for every layer of the "Honeybee Face" element are assigned there. All the elements belonging to the same category and having the same material properties are assigned to the input "_geo" of the "HB Face" node. This process applies for both of the single zone model and the multizone model, and there are no differences.

3.5.8.2. Opaque components

In this case study, the exterior, interior, floor, and roof walls are the opaque elements. The type of element can be specified in a number of inputs for the "HB Face" component. The input "_type" indicates the type of geometry and the direction in which the layers of the materials will be generated (vertically for walls or separators versus horizontally for roofs, ceilings, and roofs). The node "HB Opaque Construction" is used to modify the properties of the materials. There, the component material is identified by name and connected to a component identified as "HB Opaque Material." All of the specific material characteristics, including thickness, conductivity, density, specific heat, roughness, thermal absorbance, solar absorbance, and visual absorbance, are present in that component. In Figure 3.45, 3.46, 3.47 and 3.48 the process of assigning the material properties and layers is shown. In order to get the detailed material properties, the “Involucro Opaco” is a data base file, which contains all of the needed information regarding various types of opaque components. It is an Excel file, where the user can choose the desired material types, asign the thickness of each of the layers, and the thermal properties will be calculated. In the “_bc” input the boundary condition of the faces is stated. The boundary condition for the exterior walls and the roof components is set to “Outdoors”, the interior walls surfaces are set to “Adiabatic” and the floor is set to “Ground”.

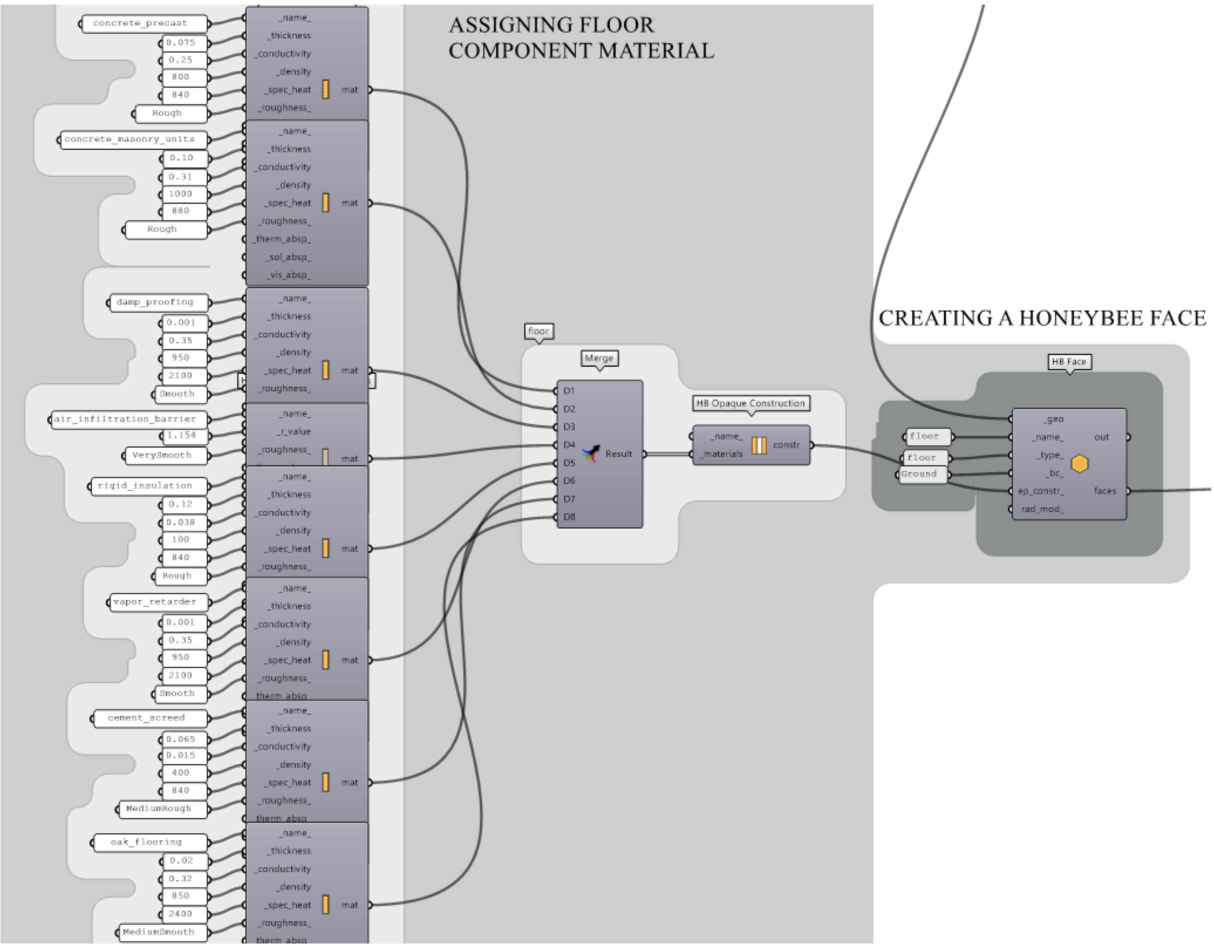


Figure 3.46 "HB Face" algorithm with construction modifier for opaque component- floor

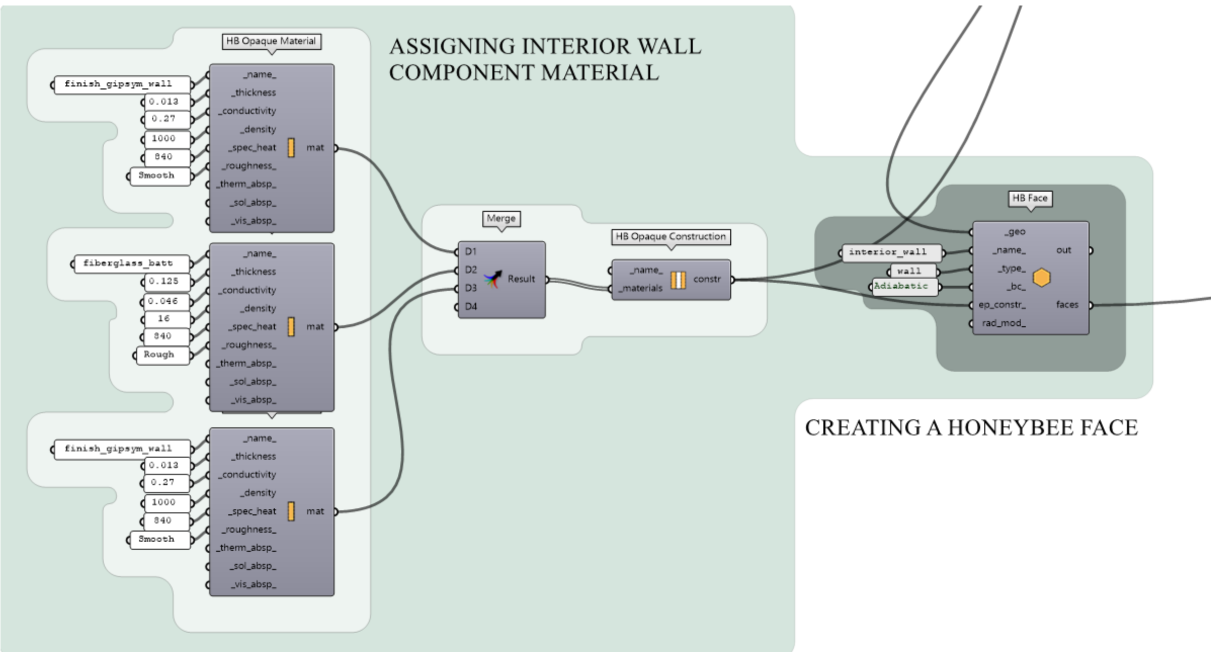


Figure 3.45 "HB Face" algorithm with construction modifier for opaque component- interior wall

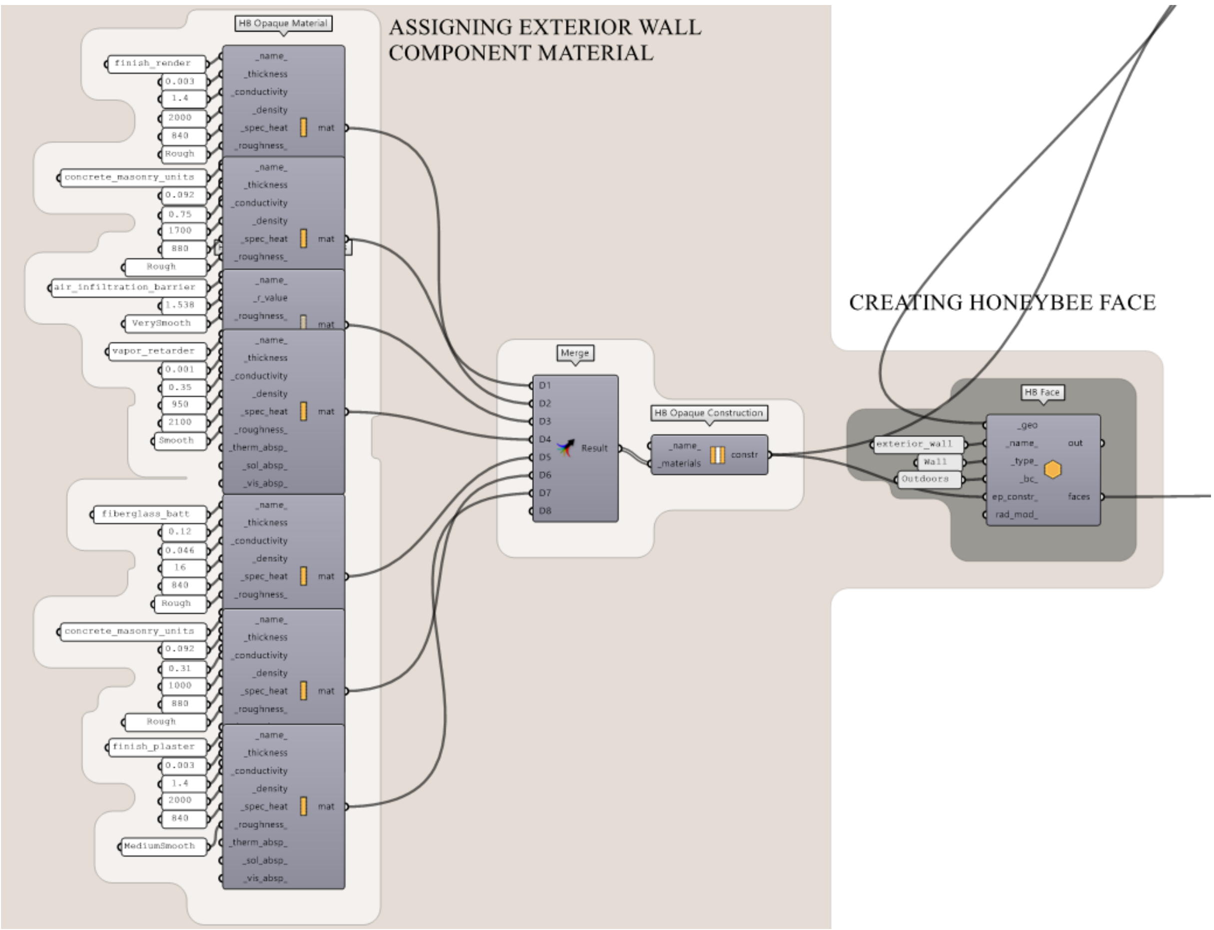


Figure 3.48 "HB Face" algorithm with construction modifier for opaque component- exterior wall

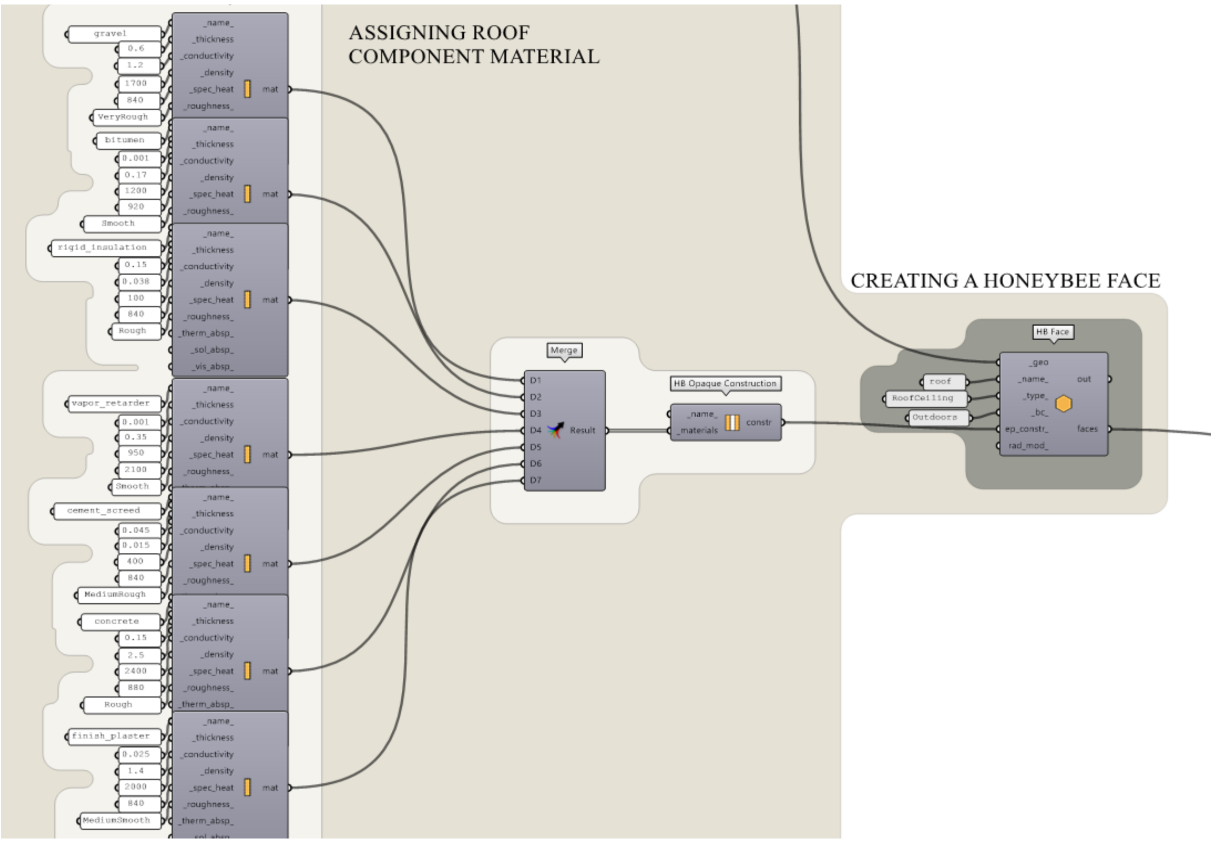


Figure 3.47 "HB Face" algorithm with construction modifier for opaque component- roof

3.5.8.3. Transparent components

The glazing element uses a different process, and the connection is slightly different. The node "HB Aperture" is applied here. Only the glazing plane is used for analysis as a surface, not the window frame (since the window frame is an opaque component, it is taken as a part of the wall area). The glass's composition is determined in the same manner as it was for the "HB Face" case. The window is made operable using a "Boolean Toggle" ss seen in Figure 3.49. The thermal transmittance (u) value of the glass is 0.4 W/m²K which is very high, and the solar factor (g) value is 35%.

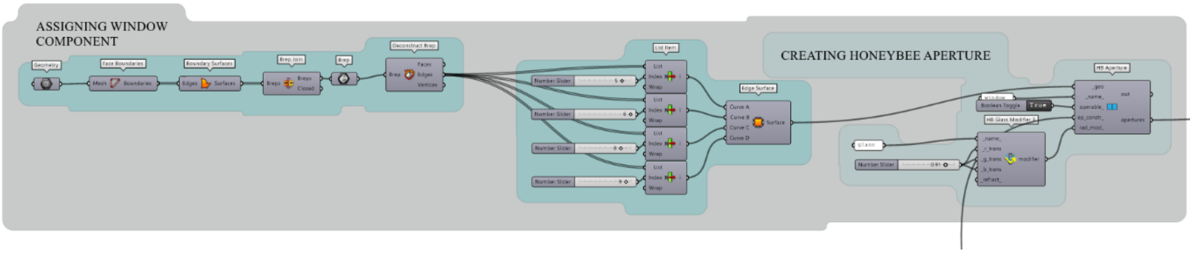


Figure 3.50 Assigning an aperture geometry using the HB Aperture component

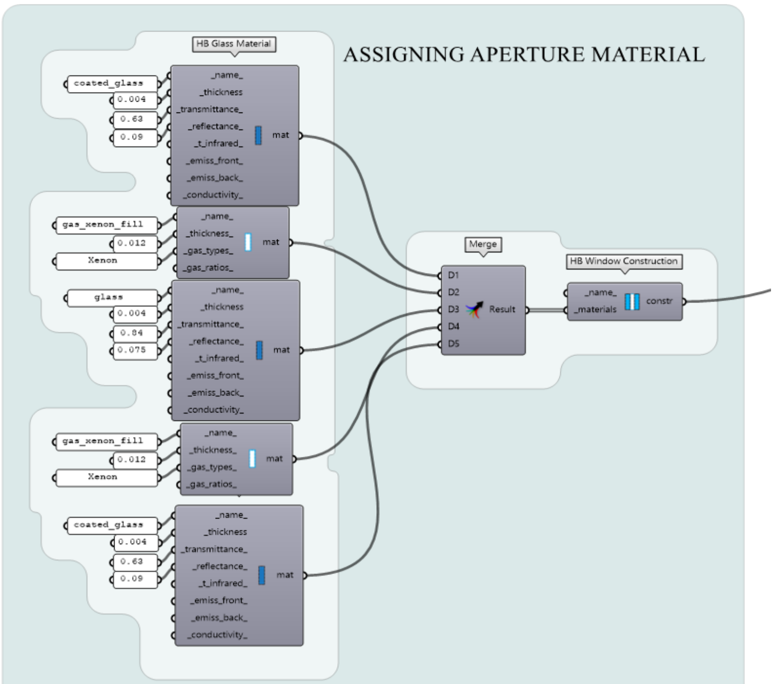


Figure 3.49 Assigning material to the transparent glass component

3.5.8.4. Constructing a Honeybee room

When all of the HB faces have the proper constructions assigned to them, the component "HB Room" is connected. In order to have a proper analytical model and for the component to function, having a closed volume is crucial here. The building program is entered as "HB ProgramType" in the "HB Room" where the schedules for infiltration, electric lighting, and equipment are assigned. The program is set to regarding to the size and capacity of the office (Figure 3.51). The status of the room's conditioning is another setting for input. A "Boolean Toggle" that is connected in this situation is set to TRUE, indicating that the office is indeed climate-controlled. Figure 3.45 depicts this procedure. The way the aperture is attached is a little different. The node "HB Add Subface" is used, where the output of the HB Room is connected to "_hb obj" and the "HB Aperture" is plugged in "_sub faces," after all HB faces have been assigned to the HB Room component and there is a closed envelope.

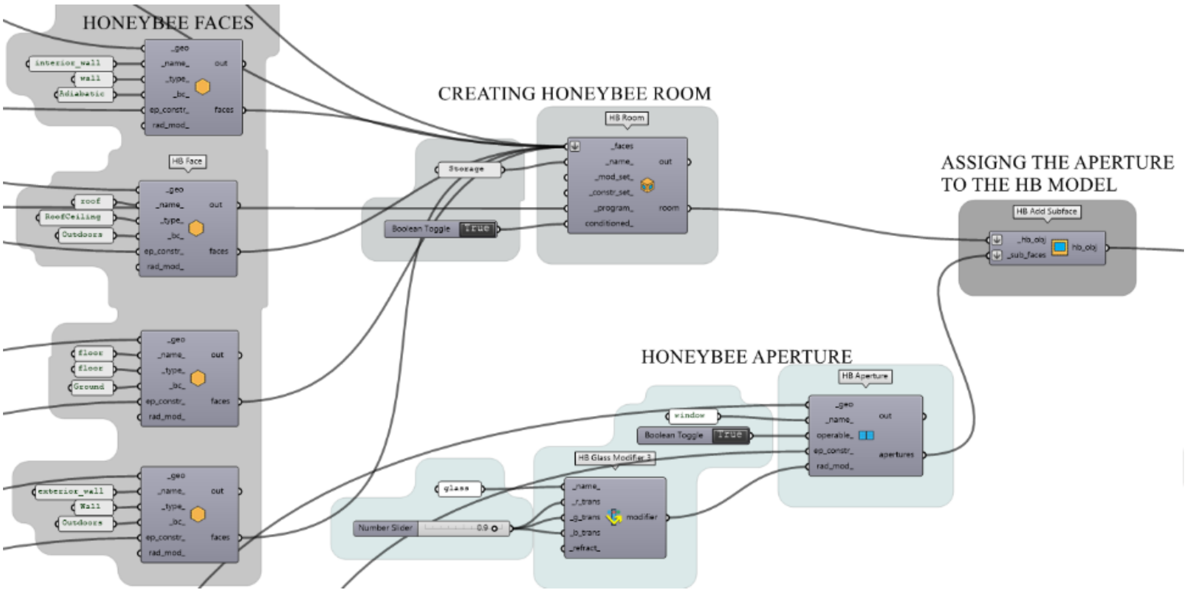


Figure 3.51 Creating a "HB Room"

The building program is entered as "HB ProgramType" in the "HB Room" where schedules and other significant data pertaining to occupancy, electric lighting, electric equipment, and infiltration are assigned. The office was built to accommodate a single occupant, so we first input the value of 0.09 (number of occupants divided by area), and then we set the power density for lighting to 7 Watts per m2. A component called "HB Daylight Control Schedule" is assigned to the lighting schedule, and its illuminance set-point is 500 lux. The input "_results" of the same component contains data from a simulation of the probability of daylight glare. A schedule is established that details the working hours each week for the electric equipment. For the electric equipment, a schedule is assigned that states the working hours of the week and implies that the electric equipment is not used during the weekends, holidays and after the working hours. The power density for electric equipment is set at 9 Watts per $m^{2.}$ Next, regarding the infiltration loads, the input for the intensity of infiltration is set 0.0003 m^3 per second, which is an average value for an average building leakage. Lastly, the input “base_program_” is where the base building program is set, and it is decided by the size of the office (Figure 3.52).

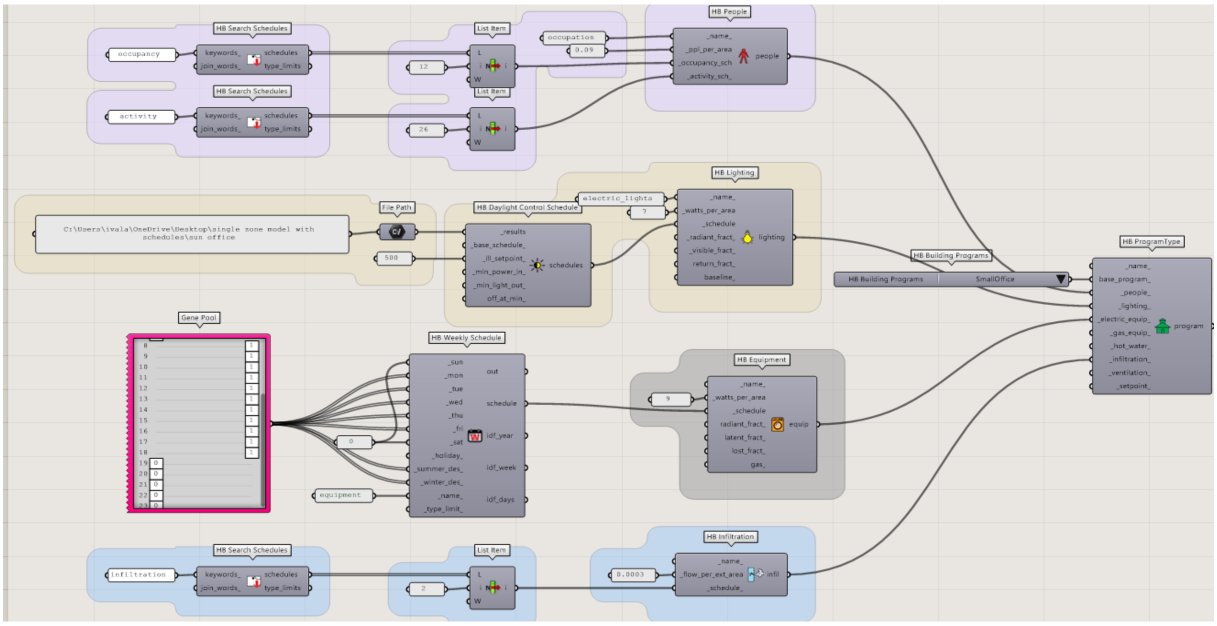


Figure 3.52 Constructing a custom building program

3.5.8.5. Assigning a shading component to apertures

For the multizone model, ststic louver shades were used. The "HB Louver Shades" components were used to add the shades to the window's exterior surface. The "HB Add Subface" command in the "_hb objs" input node of the shade component connects to the aperture geometry. The shades are generated on the designated surface as a result of this. Here, a number of variables can be changed, including the panel count, surface offset, spacing between panels, and whether they are oriented vertically or horizontally. An important thing to notice, when there are more than one window components on one wall surface, it is crucial to assign two “HB Louver Shades” components, so that the user will be able to have the freedom to manipulate the geometry of the shading device separately. The simulations were run twice, once without the louver shades and once with them, to determine how they would affect the indoor environment's thermal conditions and, consequently, how much energy would be consumed (Figure 3.53).

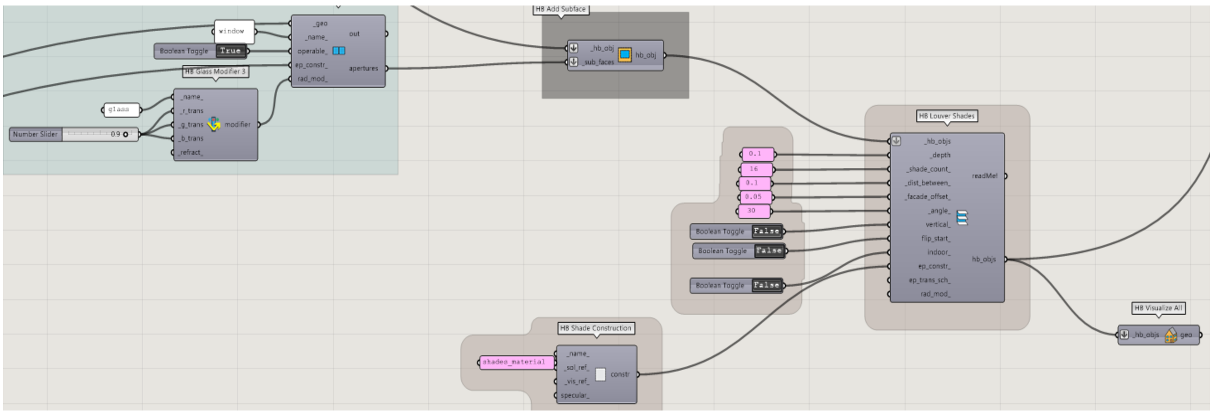


Figure 3.53 Assigning "HB Louver Shades" to the apertures

3.5.8.6. Assigning a HVAC system

The Honeybee room then receives an HVAC system so that the interior temperature can be adjusted in accordance with the needs of the occupants. The desired temperature ranges from 20 to 26 degrees Celsius. The metabolic rate of the occupants was set to 1.1 met according to the PMV results, which indicates that the people are sitting and typing. By allocating a component that regulates the clo by the outdoor conditions, the insulation of the clothing was predicted. The "Ideal Air" thermostat was put to the test to determine under what circumstances the predicted mean vote was the most neutral and the percentage of dissatisfaction was the lowest. The HVAC system's schedule controls when heating or cooling is turned on. This is done by assigning a designed weekly schedule for the summer and winter seasonal schedules. The schedule states the working hours of the week and implies that the electric equipment is not used during the weekends, holidays and after the working hours (Figure 3.54).

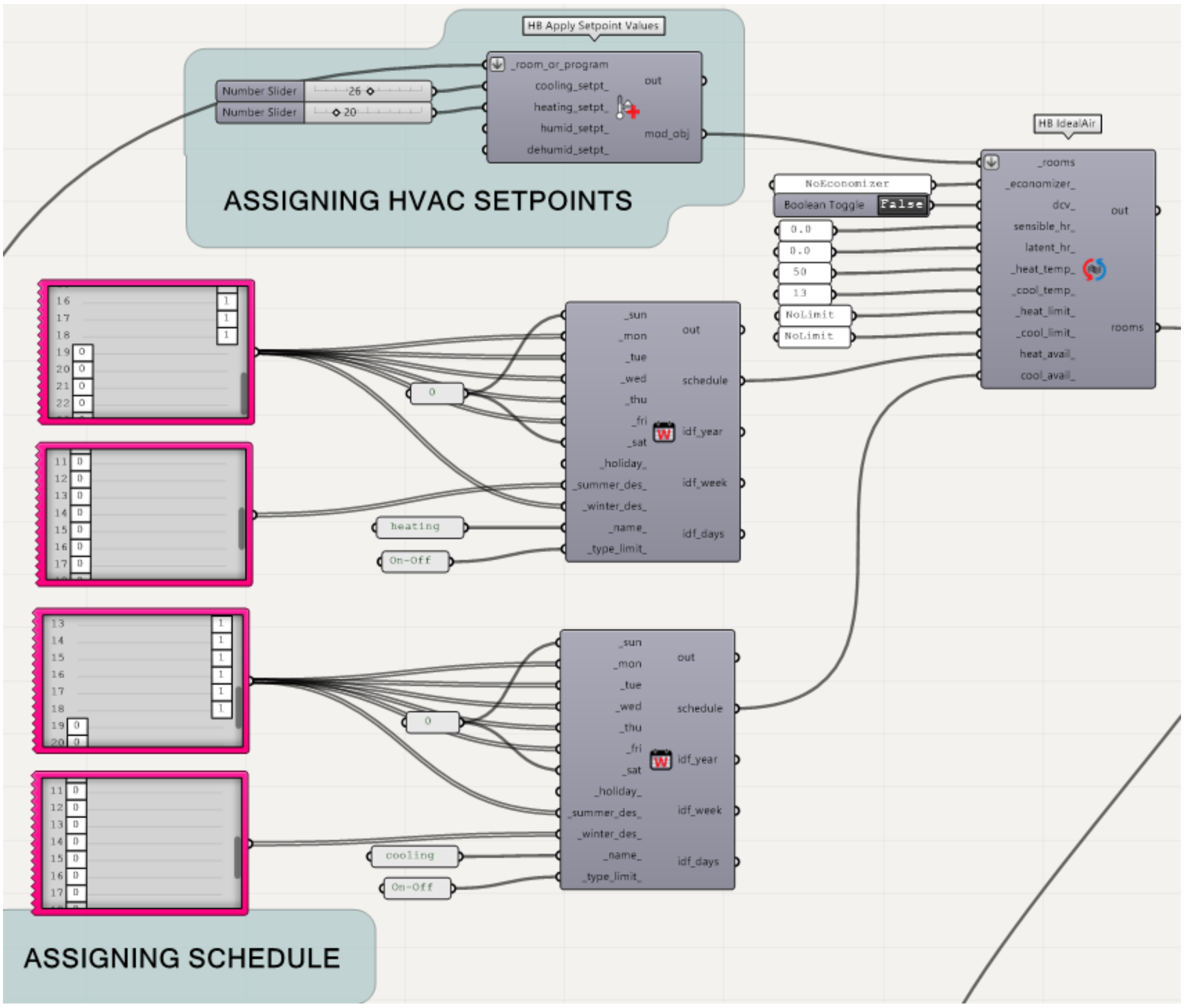


Figure 3.54 Assigning HVAC system with the component "HB Ideal Air"

Last but not least, a window opening control component is assigned to regulate the building's ventilation. When assigning the "HB Aperture" component, the apertures must be assigned as operable in order for this component to function (figure 3.55).

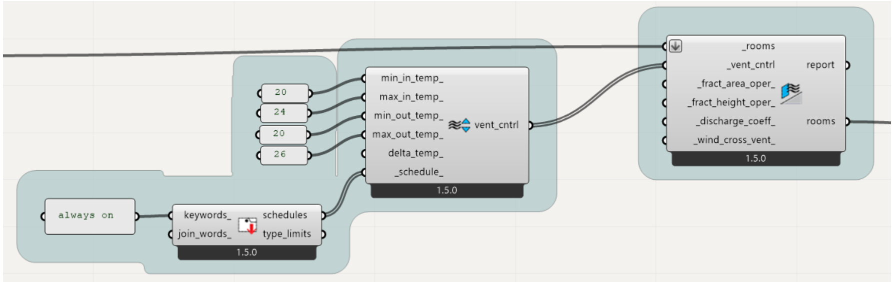


Figure 3.55 ning a window control component "HB Window Opening" to apertures

3.5.9. Simulation model inputs

The simulations carried out for this study focused on thermal comfort and energy consumption. Cross-platform use of OpenStudio was made possible by the Energy Plus engine. For a full year, the simulations were run. Italy's Turin served as the designated location. The Energy Plus weather data website provided the epw. file, which was downloaded. This file contained all the information about the local natural conditions.

"HB Simulation Parameters," a component that is used to configure these inputs, is where "HB Simulation Outputs" is first connected. By choosing sets of frequently used output variables, the user can create a simulation output object there. When "Ideal Air" systems are assigned, the zone energy use is set to true in this instance to add output for zone energy use. This covers electric appliances and systems for heating, cooling, and lighting. Next, a "Boolean Toggle" connected to "gains and losses_" with the value true also provides information on the zone's gains and losses. This provides results for a variety of parameters, including gains or losses in terms of people, solar gain or loss, infiltration gain or loss, etc. For the zone thermal comfort analysis, the "comfort metrics_" provides an output such as mean radiant temperature, air humidity, relative humidity, operative temperature, etc. "surface temperature_" and "surface energy flow_" are also taken into account as output parameters because they add outputs for both indoor and outdoor surface temperatures (which adds outputs for energy flow across all surfaces). The final input for this component is in "load type_," where a panel with the word "All" is connected. This indicates that all energy use, including heat loss from the zone, is taken into account. The component "LB Analysis Period" is used to set the analysis period after that. The parameters are predetermined to operate continuously throughout the year. With instructions on what kinds of EnergyPlus calculations should be performed, the "HB Simulation

Control (SimControl" command creates simulation controls. Except for the "_for run period," all of the inputs are set to false in this case.

Additionally, the "HB Shadow Calculator" has been delegated and is configured to perform an exhaustive interior and exterior simulation. It reproduces the model with a sunlit sky. It generates the solar rays while taking the geometries of the environment into account. The "HB Sizing Parameter" is finally assigned. The weather file is connected as a.ddy file in this instance. The design days that were used to size the HVAC system are described in this file. All of these inputs are connected to the "HB Simulation Parameters" component. These complete all the inputs required for the simulations to run in OpenStudio, along with the full HB Model and an.epw file.

In order to read the desired custom results, in this case, the desired outputs had to be added as a string to the OpenStudio component. The string is written in the format "*Output:Variable,*,Variable_name,report_frequency;*". Together with the complete HB Model and an .epw file, these complete all the inputs needed to run the simulations via OpenStudio (Figure 3.56).

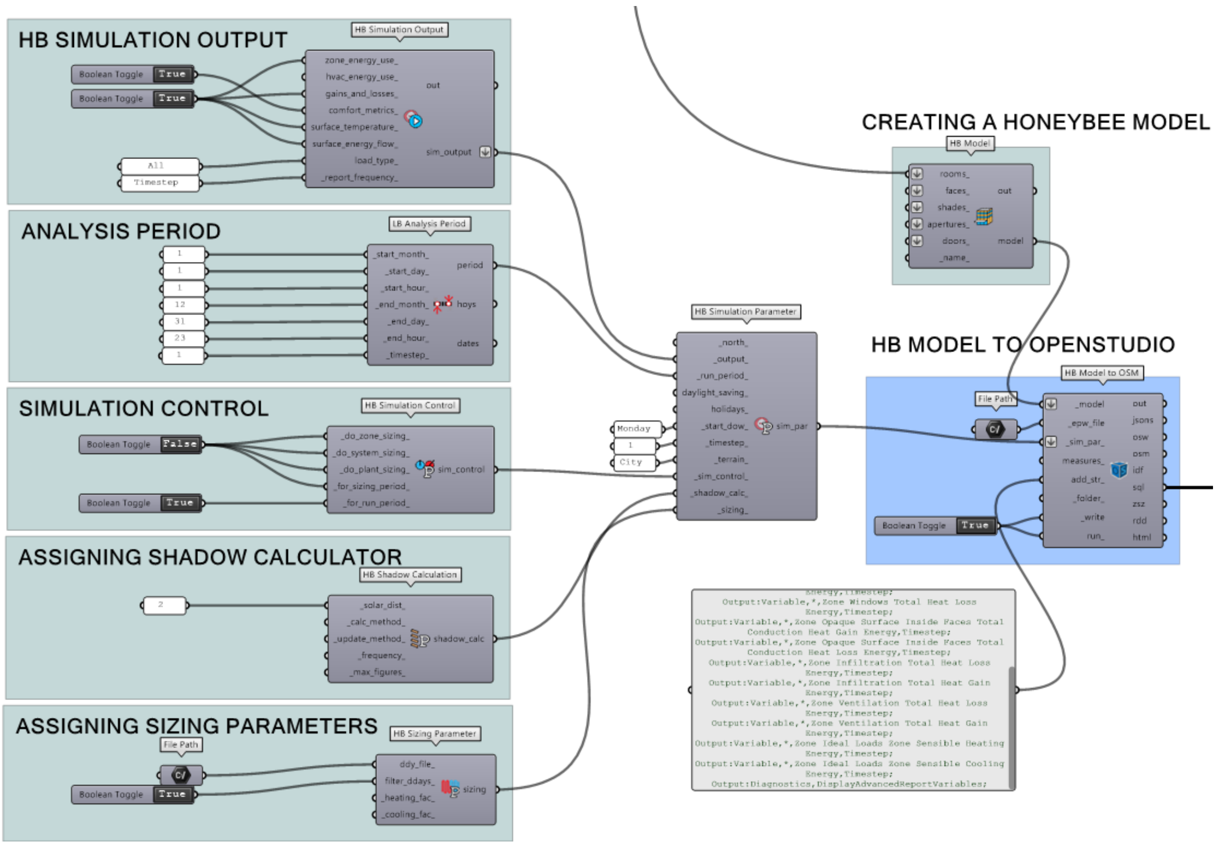


Figure 3.56 Simulation parameters for energy and thermal comfort analysis

3.5.10. Energy Simulations Visualization

Reading and visualizing the results is the final step of the energy simulations. First, a formula was chosen to calculate the results of the energy balance. The energy gains and losses are represented by the balance outputs. A component called "HB Read Custom Result" is connected to the "_sql" output on the OpenStudio component that runs the simulation in order to read the previously assigned strings as outputs. The output name for the output that is intended to be analyzed is assigned in the component that reads the custom results. The requested results that were derived in this case were: Zone People Total Heating Energy, Zone Lights Total Heating Energy, Zone Electric Equipment Total Heating Energy, Zone Windows Total Transmitted Solar Radiation Energy, Zone Windows Total Heat Gain Energy, Zone Opaque Surface Inside Faces Total Conduction Heat Gain Energy, Zone Infiltration Total Heat Gain Energy, Zone Ventilation Total Heat Gain Energy, Zone Windows Total Heat Loss Energy, Zone Opaque Surface Inside Faces Total Conduction Heat Loss Energy, Zone Infiltration Total Heat Loss Energy and Zone Ventilation Total Heat Loss Energy. It's important to note that the values were multiplied by -1 for the energy losses to appear as negative values on the chart (Figure 3.57 and Figure 3.58). Additionally, it is important to double-check the metric units because the data may be in joules and the values may need to be converted to kWh. Finally, Ladybug provides the option to visualize the data using the component "LB Monthly Chart," but in this instance the data was extracted from Grasshopper and the charts were visualized using Excel, which provides the option for a wider variety of chart types.

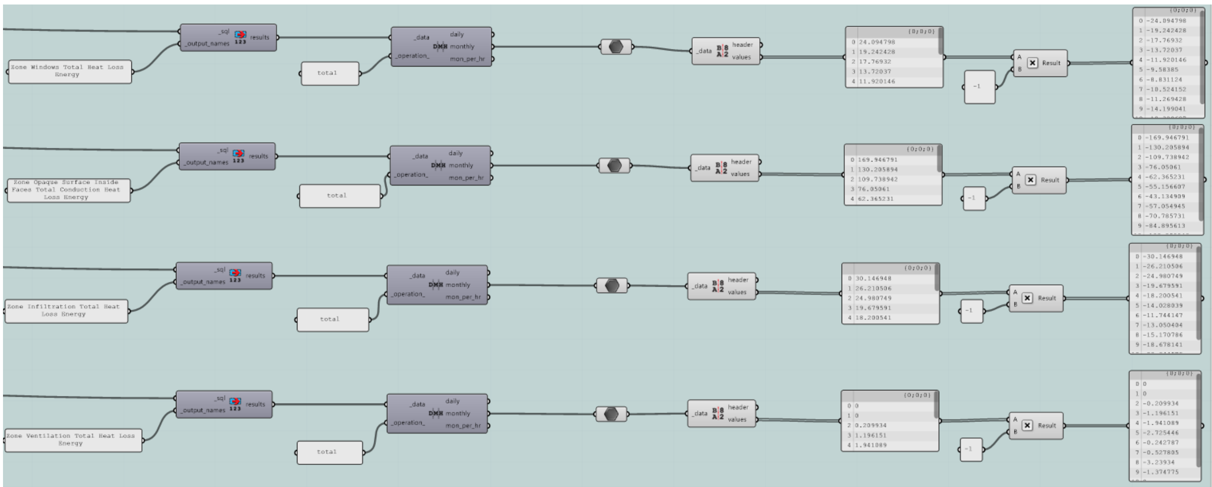


Figure 3.57 "HB Read Custom Results" requesting results for energy losses multi-zone model

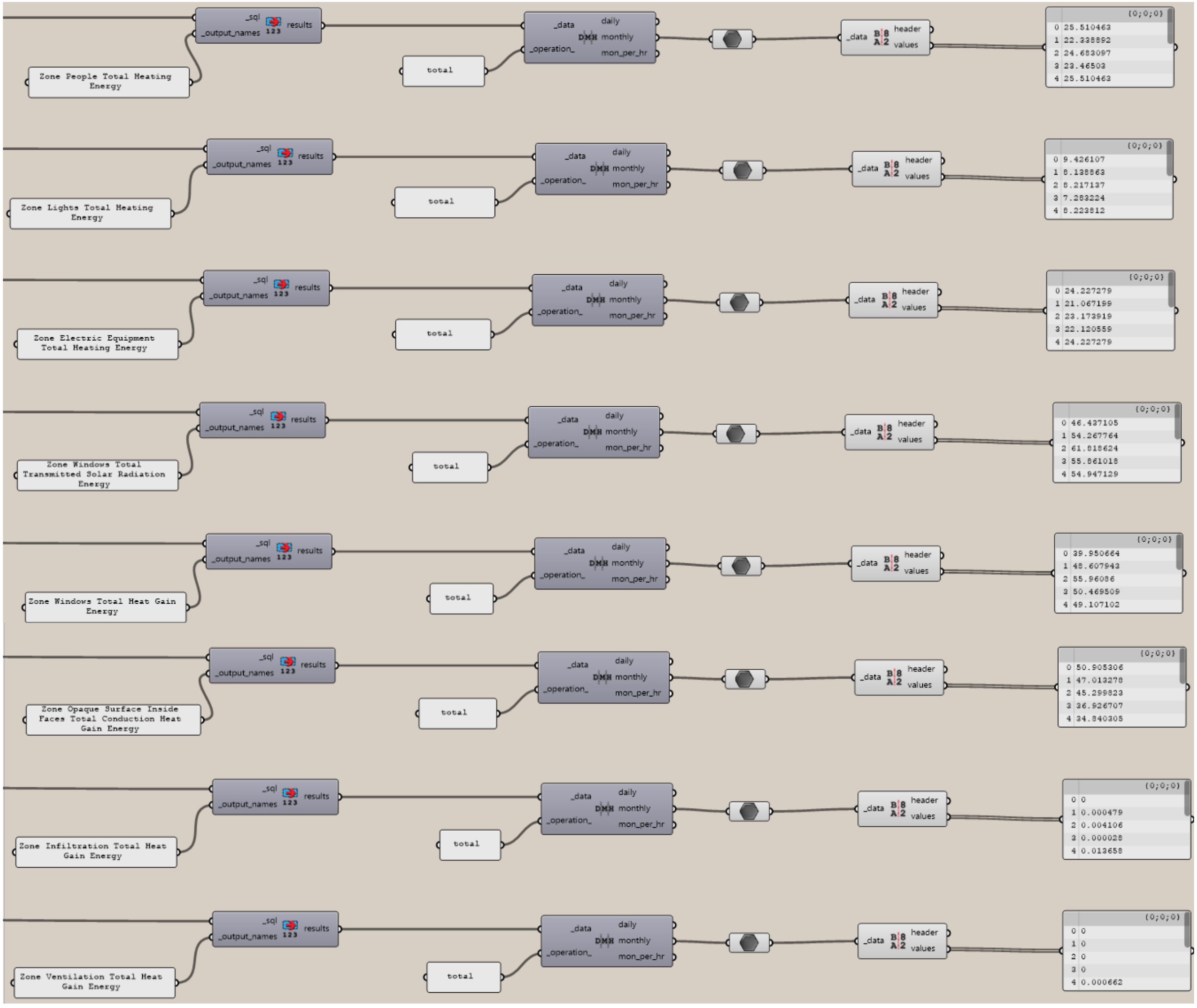


Figure 3.58 "HB Read Custom Results" requesting results for energy gains multi-zone model

Next the primary energy use was calculated. Using the component "HB Read Custom Results" that allows the users to see the specific energy results for all the components in the building that the simulations are done on. The results that were derived from this component were the energy loads. In order to convert the results to primary energy use, firstly they were divided by the specific efficiency factors (heating 0.85, cooling 3.2, electric lighting 1 and electric equipment 1) and multiplied by the specific primary energy factors (natural gas 1.05 and electricity 2.42) and lastly, the results are divided by the total area of the zone on which the analysis are done. In order to derive the zones, a "Deconstruct Data" component is assigned (Figure 3.63). Here the impact of the systems can be seen and how they correspond with the geometry that they are assigned to. A monthly or an hourly chart can be done for a graphical representation with the components "LB Monthly Chart" and "LB Hourly Chart". This process can be seen on Figure 3.60, 3.61, 3.62 and 3.63.

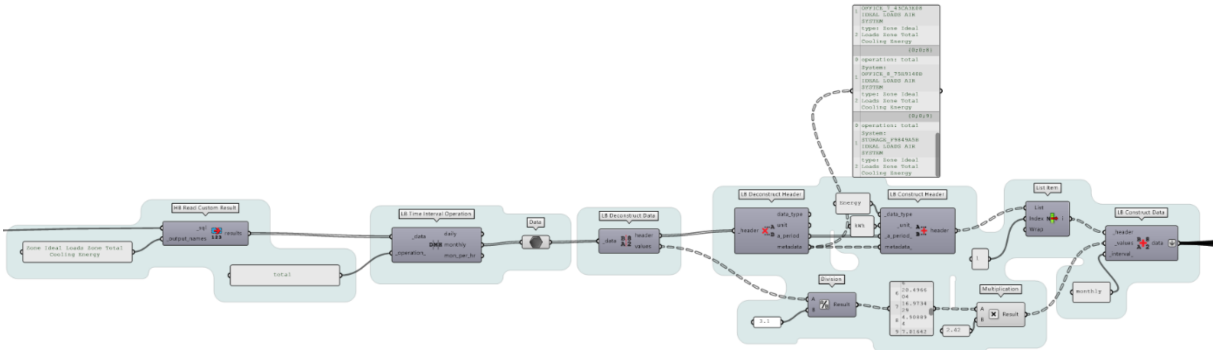


Figure 3.63 Algorithm for calculating primary energy for cooling multi-zone model

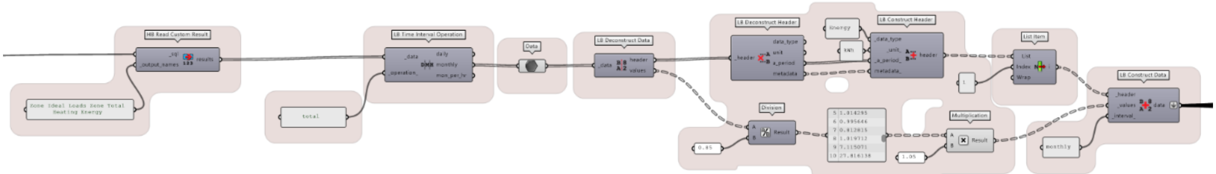


Figure 3.62 Algorithm for calculating primary energy for heating multi-zone model

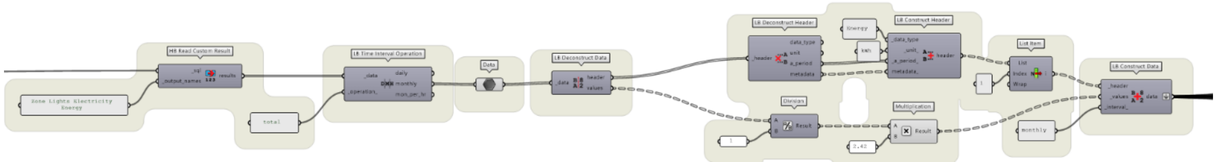


Figure 3.61 Algorithm for calculating primary energy for electric lighting multi-zone model

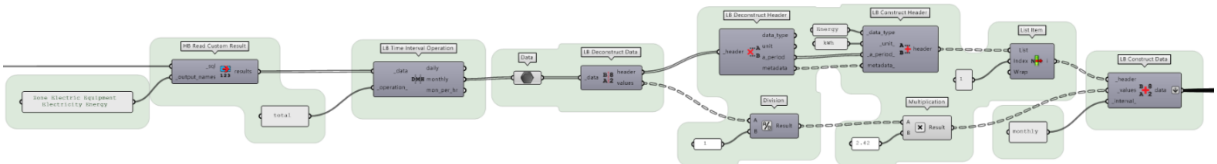


Figure 3.60 Algorithm for calculating primary energy for electric equipment multi-zone model

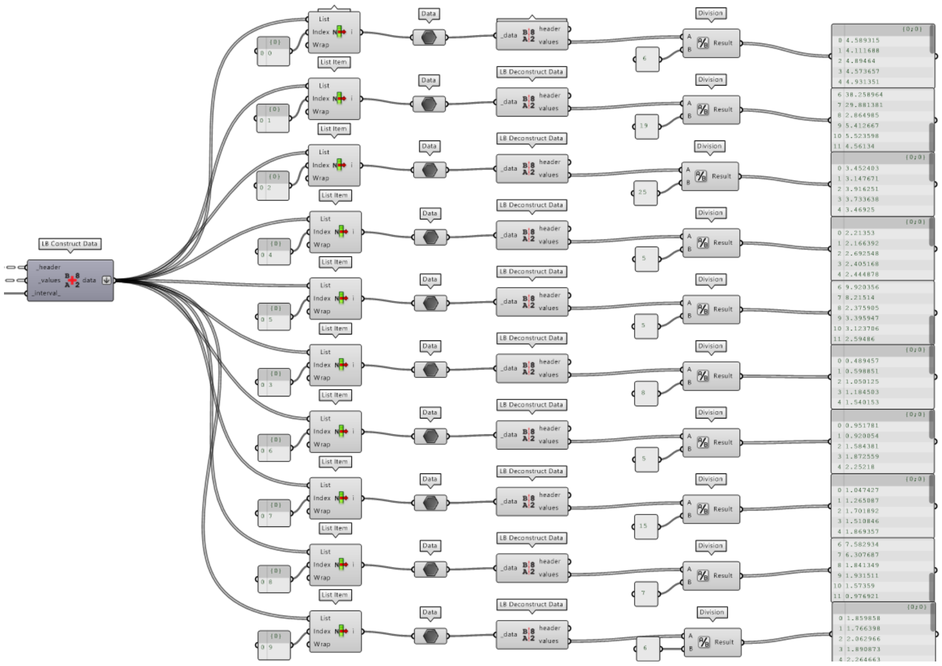


Figure 3.59 Deconstructing data to divide the primary energy use by zone area

3.5.11. Thermal Comfort Simulations Visualization

The visualization of the results is the last step in the thermal comfort simulations. Once all required inputs have been added to the OpenStudio component, the component "HB Read Room Comfort Result" is connected to the "sql" output in order to display the thermal results. Then, using the component "LB Hourly Plot," the outputs for the operating temperature, mean radiant temperature, and air temperature are visualized as a heat map (Figure 3.64).

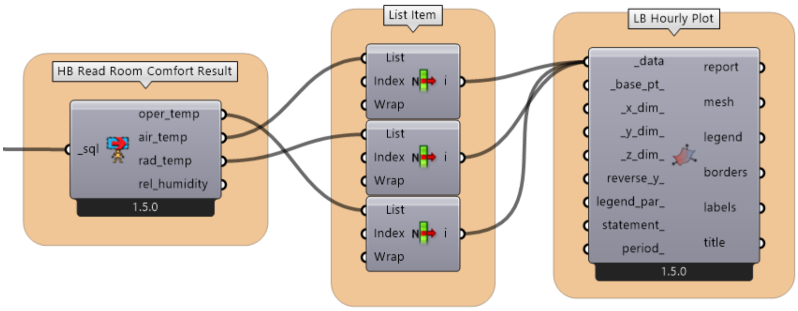


Figure 3.64 "HB Read Room Comfort Results" algorithm for thermal comfort visualization

The PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied) are the final analyses that are represented visually. This is made possible by the "LB PMV Comfort" component, which can later visualize the PMV and PPD charts. Because the values for the occupants' metabolic rates were set to 1.1 met, as they are sitting and typing. By assigning the "LB Clothing by Temperature" component, which regulates the clothing based on outdoor conditions, the insulation of the clothing was predicted. On Figure 3.65, the complete algorithm of the procedure is displayed.

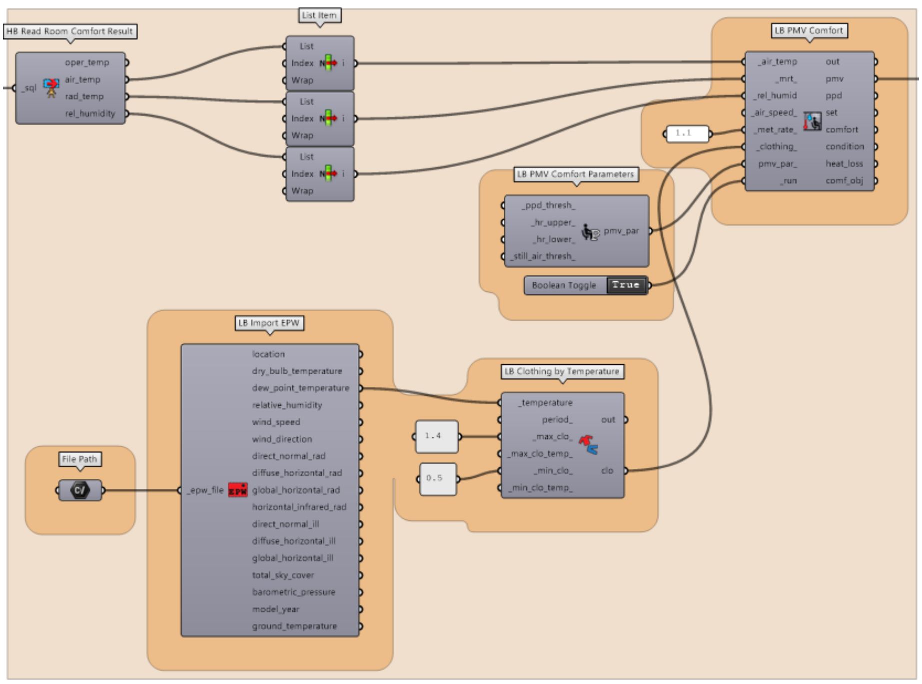


Figure 3.65 PMV analysis algorithm

4. Results of the analysis

The data presented in this chapter are the results of the building performance simulations done for both of the case studies following the workflows explained in chapter 3. This is a collection of the results regarding thermal comfort and energy simulations. The calculations of the results are done by using the Grasshopper plugin Honeybee and they are visualized using the Labybug component for monthly or hourly data visualization. In the next chapters the collection of energy and thermal comfort results are shown with comments regarding the difference when the models are simulated with or without louver shading system.

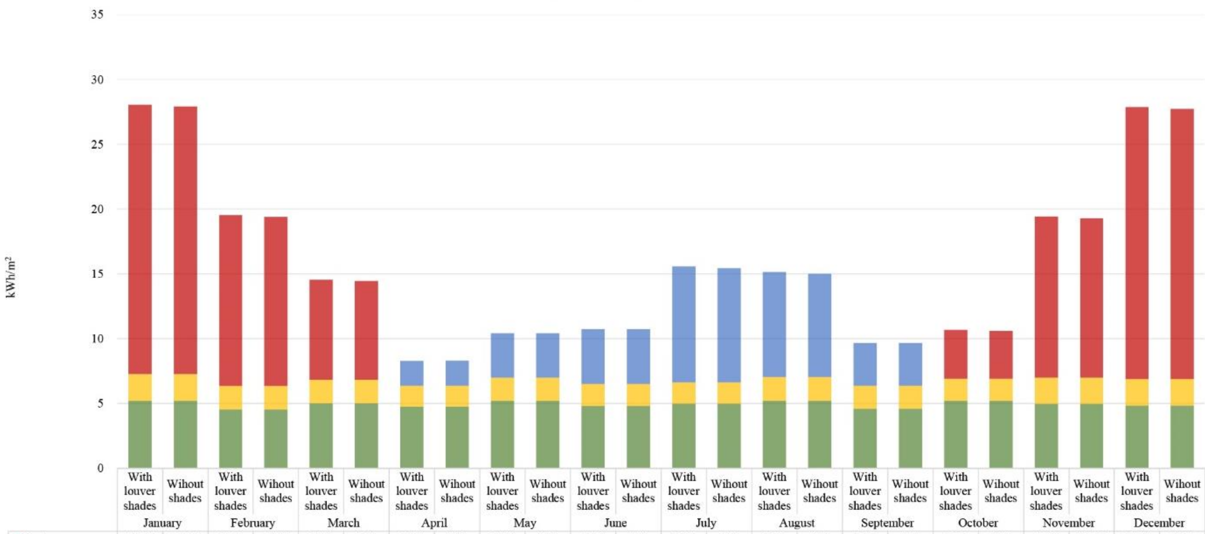
4.1. Case Study I – Results

In the further chapters there is the collection of the results from the simulations regarding the energy and thermal comfort simulations for the first case study, the single zone model.

4.1.1. Case Study I – Energy analysis results

In this section, a comparison of the energy results is done for the single zone model with the two types of simulations that are run, with louver blinds and without louver bllinds. The reasoning behind this is to see the impact of the shading sistem regarding the energy consumption. All of the data in this chapter is annual.

- *Primary Energy Use*



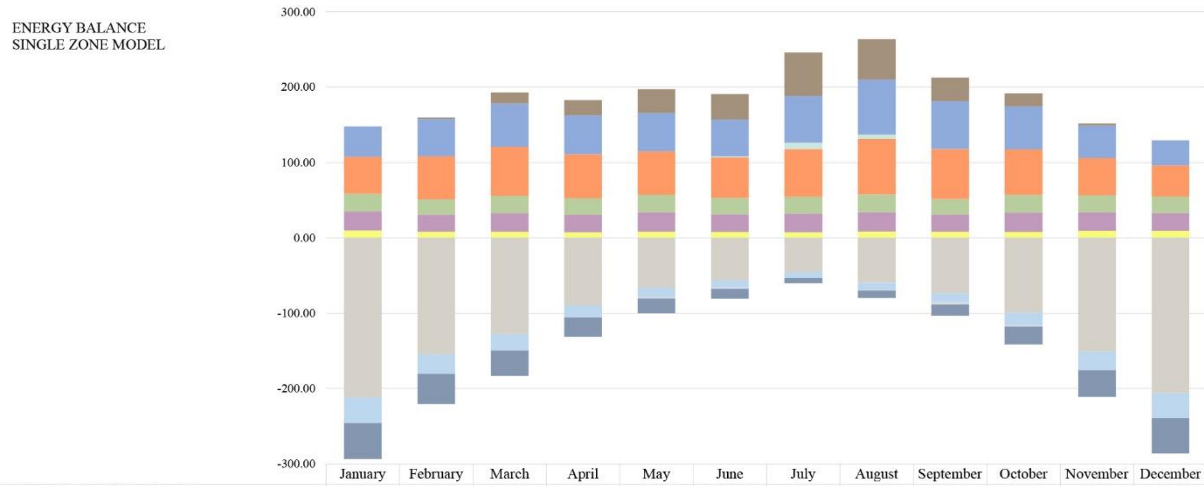
	January		February		March		April		May		June	
	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades
Heating	20.79	20.65	13.21	13.06	7.71	7.61	0.00	0.00	0.00	0.00	0.00	0.00
Cooling	0.00	0.00	0.00	0.00	0.00	0.00	1.92	1.94	3.43	3.41	4.24	4.25
Electric lighting	2.07	2.07	1.79	1.79	1.81	1.81	1.60	1.60	1.81	1.81	1.70	1.70
Electric equipment	5.20	5.20	4.55	4.55	5.03	5.03	4.78	4.78	5.20	5.20	4.81	4.81

	July		August		September		October		November		December	
	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades
Heating	0.00	0.00	0.00	0.00	0.00	0.00	3.76	3.70	12.40	12.28	20.99	20.86
Cooling	8.95	8.82	8.10	7.95	3.29	3.30	0.00	0.00	0.00	0.00	0.00	0.00
Electric lighting	1.64	1.64	1.85	1.85	1.76	1.76	1.72	1.72	2.03	2.03	2.05	2.05
Electric equipment	5.00	5.00	5.20	5.20	4.61	4.61	5.20	5.20	4.98	4.98	4.83	4.83

Figure 4.1 Primary energy use – single zone model

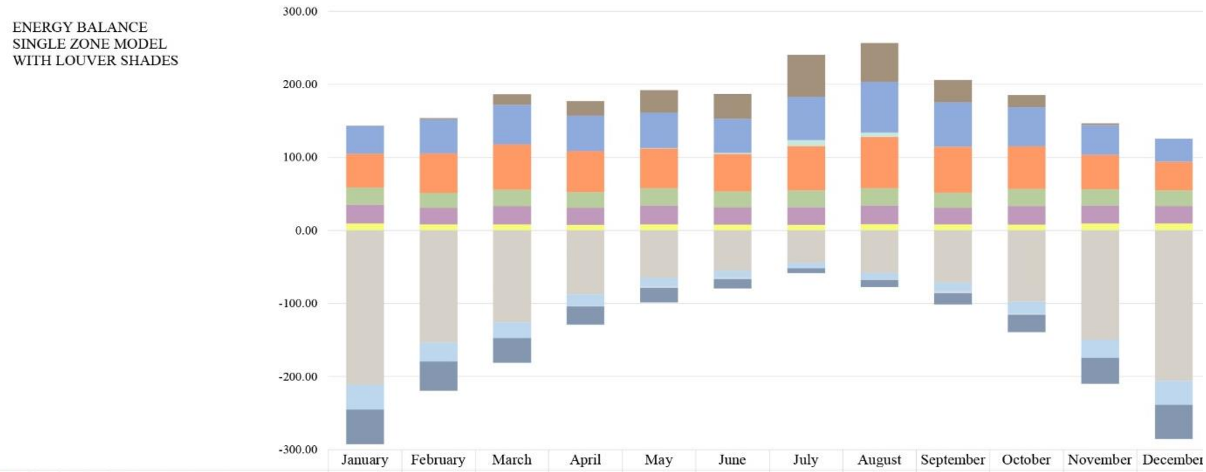
The primary energy for cooling was calculated using the value 2.45 PEF (for electric energy) and the EF of 3.1, the primary energy for heating was calculated using the value of 1.05 as a PEF (for natural gas) and the EF of 0.85. The primary energy for electric lighting and electric equipment was calculated using the value 2.45 (PEF for electric energy) and the EF of 1. Than the values are divided by the area of the zone which in this case is 11m^2. With the visualized results of the calculations (Figure 4.1), it can be seen that the peak of the cooling primary energy consumption is in the months July and August. In the case where no blinds are assigned to the model, the highest value for the energy consumption for cooling is 8.95 kWh/m^2 in the month of July, however, when louver shades are assigned the valueis decreased to 8.82 kWh/m^2. Regarding the heating primary energy use, it can be seen that the peaking values are in the winter months, more specifically in December. In the first case where no shades are assigned to the model, the highest value is 20.99 kWh/m^2 in comparison to the second case with the louver shades where the highest value is 20.56 kWh/m^2, which means that the consumption has slightly increased. Furthermore, the results regarding the primary energy use for electric lighting has the same values for the two types of simulations, but in the winter months there is higher consumption, peaking in January with 2.07 kWh/m^2. The highest primary consumption for electric equipment is in the months of January, May, August and October with a value of 5.2 kWh/m^2. The results from the two simulations (with and without louver shading system) do not differ (Figure 4.1).

- *Energy Balance*



	January	February	March	April	May	June	July	August	September	October	November	December
Infiltration Total Heat Loss Energy	-47.60	-39.65	-33.60	-25.12	-19.53	-13.09	-6.79	-9.30	-15.21	-23.86	-35.43	-46.66
Ventilation Total Heat Loss Energy	0.00	0.00	0.00	-0.65	-1.68	-1.81	0.00	-0.50	-3.25	-1.49	0.00	0.00
Windows Total Heat Loss Energy	-33.99	-26.25	-22.02	-16.04	-12.53	-9.52	-7.74	-9.79	-11.46	-16.75	-24.84	-32.99
Opaque Surface Inside Faces Total Conduction Heat Loss Energy	-211.93	-154.59	-127.60	-89.34	-66.45	-56.51	-45.54	-59.97	-73.77	-99.51	-150.79	-206.48
Infiltration Total Heat Gain Energy	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00
Opaque Surface Inside Faces Total Conduction Heat Gain Energy	0.11	1.88	15.29	20.19	31.46	33.65	58.08	53.69	31.25	17.27	2.64	0.00
Windows Total Heat Gain Energy	40.40	49.44	57.29	51.44	51.02	48.92	61.51	72.75	63.49	56.58	42.88	33.43
Ventilation Total Heat Gain Energy	0.00	0.00	0.00	0.00	0.02	1.69	8.52	5.81	0.09	0.00	0.00	0.00
Windows Total Transmitted Solar Radiation Energy	48.87	57.11	64.92	58.48	57.42	53.38	63.26	73.82	66.07	60.69	49.68	41.19
Electric Equipment Total Heating Energy	23.62	20.68	22.85	21.73	23.62	21.88	22.71	23.62	20.96	23.62	22.64	21.94
People Total Heating Energy	25.51	22.34	24.68	23.47	25.51	23.63	24.52	25.51	22.64	25.51	24.45	23.69
Lights Total Heating Energy	9.43	8.14	8.22	7.28	8.22	7.71	7.44	8.42	8.01	7.82	9.23	9.31

Figure 4.2 Energy balance without louver shades (single zone model)



	January	February	March	April	May	June	July	August	September	October	November	December
Infiltration Total Heat Loss Energy	-47.59	-39.64	-33.52	-25.04	-19.50	-13.09	-6.82	-9.29	-15.20	-23.80	-35.42	-46.66
Ventilation Total Heat Loss Energy	0.00	0.00	0.00	-0.63	-1.64	-1.87	0.00	-0.65	-3.23	-1.40	0.00	0.00
Windows Total Heat Loss Energy	-33.87	-26.09	-21.85	-15.88	-12.39	-9.39	-7.61	-9.64	-11.27	-16.54	-24.67	-32.82
Opaque Surface Inside Faces Total Conduction Heat Loss Energy	-211.33	-153.62	-125.77	-87.66	-64.92	-55.18	-44.23	-58.08	-71.82	-97.67	-149.87	-206.08
Infiltration Total Heat Gain Energy	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.00	0.00
Opaque Surface Inside Faces Total Conduction Heat Gain Energy	0.08	1.70	14.66	19.73	31.02	33.19	57.45	52.87	30.71	16.72	2.40	0.00
Windows Total Heat Gain Energy	38.08	46.64	54.29	48.93	48.65	46.84	58.93	69.51	60.45	53.73	40.45	31.44
Ventilation Total Heat Gain Energy	0.00	0.00	0.00	0.00	0.02	1.67	8.46	5.75	0.08	0.00	0.00	0.00
Windows Total Transmitted Solar Radiation Energy	46.44	54.27	61.82	55.86	54.95	51.19	60.63	70.54	62.99	57.78	47.20	39.13
Electric Equipment Total Heating Energy	23.62	20.68	22.85	21.73	23.62	21.88	22.71	23.62	20.96	23.62	22.64	21.94
People Total Heating Energy	25.51	22.34	24.68	23.47	25.51	23.63	24.52	25.51	22.64	25.51	24.45	23.69
Lights Total Heating Energy	9.43	8.14	8.22	7.28	8.22	7.71	7.44	8.42	8.01	7.82	9.23	9.31

Figure 4.3 Energy balance with louver shades (single zone model)

Regarding the energy balance, it can be seen that the highest energy gains are from windows total transmited solar radiation energy with the higher values in the summer months, however in the summer months, the opaque surface inside faces total conduction heat gain energy is also high peaking in July with 57.45 kWh. The lights total heating energy, the people total heating energy and the equipment heating energy are constant throught the year. Regarding the energy losses, the highest energy loss is by opaque surface inside faces total conduction energy, peaking in the month of January with 211.33 kWh. The windows total heat lossand the total infiltration losses are increased in the cooler months. The difference in the results is slight between the two cases, with and without louver shading system. The window solar and total gains are slightly lower in the case where louver shades were assigned (Figure 4.2 and 4.3).

4.1.2. Case Study I – Thermal comfort results

In this chapter, a comparison of the thermal comfort results is done for the single zone model with the two types of simulations that are run, with louver blinds and without louver blinds. The reasoning behind this is to see the impact of the shading system regarding the thermal comfort. All of the data in this chapter is annual. This chapter discusses the difference between the results of the two cases regarding operative temperature results and the predicted mean vote results.

- *Average Operative Temperature*

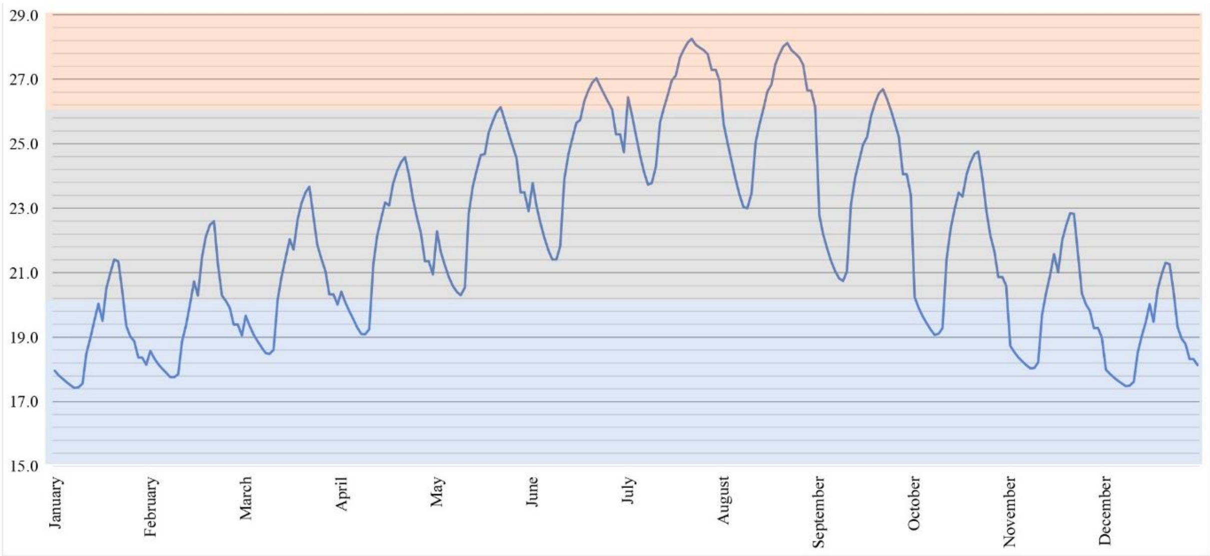


Figure 4.5 Average operative temperature without shades (single zone model)

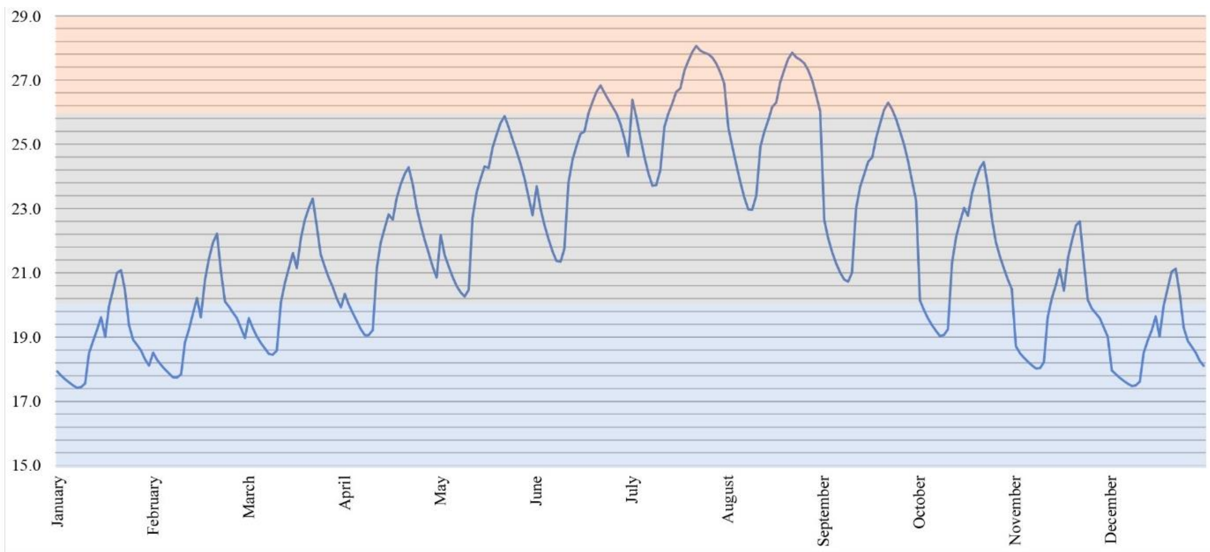


Figure 4.4 Average operative temperature with shades (single zone model)

Operative temperature is a simplified measure of human thermal comfort derived from air temperature, mean radiant temperature and air speed. It is calculated using the formula to = (tr + (ta x √10v)) / (1+√10v) where ta- air temperature (Cº), tr- mean radiant temperature (Co) and v- air speed (m/s). On Figure 4.8, the results are shown in percentage of values below, in and above the set treshold of 20º to 26º . In the case without the shading device, the percentage of values above the treshold are 29.2%, in the treshold are 55.5% and above 15.3%. For the second case, when the shades are assigned, the percentage of values above the treshold are 32.3%, in the treshold are 54.9% and above 12.8%.

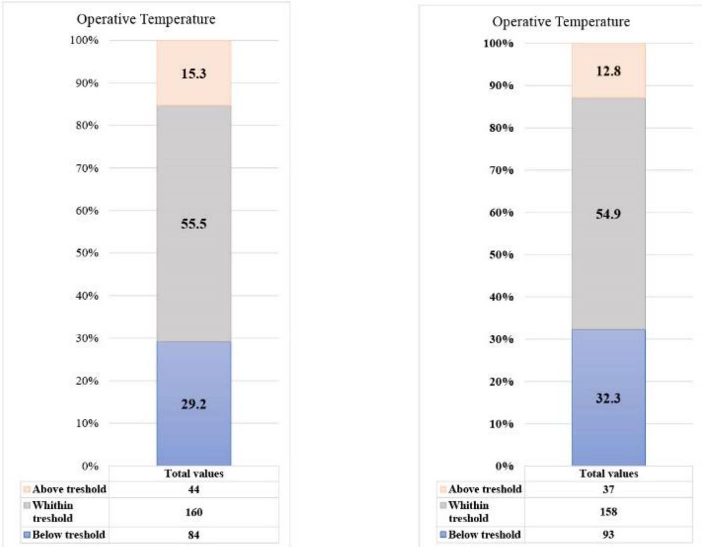


Figure 4.8 Average operative temperatures values below, in and above threshold

- *Predicted Mean Vote*

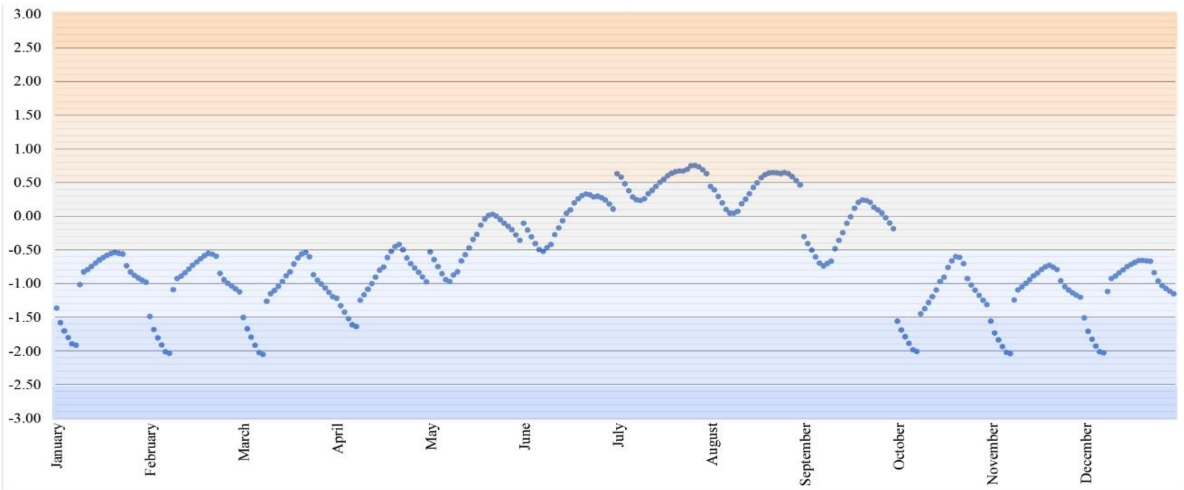


Figure 4.7 PMV without shades (single zone model)

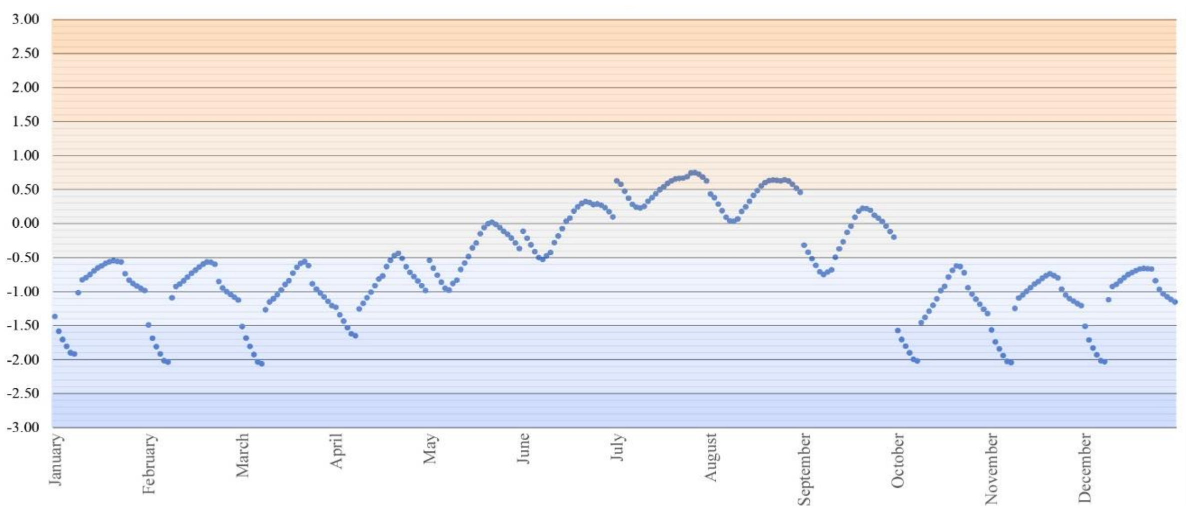


Figure 4.6 PMV with shades (single zone model)

The calculation for Predicted Mean Vote takes into consideration the air temperature, mean radiant temperature, relative humidity, air velocity, metabolic rate of the occupants and the clothing insulation. It is a comfort metrics that represents how the occupants experience the interior thermal conditions of the construction. With the simulation results, the values that were acquired, it can be seen that in both situations, with or without louver shading system, the PMV results are quite similar. In both of the cases, in the summer months there is a neutral sensation of the ocupants, but in the winter months, the occupants experience sensations that vary from slightly cold and cool (Figure 4.9).

Figure 4.9 PMV percentage of values regarding the sensation of the occupants

4.1.3. Comments on the results for case study I

With the collection of the results discussed in the previous chapter it evident that the implementation of a shading device does make a difference in the overall performance of the building, however, it is a slight difference.The reasoning behind this is the small window oppening, which in comparison to the wall surfaces and the total area of the construction, is undersized. Overall, regarding the energy consumption, the results are relatively high when the type and size of the construction is taken into consideration. The reasoning behind this is the types of materials used for the components of the construction. The components do not have insulation layes which can not block the influence of the exterior conditions penetrating the interior space. Regarding the thermal results, the HVAC system controls the temperature of the indoor environment, so with the results of the average operative temperature and PMV it can be seen that the thermal comfort of the office is satisfying.

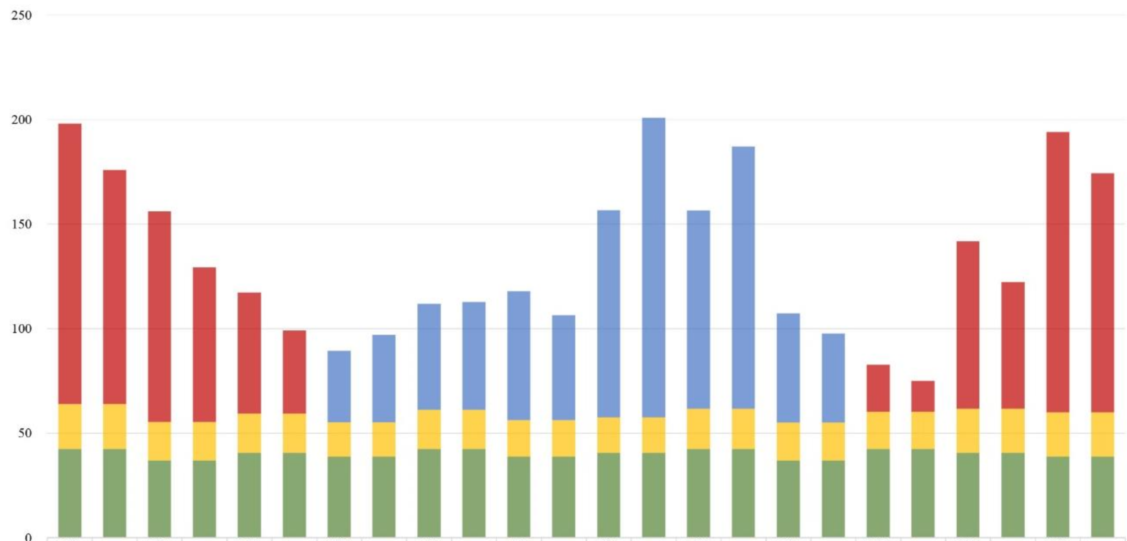
4.2. Case Study II – Results

The outcomes of the energy and thermal comfort simulations for the multi-zone model, the second case study, are collected in the following chapters.

4.2.1. Case Study II – Energy analysis results

In this section, the energy results from the two types of simulations—those with and without louver blinds—for the multi-zone model are compared. This is being done in order to evaluate how the shading system will affect energy usage. The content of this chapter is on annual level.

- *Primary Energy Use*

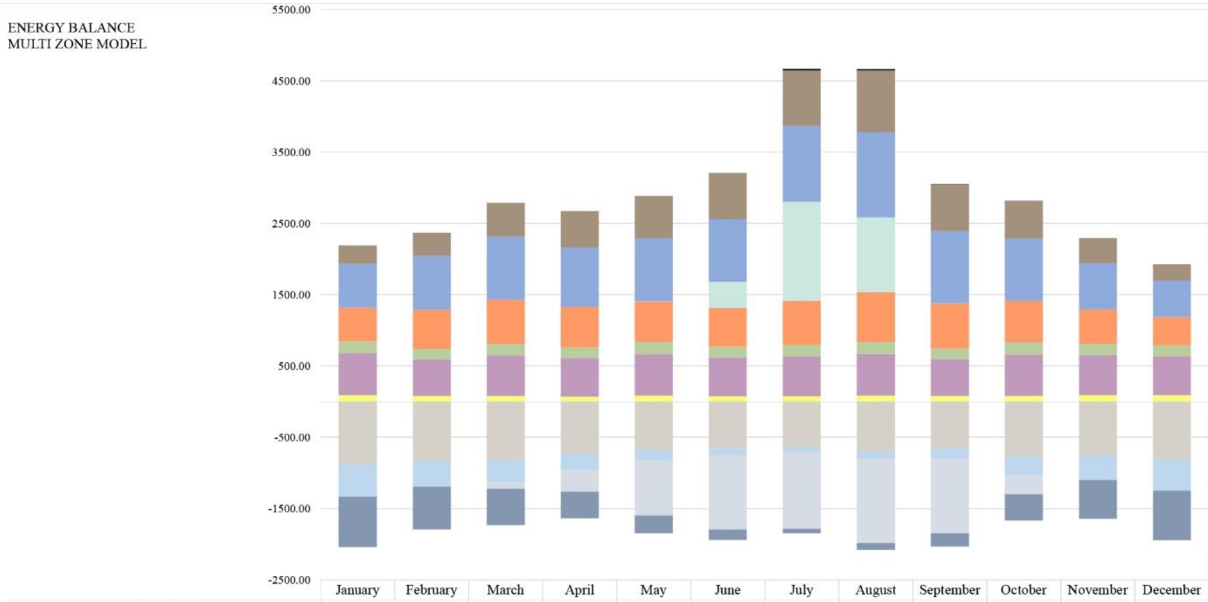


	January		February		March		April		May		June		July		August		September		October		November		December	
	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades
Heating	134	112	101	74	58	40	0	0	0	0	0	0	0	0	0	0	0	0	22	15	80	61	134	114
Cooling	0	0	0	0	0	0	34	42	51	52	62	50	99	143	95	125	52	42	0	0	0	0	0	0
Electric lighting	21	21	19	19	19	19	17	17	19	19	18	18	17	17	19	19	18	18	18	18	21	21	21	21
Electric equipment	43	43	37	37	41	41	39	39	43	43	39	39	41	41	43	43	37	37	43	43	41	41	39	39

Figure 4.10 Primary energy use (multi-zone) model

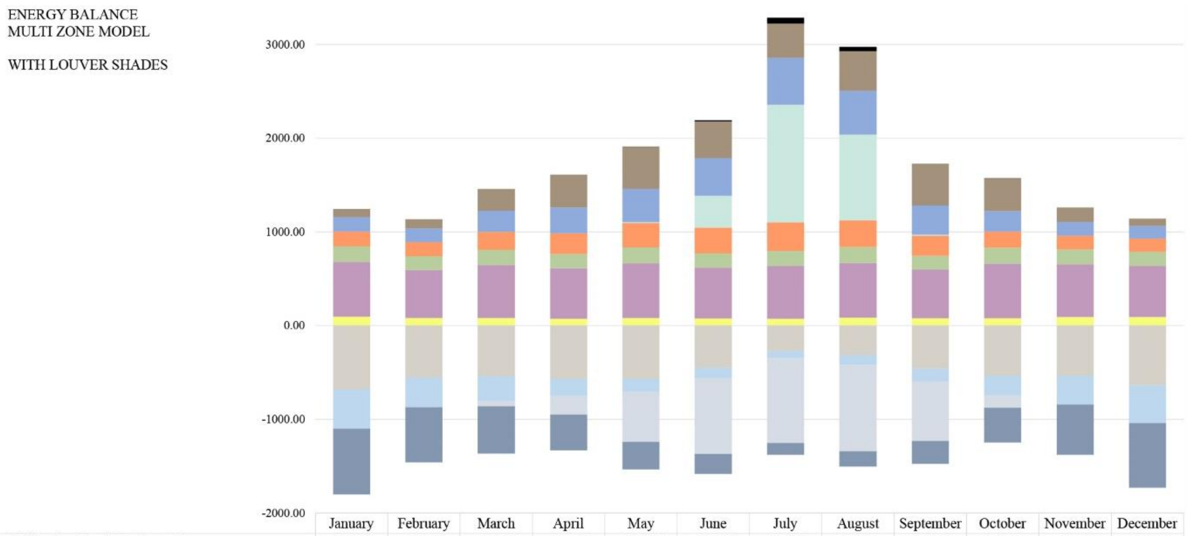
The value 2.45 PEF (for electric energy) and the EF of 3.1 were used to calculate the primary energy for cooling, while the value 1.05 PEF (for natural gas) and the EF of 0.85 were used to calculate the primary energy for heating. The value 2.45 (PEF for electric energy) and EF of 1, which are the same values for calculating the primary energy use for electric equipment, were used to calculate the primary energy for electric lighting. The values are then split by the particular zone area. The calculations' visual results (Figure 4.10) show that the summer months—more specifically, the months of July and August—are when cooling primary energy consumption peaks. The highest value for cooling energy consumption when no blinds are assigned to the model is 143 kWh/m2 in the month of July; however, when louver shades are assigned, the value drops to 99 kWh/m2. It is clear that the peak values for the primary energy use for heating occur during the winter, specifically in December and January. The highest value in the first scenario, where no shades are assigned to the model, is 112 kWh/m2, while the highest value in the scenario with louver shades is 134 kWh/m2, indicating an increase in consumption. Additionally, the results for the two types of simulations show that the primary energy use for electric lighting has the same values, but that consumption increases in the winter and peaks in January, November and December at 21 kWh/m2. With a value of 43 kWh/m2, the months of January, May, August, and October have the highest primary consumption for electric equipment, however, the result values from the two simulations (with and without louver shading system) do not differ (Figure 4.10).

- *Energy Balance*



	January	February	March	April	May	June	July	August	September	October	November	December
Infiltration Total Heat Loss Energy	-711.12	-600.23	-513.42	-374.22	-248.22	-147.93	-66.68	-97.49	-182.16	-370.78	-545.12	-697.19
Ventilation Total Heat Loss Energy	0.00	0.00	-92.73	-309.51	-772.16	-1042.58	-1069.37	-1175.47	-1047.89	-279.50	0.00	0.00
Windows Total Heat Loss Energy	-449.95	-362.43	-307.46	-217.53	-147.94	-102.42	-79.09	-105.49	-144.33	-250.50	-348.79	-439.79
Opaque Surface Inside Faces Total Conduction Heat Loss Energy	-882.84	-830.39	-820.21	-735.29	-679.31	-650.78	-632.84	-700.95	-658.21	-770.49	-751.85	-809.38
Infiltration Total Heat Gain Energy	0.00	0.00	0.00	0.00	0.24	5.31	20.04	16.42	0.24	0.01	0.00	0.00
Opaque Surface Inside Faces Total Conduction Heat Gain Energy	261.89	322.91	473.36	507.72	593.92	640.70	780.22	864.30	649.96	531.50	351.52	229.86
Windows Total Heat Gain Energy	613.02	757.98	888.80	833.72	880.26	877.02	1067.38	1195.88	1018.13	870.77	651.27	511.72
Ventilation Total Heat Gain Energy	0.00	0.00	0.00	0.00	6.59	367.13	1387.66	1048.67	3.68	0.07	0.00	0.00
Windows Total Transmitted Solar Radiation Energy	472.69	550.99	622.07	569.05	569.54	542.98	617.11	701.49	630.75	585.89	480.01	399.40
Electric Equipment Total Heating Energy	167.61	145.75	160.32	153.03	167.61	153.03	160.32	167.61	145.75	167.61	160.32	153.03
People Total Heating Energy	584.73	512.04	565.77	537.85	584.73	541.54	562.08	584.73	518.89	584.73	560.50	543.12
Lights Total Heating Energy	93.28	80.54	81.31	72.07	81.38	76.27	73.62	83.37	79.31	77.41	91.32	92.10

Figure 4.11 Energy balance without louver shades (multi-zone model)



	January	February	March	April	May	June	July	August	September	October	November	December
Infiltration Total Heat Loss Energy	-703.78	-588.85	-502.59	-381.36	-294.47	-215.15	-126.65	-162.59	-243.22	-368.78	-534.31	-690.08
Ventilation Total Heat Loss Energy	0.00	0.00	-53.80	-197.70	-533.09	-807.08	-905.64	-921.91	-638.50	-135.73	0.00	0.00
Windows Total Heat Loss Energy	-418.44	-317.47	-267.10	-185.53	-140.60	-105.24	-78.36	-102.17	-132.09	-204.86	-308.00	-401.42
Opaque Surface Inside Faces Total Conduction Heat Loss Energy	-680.81	-554.48	-541.47	-566.15	-567.64	-455.47	-268.98	-317.22	-460.71	-537.03	-534.54	-639.39
Infiltration Total Heat Gain Energy	0.00	0.00	0.00	0.00	0.18	11.18	63.02	46.86	0.37	0.03	0.00	0.00
Opaque Surface Inside Faces Total Conduction Heat Gain Energy	86.54	97.46	232.64	348.10	450.03	391.95	368.16	422.45	445.55	349.28	151.63	77.86
Windows Total Heat Gain Energy	154.88	148.80	223.70	275.93	354.88	401.12	497.80	466.73	313.76	219.59	150.30	133.54
Ventilation Total Heat Gain Energy	0.00	0.00	0.00	0.04	7.72	341.91	1255.12	912.93	7.04	0.16	0.00	0.00
Windows Total Transmitted Solar Radiation Energy	157.19	150.42	193.70	222.29	260.22	272.69	305.03	287.90	215.86	172.71	145.58	140.07
Electric Equipment Total Heating Energy	167.61	145.75	160.32	153.03	167.61	153.03	160.32	167.61	145.75	167.61	160.32	153.03
People Total Heating Energy	584.73	512.04	565.77	537.85	584.73	541.54	562.08	584.73	518.89	584.73	560.50	543.12
Lights Total Heating Energy	93.28	80.54	81.31	72.07	81.38	76.27	73.62	83.37	79.31	77.41	91.32	92.10

Figure 4.12 Energy balance with louver shades (multi-zone model)

Regarding the energy balance, it can be seen that the highest energy gains are from windows total transmited heat energy with the peaking values in the summer months, however, in the case when the louver shading system was assigned, these values were lower. The window total heat gains with the highest value of 1195.9 kWh is in August. The values for the case where the louver shades are assigned are decreased, with a maximum value of 497.8 kWh in July. The opaque surface inside faces total conduction heat gain energy is also high peaking in August with 864.3 kWh, which has decreased in the second simulation with 445.5 kWh in September. Also in the summer months (July and August) the total ventilation heat gains are high, peaking in July with 1387.6 kWh. These values are slightly lower in the case then louver shades were assigned, with the higher value of 1255.1 kWh in July. The infiltration total gains are present in the warmer months, peaking in July with 20 kWh. These values are slightly higher in the sacond case, with the maximum total value of 63 kWh. The lights total heating energy, the people total heating energy and the equipment heating energy are constant throught the year. Regarding the energy losses, the highest energy loss is by opaque surface inside faces total conduction energy, peaking in the month of January with 882.8 kWh. The values are decreased for the second type of simulation, with peaking value of 680.0 kWh. The windows total heat loss and the total infiltration losses are increased in the cooler months. In the summer months the ventlation total heat enegy losses are increased, peaking in August with 1175.5 kWh. These values are decreased in the case with the louver blinds, with a maximum value of 921.9 kWh in August. Overall, the gains and losses for the second simulation (with the louver shades) have decreased significally (Figures 4.11 and 4.12).

4.3.2. Case Study II – Thermal comfort results

In this chapter, the thermal comfort results for the multi-zone model are compared for the two simulation types that are carried out: those with and those without louver blinds. This is being done in order to assess how the shading system will affect the thermal comfort. The information in this chapter is all annual. In terms of operative temperature, air temperature, mean radiant temperature, predicted mean vote, and predicted percentage of dissatisfied results, this chapter compares the outcomes of the two cases.

- *Average Operative Temperature*

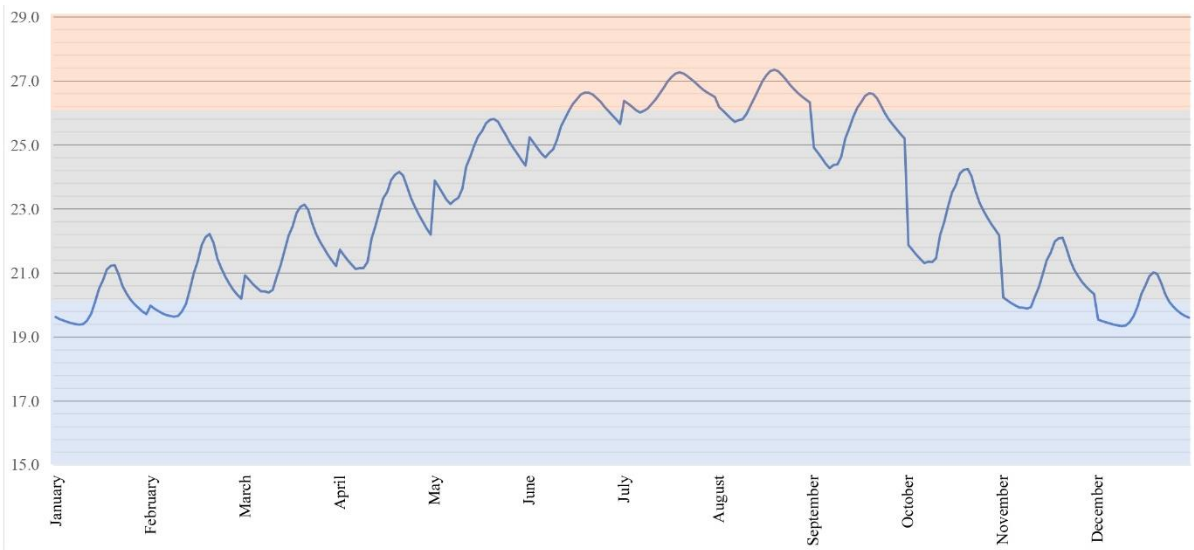


Figure 4.14 Operative temperature - without louver shades (multi-zone model)

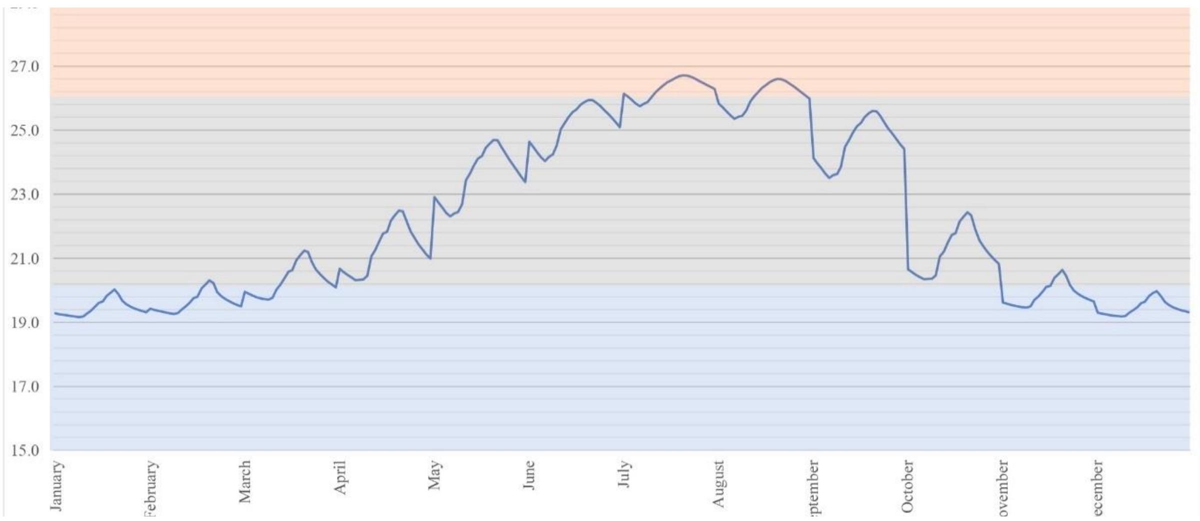


Figure 4.13 Operative temperature - with louver shades (multi-zone model)

A simple measurement of human thermal comfort, operational temperature is derived from air temperature, mean radiant temperature, and air speed. The formula to calculate it is $t_o = (t_r + (t_a \times 10v)) / (1+10v)$, where ta stands for air temperature (C°), tr for radiant temperature (C°), and v for air speed (m/s). The results are displayed on Figure 4.15 as a percentage of values below, within, and above the predetermined threshold of 20° to 26°. Without the shading device, there are 20.8% of values that are above the threshold, 64.3% that are in the threshold, and 14.9% that are above the threshold. When the shades are applied to the second case, the proportion of values above the threshold is 11.5%, in the threshold is 56.6%, and above 31.9% (Figure 4.15).

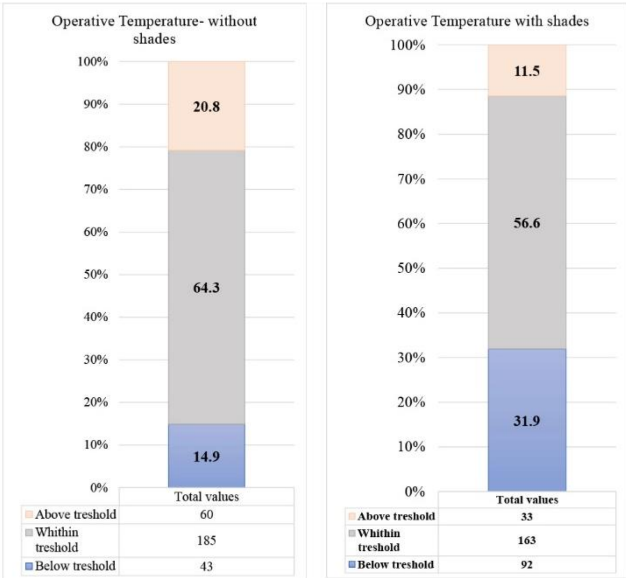


Figure 4.15 Average operative temperatures values below, in and above threshold (multi-zone model)

- *Predicted Mean Vote*

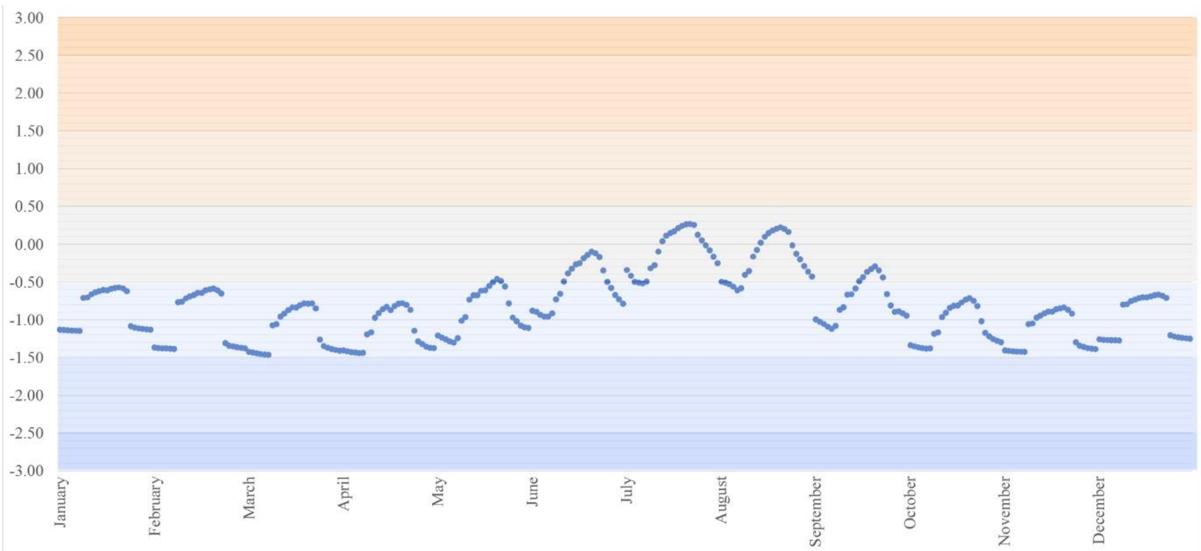


Figure 4.16 PMV - without louver shades (multi-zone model)

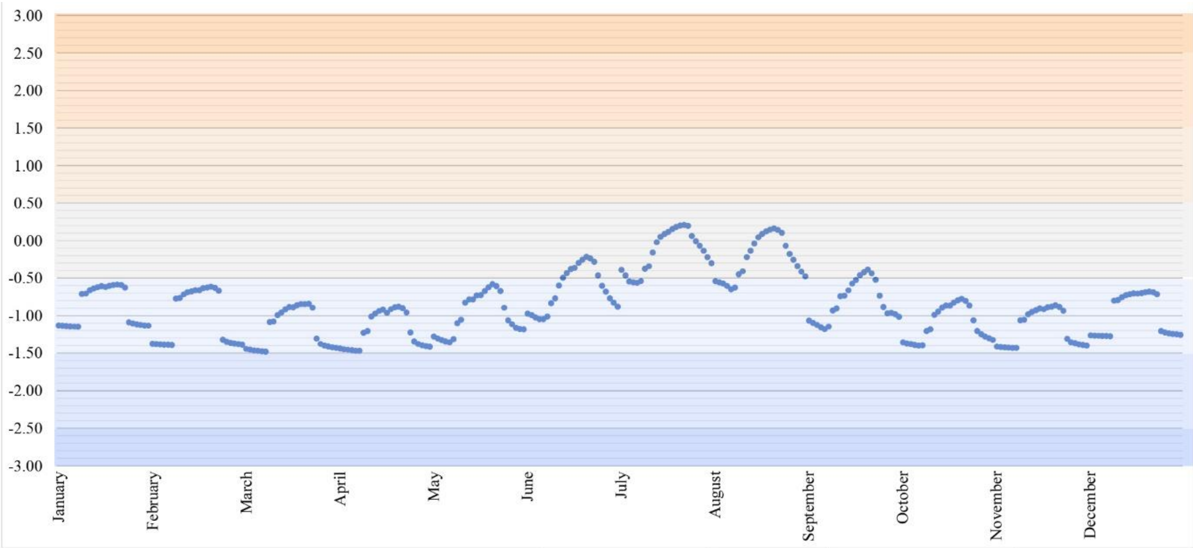


Figure 4.17 PMV - with louver shades (multi-zone model)

The air temperature, mean radiant temperature, relative humidity, air velocity, metabolic rate of the occupants, and clothing insulation are all taken into account when calculating the predicted mean vote. It is a measure of comfort that depicts how building occupants feel about the interior thermal conditions. With the help of the simulation results and values that were collected, it is clear that the PMV results in both cases—with or without a louver shading system—are fairly comparable. In the first case, occupants have a neutral feeling 21.2% of the time but 78.8% of the time the feeling is slightly cold. In the second case, occupants have a neutral feeling 18.1% of the time but 81.9% of the time the feeling is slightly cold. Overall In the summer months in both cases, the sensation is neutral, but in the winter months the sensation is slightly cold (Figure 4.18).

Figure 4.18 PMV percentage of values regarding the sensation of the occupants (multi-zone model)

4.3.3. Comments on the results for case study II

The implementation of a shading device does affect the overall performance of the building, with a great significance, according to the results compiled and discussed in the previous chapter. When the type and size of the construction are taken into account, the overall energy consumption results are relatively normal. The construction programs and schedules, as well as the materials used for the various components, are the cause of this. Given that the HVAC system regulates the temperature of the indoor environment, the thermal comfort of the office can be seen to be satisfactory based on the average operative temperature and PMV results, however, in both cases, the sensation of the building might slightly colder.

5. Discussion

This research focuses on reviewing the building performance simulation tools and finding the link between the building information modelling software programs and the performance simulation software programs. The focus was discovering the link between the BIM program Revit which is used in this research and Grasshopper as a VPL program on the Rhino interface, which does the building simulation performance analysis.

Various workflows have been investigated in this research, to have a smooth data transfer when exporting the models from one to another software program. After the literature review that provided information about the available options on the market, the decision was made to use these two workflows - first one being the traditional exportation process using either a .DWG or .DXF file format and then importing it on the Rhino interface – the second one is using the new plug-in called Speckle that connects Revit and Grasshopper via online cloud service. The first workflow was used for exporting the single zone model and the second workflow was used for exporting the multi-zone model. This research was based on understanding how to get to the results of the building performance regarding thermal comfort and energy evaluation in the early design stages.

5.1. Strengths of the study

Firstly, the building information modelling program Revit, is the most used BIM program by architects and engineers today. It offers a wide variety of families (model geometries), various types of materials and the option to edit them if that is required or desired. It offers the possibility not only to model geometries, but to assign system, properties and schedules on the construction. The exportation process of the model is quite simple, there are not many requirements to be undertaken in this step.

Regarding the exportation processes, both in the first and in the second case study, the process is quite simple. It does not require many additional steps to get the model from Revit to Rhino. However, Speckle gives the users the opportunity to choose which geometry to export. The model can be exported either by choosing the components by categories or it can be exported as a whole construction. One thing that Speckle offers the users, is the ability for backwards interoperability regarding geometry modifications. If the adapted geometry is "baked" on the Grasshopper interface, it can easily be sent to the Revit interface, using the speckle online stream can then be received on Revit. Also, Speckle is easy to download, and is free of charge. All the information that is sent on the online Speckle stream can be accessed at any time, it can be modified, and it will stay there until the user decides to erase it. Regarding the traditional exportation process, the only option of exportation is the whole geometry. An important thing to keep in mind are the modelling units, which must be the same for both Revit and Rhino.

Next, Grasshopper with its plug-ins, is a very powerful tool. It offers the users a wide variety of actions that can positively affect the work of architects and engineers. It is a software in which almost everything is possible. It offers the options for parametric modelling, buildings evaluations, rendering images etc. Once the models were transferred onto the Rhino and Grasshopper interface where OpenStudio was used, that serves as a link to EnergyPlus in order to run the energy and thermal comfort simulations. This gives the user freedom to assign properties to the analytical model in order to have more accurate results.

The running time of the simulations in this specific case, was quite low. For the first case study, it took about 3 minutes for the simulations to be done, for both thermal comfort and energy evaluation. For the second case study, the running time for the simulations took around 5 minutes also for both analyses.

Once the simulations have finished, Honeybee offers many options to analyse the outputs. Here all the energy and thermal comfort results have been read by the Honeybee "HB Read Room Results" components, which separate the required data and get it ready for visualization. In the meantime, the user could transform and edit the data that had been read before visualizing it. For example, in the case of primary energy calculations, the data from the "HB Read Room Custom Results" has been deconstructed and edited using mathematical equations before plugging it in the component for the visualization part. Using Ladybug components, the various data collections can be visualized.

5.2. Limitations of the study

One of the first issues that were met while doing this research, it was the lack of information available regarding this subject. Since Grasshopper offers so many options for parametric modelling, building performance evaluation etc. it becomes quite complicated for the user to find its way in the numerous tools. Many architects avoid using such programs, because of the learning curve. In this specific case, when constructing the analytical model and when schedules were assigned many errors occurred, to which there was no information about their solution.

Secondly, when using the workflows mentioned in the chapter "Methodology", the geometry modifications that were done in order to get the model ready for simulations, were quite excessive. An example for this is the geometry modification for the second case study, the multizone model. Because of the irregular shape of the exterior walls (the curved walls) the geometry had to be modified in order to be usable. First it had to be deconstructed and then reconstructed with the process of constructing multiple surfaces as segments. This process was repeated for all the irregular surfaces (floors and ceilings/roofs).

Furthermore, the complexity of the model plays a big part in the simulation process. Even though for both case studies the running time was quite low, for the second case study the program crushed multiple times after the simulation was over. Because of the complexity of the model geometry after the modifications and after assigning all the systems, programs, material properties etc. the Grasshopper file became quite heavy. This resulted in difficulty in all the actions that followed.

Lastly, whilst assigning shading element the possibility of constructing dynamic shading system was not an option that was feasible. The only option at this point is to construct a shading device to which a transmittance schedule could be assigned regarding either direct sunlight or daylight glare probability analysis results, however, this type of component is not taken into consideration when energy and thermal simulations are done.

5.2.1. Correction of multi-zone model (case study III)

An important step for analysing the building performance is the modelling process of the interior walls. Regarding the required analytical model for energy and thermal simulations, it is important for the zones to interact with each other and there should not be voids between the surfaces. For the energy analysis to be accurate, a third case study was conducted to correct some of the issues of the exportation process for the multi-zone model. The third case study is consisted of a multizone model which is simplified in order to understand the differences in the outcomes. The important difference in both models, was the selection of the surfaces of the interior walls for the analysis. In the first exportation process, for the multizone model, the rooms were assigned with the default Revit option, which is explained in chapter 3.5.3. Once the model is exported, the rooms are accepted by Grasshopper with voids between each of them. This represents a problem once the energy analysis is run, since the interior surfaces are set to adiabatic and do not correlate to each other, each zone functions as a separate, not as a whole enclosed construction. This leads to inaccurate energy results. This issue was fixed in the third model in Revit. This model was constructed of 3 rooms, two offices with different sizes and a corridor. In order to have the option to choose middle wall surfaces, another approach was taken in comparison to the second case study. Instead of modelling the interior walls as a solid component, using Revit wall family, the zones were separated using the component "Room Separators", which creates zone separations without the wall volumes (Figure 5.1 and 5.2)

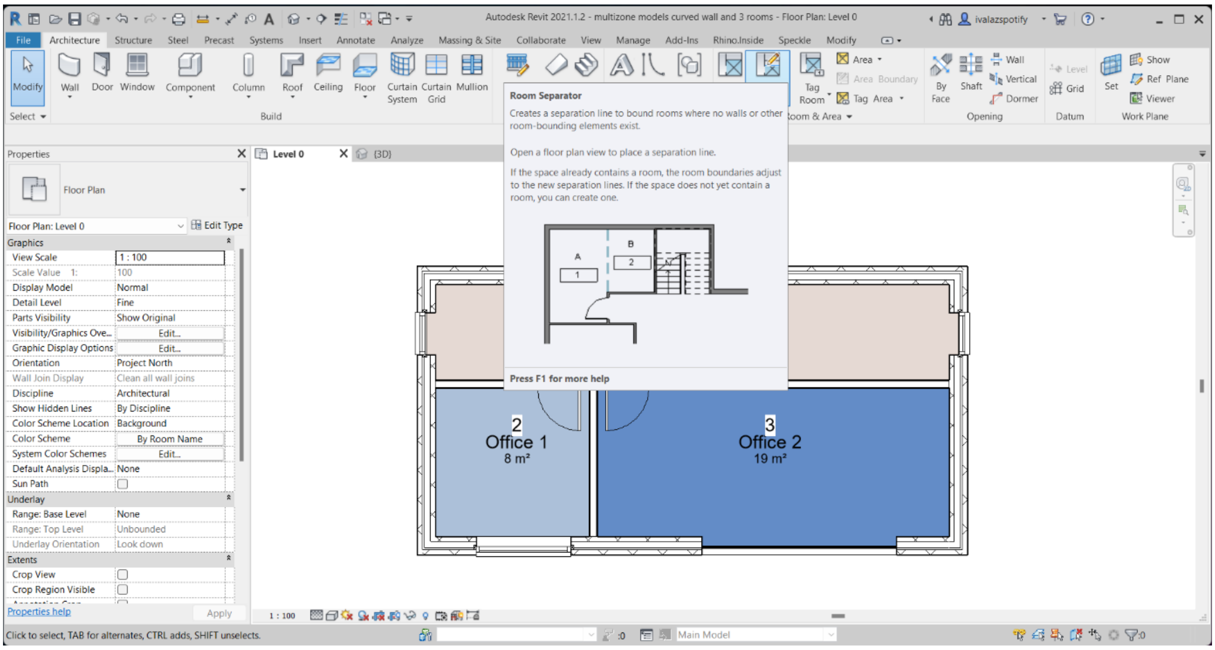


Figure 5.2 Using the command "Room Separator" to construct enclosed room volumes (Case study 3)

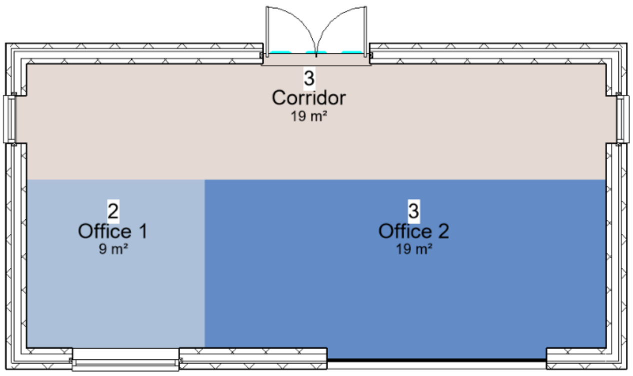


Table 5-1 Window to wall ratio (case study 3)

Room type	Wall Area $[m^2]$	Glazing Area $[m^2]$	WWR [%]
Office 1	5	2.6	52.0
Office 2	20.1	9.3	46.3
Corridor	11.7	2.9	24.8
All Rooms	36.8	14.8	40.2

Figure 5.1 Corrected room volumes on Revit (Case study 3)

Once the process of the model adjustments was done, the model was exprted using the Speckle stream with the same process previously mentioned in chapter 3.5.4. The transferred geometry was room volume, walls and windows. The reasoning behind the transfer of the wall geometry is that the glazing element in office 2 was modeled using the component "Curtain Wall" and once it is received by speckle, it is recognized as a wall element ratheer than a glazing element. On Figure 5.4 the accepted geometry can be seen on the Speckle stream, where it is evident that the issue with the gaps between the zones is no longer present.

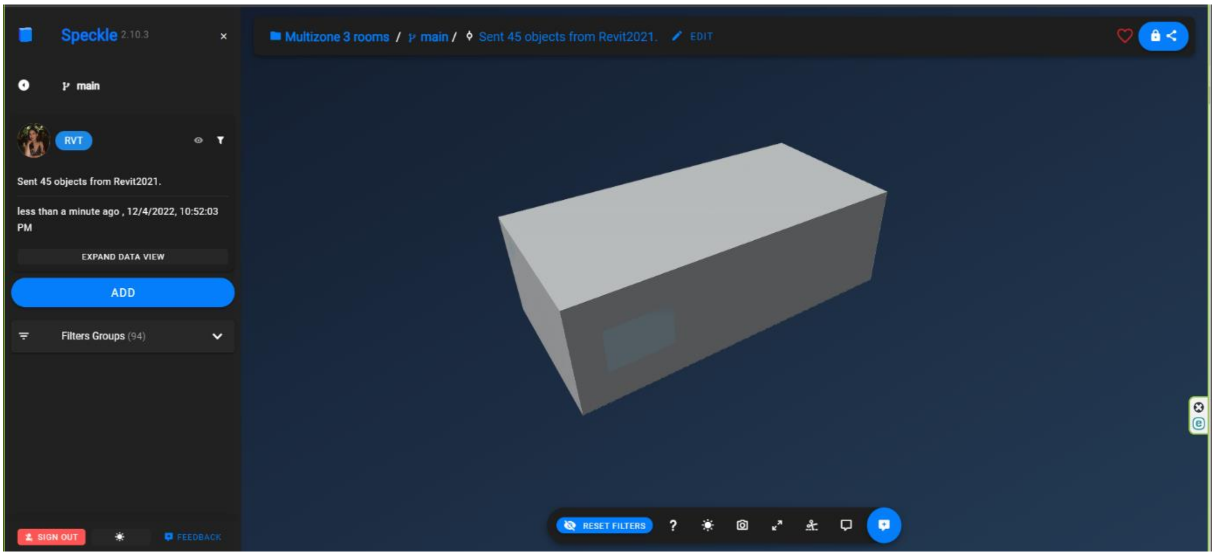
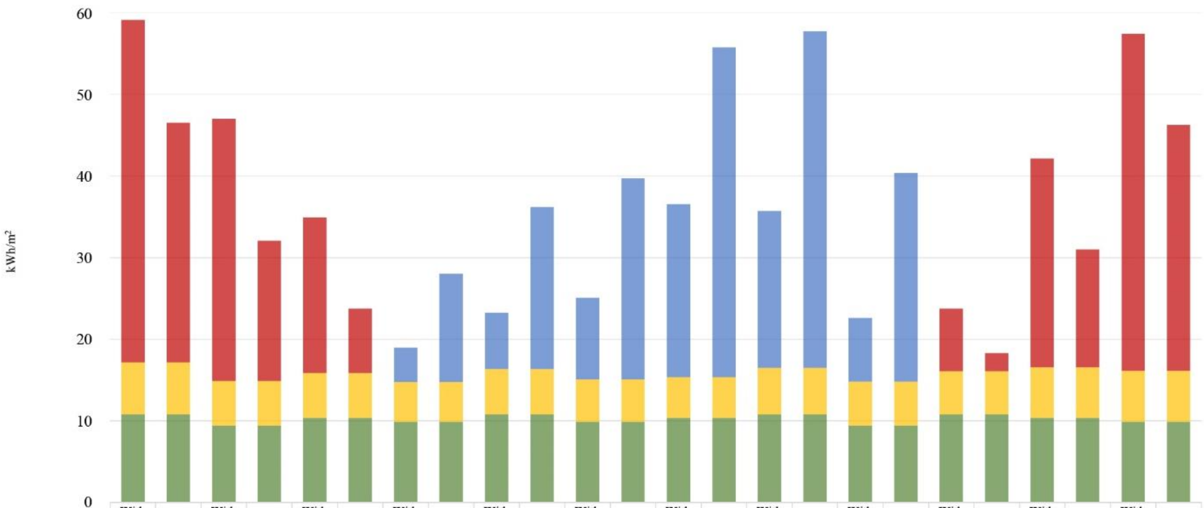


Figure 5.3 Received model geometry in Speckle (Case study 3)

The importation of the geometry in Grasshopper was the same as the importation of the case study II multi zone model geometry (chapter 3.5.6.). Once the geometry was on the Grasshopper interface, the process of constructing the Honeybee model applied in this case as well, with a slight change, when the surfaces were assigned as Honeybee faces, it was important to use only one surface that is shared by the zones, meaning, the middle surface that the zones share, was assigned to both Honeybee room components, instead of constructing two separate HB faces. This solves the issue of repetition when assigning the faces, and the program recognizes it as one wall, with correct thickness, in comparisson of the second case study, where there was a duplication of surfaces, which meant that the interior surfaces have double the thickness. The materials assigned on the HB Faces, are the same materials used for the case study II, the multi zone model (chapters 3.5.8.2 and 3.5.8.3.).

Next, on this model, the preparations for the simulations and the thermal comfort and energy performance simulations were done as in the previous two case studies. More speciffically, the workflow explained in the chapters 3.5.8., 3.5.9., 3.5.10. and 3.5.11. in order to calculate the thermal balance, primary energy use, average operative temperature and the predicted mean vote.

- *Primary Energy Use*

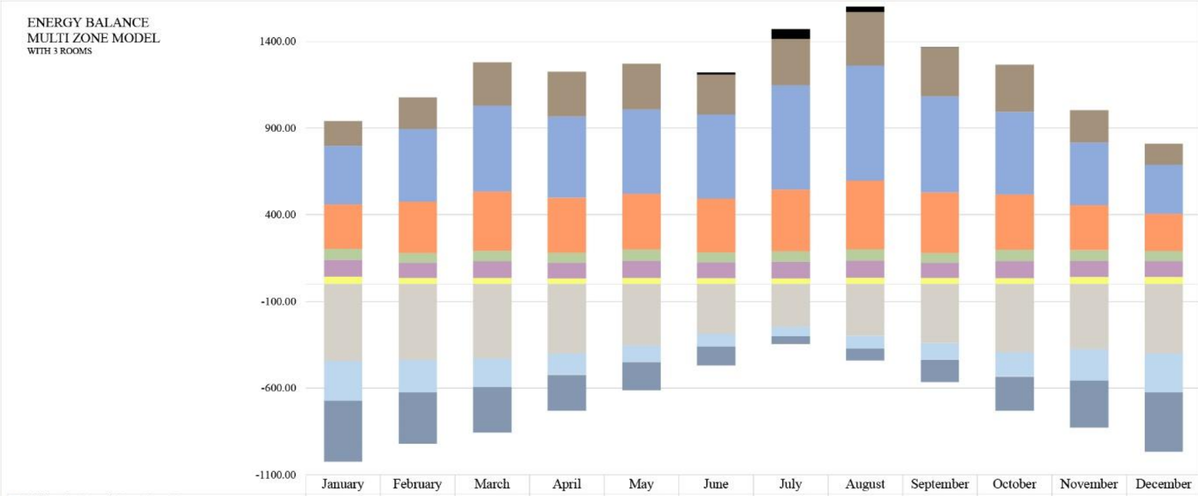


	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades	With louver shades	Wihout shades
	January		February		March		April		May		June		July		August		September		October		November		December	
Heating	41.9	29.4	32.1	17.2	19.0	7.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.7	2.2	25.6	14.4	41.3	30.1
Cooling	0.0	0.0	0.0	0.0	0.0	0.0	4.2	13.2	6.9	19.8	10.0	24.6	21.2	40.4	19.2	41.2	7.8	25.6	0.0	0.0	0.0	0.0	0.0	0.0
Electric lighting	6.4	6.4	5.5	5.5	5.5	5.5	4.9	4.9	5.5	5.5	5.2	5.2	5.0	5.0	5.7	5.7	5.4	5.4	5.3	5.3	6.2	6.2	6.3	6.3
Electric equipment	10.8	10.8	9.4	9.4	10.3	10.3	9.9	9.9	10.8	10.8	9.9	9.9	10.3	10.3	10.8	10.8	9.4	9.4	10.8	10.8	10.3	10.3	9.9	9.9

Figure 5.4 Primary energy use (three zone model)

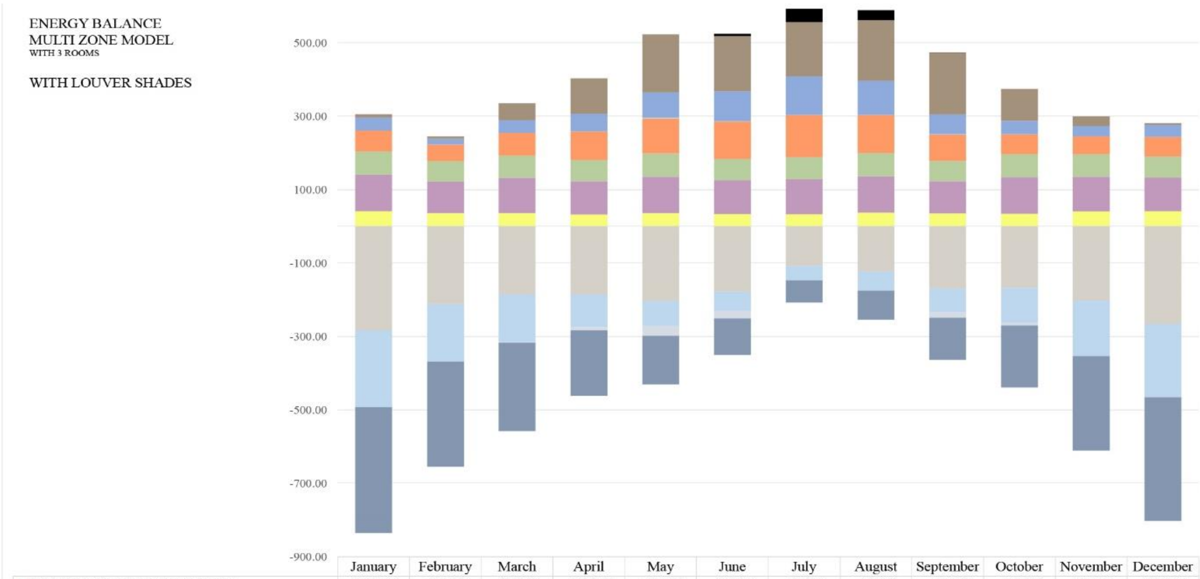
The value 2.45 PEF (for electric energy) and the EF of 3.1 were used to calculate the primary energy for cooling, while the value 1.05 PEF (for natural gas) and the EF of 0.85 were used to calculate the primary energy for heating. The value 2.45 (PEF for electric energy) and EF of 1, which are the same values for calculating the primary energy use for electric equipment, were used to calculate the primary energy for electric lighting. The values are then split by the particular zone area. The calculations' visual results (Figure 5.4) show that the summer months—more specifically, the months of July and August—are when cooling primary energy consumption peaks. The highest value for cooling energy consumption when no blinds are assigned to the model is 41.2 kWh/m2 in the month of August; however, when louver shades are assigned, the value drops to 19.2 kWh/m2. It is clear that the peak values for the primary energy use for heating occur during the winter, specifically in December and January. The highest value in the first scenario, where no shades are assigned to the model, is 30.1 kWh/m2 in December, while the highest value in the scenario with louver shades is 41.9 kWh/m2 in January, indicating an increase in consumption when the shades are assigned. Additionally, the results for the two types of simulations show that the primary energy use for electric lighting has the same values, but that consumption increases in the winter and peaks in January, November and December at 6.4 kWh/m2. With a value of 10.8 kWh/m2, the months of January, May, August, and October have the highest primary consumption for electric equipment, however, the result values from the two simulations (with and without louver shading system)

- *Energy Balance*



	January	February	March	April	May	June	July	August	September	October	November	December
Infiltration Total Heat Loss Energy	-351.83	-298.92	-262.56	-204.39	-162.16	-109.82	-46.17	-68.86	-128.40	-195.20	-270.59	-344.34
Ventilation Total Heat Loss Energy	0.00	0.00	-0.38	-3.88	-2.77	0.00	0.00	0.00	-0.44	-2.19	0.00	0.00
Windows Total Heat Loss Energy	-229.73	-186.37	-162.72	-120.69	-94.62	-72.89	-56.58	-73.04	-96.93	-138.79	-179.66	-223.91
Opaque Surface Inside Faces Total Conduction Heat Loss Energy	-443.37	-437.29	-430.90	-400.89	-353.42	-287.03	-244.66	-299.06	-339.23	-393.43	-376.76	-399.46
Infiltration Total Heat Gain Energy	0.00	0.00	0.00	0.00	0.23	13.03	57.29	42.46	2.09	0.00	0.00	0.00
Opaque Surface Inside Faces Total Conduction Heat Gain Energy	142.89	180.48	250.44	259.54	264.53	229.56	265.33	306.92	281.57	271.79	186.52	120.68
Windows Total Heat Gain Energy	338.77	419.75	495.02	468.13	486.35	484.68	602.97	664.60	554.33	477.09	359.89	282.62
Ventilation Total Heat Gain Energy	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Windows Total Transmitted Solar Radiation Energy	255.13	298.58	340.97	317.37	321.07	309.75	356.91	396.54	350.08	319.11	259.91	214.90
Electric Equipment Total Heating Energy	63.31	55.05	60.56	57.80	63.31	57.80	60.56	63.31	55.05	63.31	60.56	57.80
People Total Heating Energy	99.07	86.75	95.85	91.12	99.07	91.75	95.23	99.07	87.91	99.07	94.96	92.02
Lights Total Heating Energy	41.48	35.81	36.16	32.05	36.19	33.91	32.74	37.07	35.27	34.42	40.61	40.95

Figure 5.5 Energy balance without louver shades (three zone model)



	January	February	March	April	May	June	July	August	September	October	November	December
Infiltration Total Heat Loss Energy	-343.46	-285.85	-240.61	-178.18	-132.48	-99.30	-60.65	-79.09	-115.35	-169.20	-257.51	-336.85
Ventilation Total Heat Loss Energy	0.00	0.00	-0.98	-10.08	-27.04	-20.99	0.00	0.00	-15.07	-7.33	0.00	0.00
Windows Total Heat Loss Energy	-208.55	-157.18	-130.76	-88.46	-67.74	-52.20	-39.82	-51.67	-63.94	-94.71	-150.73	-199.17
Opaque Surface Inside Faces Total Conduction Heat Loss Energy	-283.93	-211.72	-185.32	-185.28	-203.22	-177.90	-107.81	-123.36	-169.72	-167.85	-202.81	-266.27
Infiltration Total Heat Gain Energy	0.00	0.00	0.00	0.00	0.09	5.93	36.50	26.58	0.09	0.00	0.00	0.00
Opaque Surface Inside Faces Total Conduction Heat Gain Energy	9.76	5.43	46.59	95.80	157.96	150.35	147.43	165.48	168.48	87.58	26.11	5.92
Windows Total Heat Gain Energy	35.23	16.39	33.90	48.72	69.31	81.58	105.28	93.39	54.10	35.83	28.08	32.36
Ventilation Total Heat Gain Energy	0.00	0.00	0.03	0.00	0.81	0.41	0.00	0.00	0.14	0.01	0.00	0.00
Windows Total Transmitted Solar Radiation Energy	57.10	45.19	62.19	77.73	96.05	102.59	114.98	103.81	72.40	54.54	49.00	52.64
Electric Equipment Total Heating Energy	63.31	55.05	60.56	57.80	63.31	57.80	60.56	63.31	55.05	63.31	60.56	57.80
People Total Heating Energy	99.07	86.75	95.85	91.12	99.07	91.75	95.23	99.07	87.91	99.07	94.96	92.02
Lights Total Heating Energy	41.48	35.81	36.16	32.05	36.19	33.91	32.74	37.07	35.27	34.42	40.61	40.95

Figure 5.6 Energy balance with louver shades (three zone model)

Regarding the energy balance, it can be seen that the highest energy gains from the energy simulation result for the first case, without the shading device, are from windows total transmited heat energy with the peaking values in the summer months more speciffically in August with the highest value of 664 kWh, however, in the case when the louver shading system was assigned, these values were decreased, with the highest value in July which is 105.3 kWh.The window total heat gains with the highest value of 1195.9 kWh is in August. The opaque surface inside faces total conduction heat gain energy is also high peaking in August with 306.2 kWh, which has decreased in the second simulation with 165.8 kWh in September. The infiltration total gains are present in the warmer months, peaking in July with 57.3 kWh. These values are slightly lower in the sacond case, with the maximum total value of 36.5 kWh. The lights total heating energy, the people total heating energy and the equipment heating energy are constant throught the year. Regarding the energy losses, the highest energy loss is by opaque surface inside faces total conduction energy, peaking in the month of January with 443.4 kWh. The values are decreased for the second type of simulation, with peaking value of 283.9 kWh. The windows total heat loss and the total infiltration losses are increased in the cooler months peaking in January with 351.8 kWh, and it is slightly decreased in the case with the shades to 343.5 kWh. In the summer months the ventlation total heat enegy losses are increased, peaking in August with 229.7 kWh. These values are decreased in the case with the louver blinds, with a maximum value of 208.6 kWh in August. Overall, the energy gains and losses for the second simulation (with the louver shades) have decreased significally (Figures 5.5 and 5.6).

- *Average Operative Temperature*

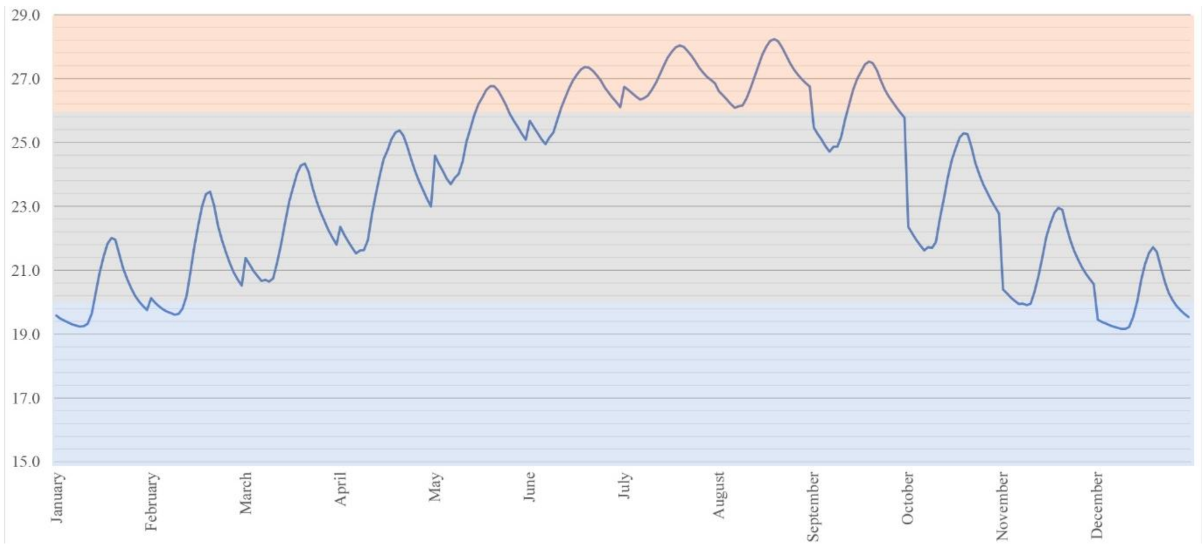


Figure 5.7 Operative temperature without blinds (three zone model)

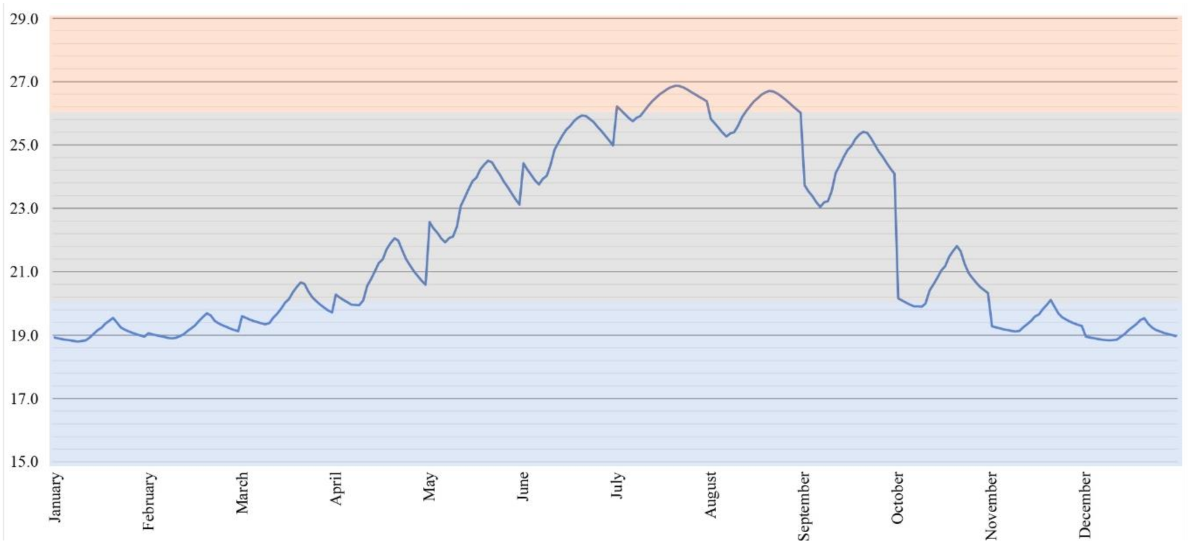


Figure 5.8 Operative temperature without blinds (three zone model)

The results from the average operative temperature the are shown in percentage of values below, in and above the set treshold of 20º to 26º. In the case without the shading device, the percentage of values above the treshold are 29.2%, in the treshold are 57.3% and above 13.2%. For the second case, when the shades are assigned, the percentage of values above the treshold are 11.8%, in the treshold are 47.6% and above 40.6% (Figure 5.9).

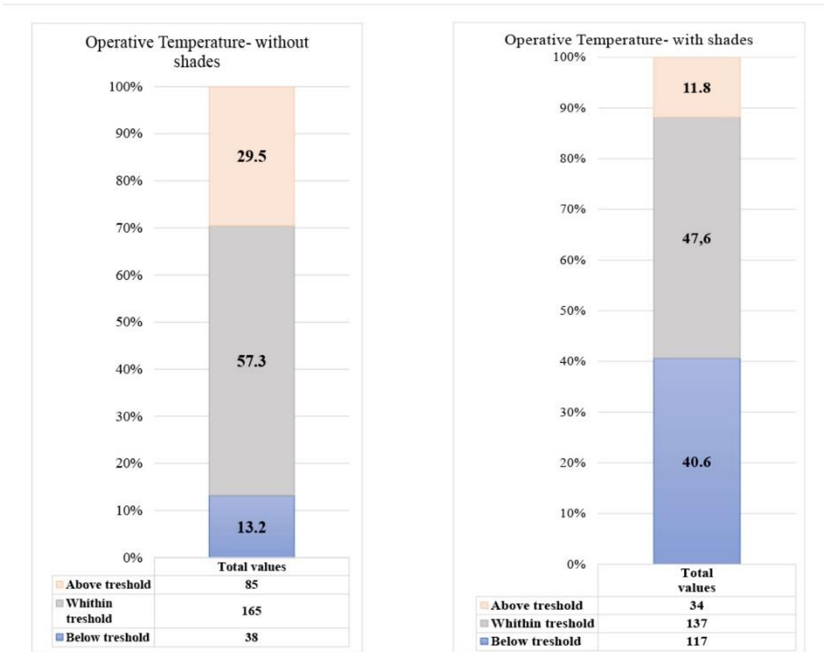


Figure 5.9 Average operative temperatures values below, in and above threshold (three zone model)

- *Predicted Mean Vote*

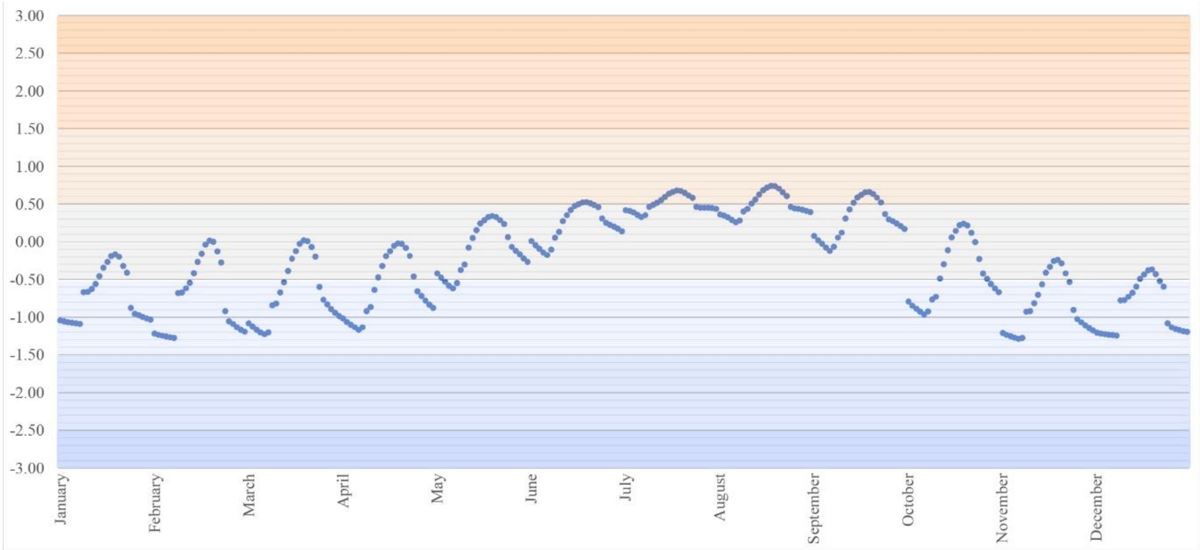


Figure 5.11 PMV - without louver shades (three zone model)

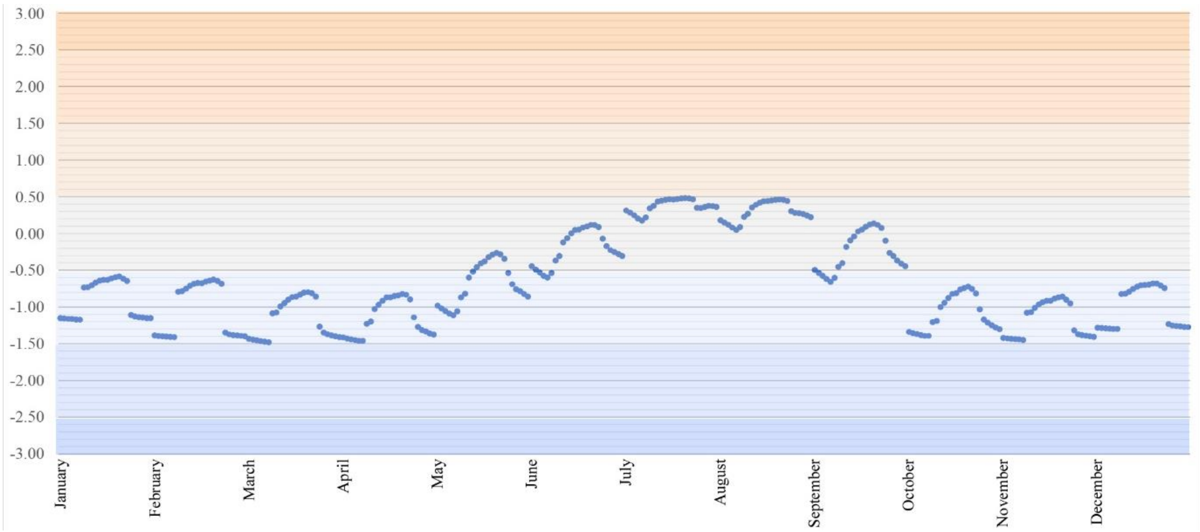


Figure 5.10 PMV - with louver shades (three zone model)

With the help of the simulation results and values that were collected, it is clear that the PMV results in both cases—with or without a louver shading system—are fairly comparable. In the first case, occupants have a neutral feeling 21.2% of the time but 78.8% of the time the feeling is slightly cold. In the second case, occupants have a neutral feeling 18.1% of the time but 81.9% of the time the feeling is slightly cold. Overall In the summer months in both cases, the sensation is neutral, but in the winter months the sensation is slightly cold (Figure 5.12).

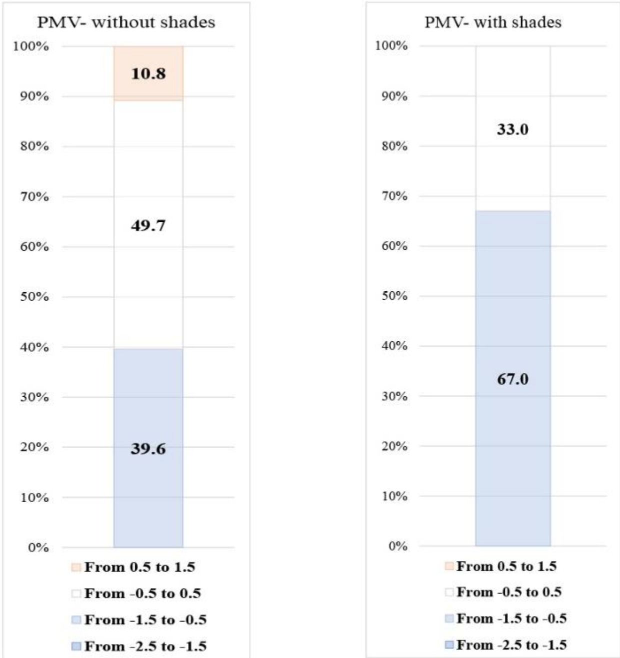


Figure 5.12 PMV percentage of values regarding the sensation of the occupants (three-zone model)

5.2.1.1. Comments on the results (three-zone model)

With the correction of the model geometry, it can be trusted that the accuracy of the results is higher. Regarding the overall performance of the third case study, it can be seen that once again the shading device does make a change in the energy and thermal comfort results. The overall energy consumption results are fairly typical when type and size of the construction are taken into account. The reason for this is due to the construction programs and schedules, as well as the materials used for the various components. The thermal comfort of the office can be judged to be satisfactory based on the average operative temperature and PMV results, but in both cases, the building may feel a little bit colder in the case when the louver blinds were assigned. This is because the HVAC system controls the temperature of the indoor environment.

5.3. Possibility of backwards interoperability

If the user follows the first workflow mentioned in this research, the traditional exportation method using .DXF or .DWG file format, the possibility of automated interoperability is not existent. However, the simulations produce information where it can give a guide if some design measures must be undertaken to improve the building's performance.

Regarding the second workflow, when using the Speckle stream, the possibility of backward interoperability is possible but to some extent. If the geometry is modified on Grasshopper, and later is "baked", it can be transferred to Revit using the Speckle connector.

However, the geometry that is received in Revit, will not have any material properties, and it will be perceived by Revit as a generic geometry. But since Speckle is relatively new on the market, it is not fully developed yet, meaning that the backwards interoperability option might be available in near future.

5.4. Recommendations and implications for further research

If used correctly, Grasshopper is a tool that can provide aid to architects and engineers in the further development of a project. With the variety of tools that it offers, it can help understand the conditions of a building that is yet to be constructed. However, an important piece of information that should be considered it, that the construction of the analytical model geometry should start at the beginning of constructing the virtual model, on the BIM interface. The importance of this is, once the geometry is modelled correctly, the easier and more efficient the building of analytical model will be later. Regarding the exportation method, both methods used had given valid results, however, the exportation process with Speckle is less time consuming and easier to use. The Speckle development team, states that the next step of its development, is the possibilities of transferring material properties. As of now, the material properties have to be implemented manually if either one of these two workflows are followed.

6. Common discussion with collaborator Mila Shoshev

This research is a collaboration with my colleague, Mila Shoshev. She covers the part of the research where daylight and glare are analysed, using the Revit plug-in called Rhino Inside Revit for transferring data from the BIM environment to Grasshopper. The research was done on the same models, using different workflows. The literature review regarding the research was conducted by both collaborators, and then after the collection of KPIs and understanding the opportunities on the market regarding BPSTs, it was divided into two parallel research activities.

6.1. Comparisons of studies

Both studies were done on the same construction models but using different exportation methods for transferring the information on another software program. However, since the performance indicators analysed for the evaluation of the construction are different, the workflows are compared until the exportation process and geometry modifications on the Grasshopper interface.

Firstly, the connection between Revit and Grasshopper through RIR happens on the Revit interface. Rhino is opened directly on the tab named “Rhino” and by clicking on the “Start” which opens the software on the Revit interface. This is the first difference in the exportation methods, where if the traditional method is used, the program Rhino is opened independently from Revit. Later, the user could import the model by component categories or by rooms, which are the two exportation methods used by the collaborator Mila Shoshev.

Next, for the first case study, the model has been exported onto Grasshopper by category type. On the RIR interface, the used has an opportunity to choose which elements are going to be implemented in Grasshopper. In comparison to the traditional .DWG or .DXF file type of exportation, where all the geometry modelled on the Revit interface are transferred. Later, for the second case study, the model is exported by rooms, which is the same process as the exportation using Speckle. This process is similarly executed by both Speckle and RIR. The model is imported onto the Grasshopper interface as room volumes, in both cases using the interior surfaces of the model as boundaries. RIR offers the opportunity for the exportation of the material properties from Revit onto Grasshopper.

However, due to the complexity and inaccuracy of the conversion of the material properties, the collaborator did not incorporate this step. Regarding backwards interoperability, RIR offers a back-and-forth data transfer. This means that if any changes are made on the Revit model, the adaptation of the geometry automatically is transferred onto the Rhino interface. However, Rhino inside Revit has a learning curve, and the users must make research on how to implement this connecting software in their workflow. Rhino Inside Revit only offers the option of opening one file at a time, meaning that the user can not have two or more files opened and working at the same time.

Regarding the simulations done, the energy simulations used Honeybee with the engine EergyPlus connecting through OpenStudio, and for the visual comfort analysis Honeybee with the engine Radiance was used. The visual comfort analysis overall took 2 minutes for the single zone model and 4 to 5 minutes for both multizone models until the running time was done. However, in order to calculate all the KPIs, they had to be done as separate simulations. Compared to the thermal and energy simulations, that use the component from OpenStudio and run all of the analysis all together, the glare and visual comfort analysis were overall more time consuming, where the DGP was the most time-consuming simulation.

This process can be seen on figure 6.1, where the two parallel research activities are compared and explained.

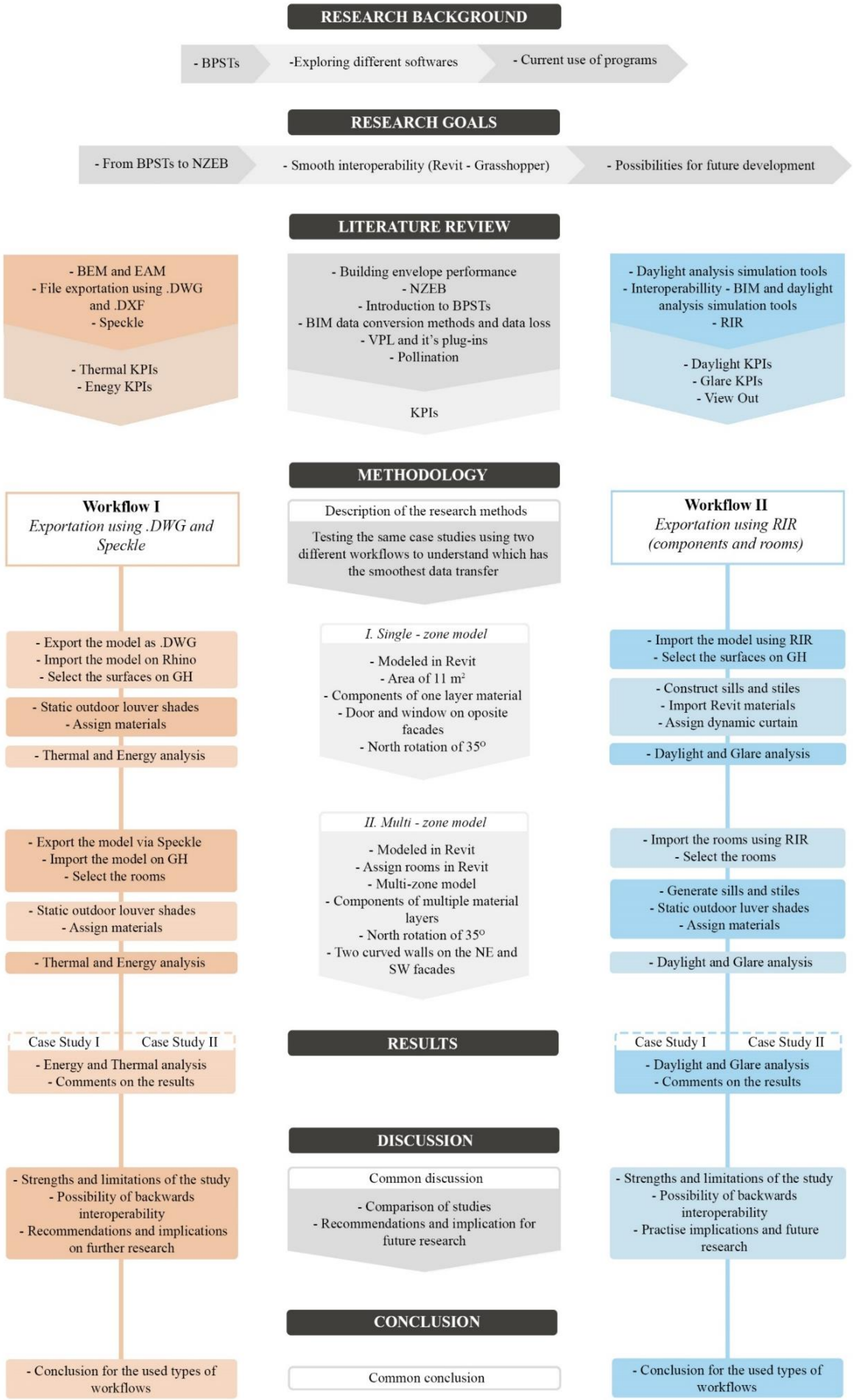


Figure 6.1 Comparison of research activities between the collaborator Mila Shoshev

6.2. Recommendations and implications on future research

Derived from both research activities, it can be understood that few steps must be taken into consideration in order to have smooth building performance simulations. Firstly, when the geometry is being modelled, the users must keep in mind the common Revit geometry modifications that later simplify the geometry adaptation on Grasshopper. Those are, modelling the walls with the "mitter" join, modelling the floors and roofs using the interior wall surfaces as boundaries. Following these steps, the enclosed boundary can be guaranteed for the use of Honeybee. If a multi-zone model is exported, the process can be simplified by the exporting the geometry as room volumes, however, an important thing to have in mind is to export the room volumes correctly. This means, that between the zone's volumes, there should not be any gaps in the model, but to have the middle wall surfaces chosen. This can be done with the command "Room Separators" on the Revit interface, where instead of modelling the interior walls, only the room separators are assigned. Once the geometry was on the Grasshopper interface, the procedure for building the Honeybee model also applied in this case, with a minor modification. It was crucial to use only one surface that is shared by the zones when the surfaces were assigned as Honeybee faces, which means that the middle surface that the zones share was assigned to both Honeybee room components rather than assigning two separate HB faces. This solves the issue for the zones to interact with each other and to avoid the issue of duplication of wall thicknesses which leads to have more accurate and reliable thermal comfort, energy performance, visual comfort and glare analysis.

Finally, for the simulation process to be smooth and quicker, it is crucial to keep the Grasshopper canvas as clean as possible, meaning that the excess components that are either not used or irrelevant for the simulation, to be erased, since they make the file heavier, and that way the file's responding time becomes slower, and the possibilities of the program crashing are much higher. As the complexity and the size of the model on which simulations are done becomes bigger, this step becomes more important.

7. Conclusion

The outcomes derived from this research can help the users understand the current situation of what the most popular BPSTs have to offer. Firstly, from the literature review, it can be concluded that nowadays, the market offers many possibilities and variations of building simulation tools, which can help the users produce better products and guarantee buildings with greater quality. However, since most of the simulation tools are quite complex, it can be understood that great percentage of architects and engineers avoid their implementation in project designs. The information online regarding the use of various simulation tools is quite limited. It can be concluded that there is a learning curve when understanding how these tools function. It can be understood that the building simulation tools are not accessible to everyone because of reasons mentioned above. Revit is the most used BIM software by architects and engineers nowadays. It offers a wide range of opportunities for modelling building geometry, but also incorporating systems and materials for the construction. Even though, Revit offers the users to analyse some aspects of the building performance, it can be concluded that this analysis can be insufficient and/or limited. That is the reasoning behind the implementation of Grasshopper through Rhino, which allows us to construct a parametric workflow on a software program which uses VPL.

Regarding the two considered workflows, the traditional method and the exportation process using the Speckle stream, the deriving of results was successful in both cases. However, both methods are quite different. The traditional method is the simplest method of exportation. It does not require any complex measures to be undertaken in order to get correct geometry exportation. In comparison, the Speckle stream gives the freedom for the users to choose what geometry they desire to be exported. It was noticed that the information that was transferred on the speckle stream could be always accessed. An important thing to notice, is that if the users have multiple projects that they are working on, they should open new streams for each of the projects. Since speckle is a relatively new tool, it is still in the process of development. Overall, the transportation of information with the Speckle stream was less time consuming, and since it gives the option to export the model by categories, it creates an environment for easier selection of geometry for analysis on Grasshopper. Also, with the traditional DWG exportation method, the geometry is firstly accepted by Rhino and later it is assigned on Grasshopper, in comparison to the Speckle stream, where the geometry is accepted directly in Grasshopper.

Once the geometry is on the Grasshopper interface, the adaptation is made. This process depends on the complexity and size of the model geometry. The so called “irregular” geometries such as the curved walls, are not recognized in Honeybee. Which means that the adaptation must be made manually. The adaptation requires division of the wall in segments and constructing a completely new analytical geometry for the irregular surface. This process took a significant amount of time on the Grasshopper UI. Overall, these geometries should be avoided when modelling in Rhino for analysing, since it is easier to correct the model irregularity on the BIM software rather than in the VPL environment. Another important thing to notice is when the model is exported with .DWG file format, the model units of Revit and Rhino must be the same so that the model can be accepted with the accurate dimensions.

Regarding the thermal comfort and energy performance of the buildings, when the geometry is exported as room volumes for the multizone model, it is important to follow the modelling process explained for the corrected multi-zone model (three room model) mentioned in the discussion part, for the interior walls. This solved the issue of the gaps present between each of the interior wall surfaces, which later gave more accurate results, since the model zones could finally correspond to each other and function as a whole building construction.

Once the user has the corrected geometry ready, all the inputs regarding material properties, energy loads, systems and schedules are assigned. The information that these components are provided play a key factor in the results that are later derived. An important point is that the "Honeybee aperture" element does not have the opportunity to have the window frame assigned, which means, that the thermal transmittance value that is assigned for aperture element it is not entirely accurate. Overall, the accuracy of the results depends on all the inputs that are assigned to the model. These need to be as accurate as possible to have results that are going to be of use for further design decisions.

Lastly, the backwards interoperability is an issue that is not resolved in these two workflows, which creates an issue if some changes should be done on the geometry. This process is much more difficult to do with the traditional .DWG exportation method, since all the geometry must be imported again and assigned on Grasshopper. With the Speckle stream, this is more feasible since the geometry is imported on the Grasshopper interface directly.

8. Common conclusion with collaborator Mila Shoshev

Once both research activities were finished, a common conclusion was derived together with the collaborator. The process was divided into three crucial stages: before, during and after the implication of case studies. The stage that is before the case studies were conducted, takes into consideration all the information that was available to dissect and implement into the research from books, research papers, articles, forums and users' experience. This was important in order to understand what is available for the users nowadays when it comes to choosing and implementing the appropriate BPSTs in their work. Once the data was collected, it was decided to further continue the research specifically for Revit as BIM software and Grasshopper as a program which uses VPL. Overall, it was found that the information regarding their interoperability was insufficient. This process can be seen on figure 8.2.

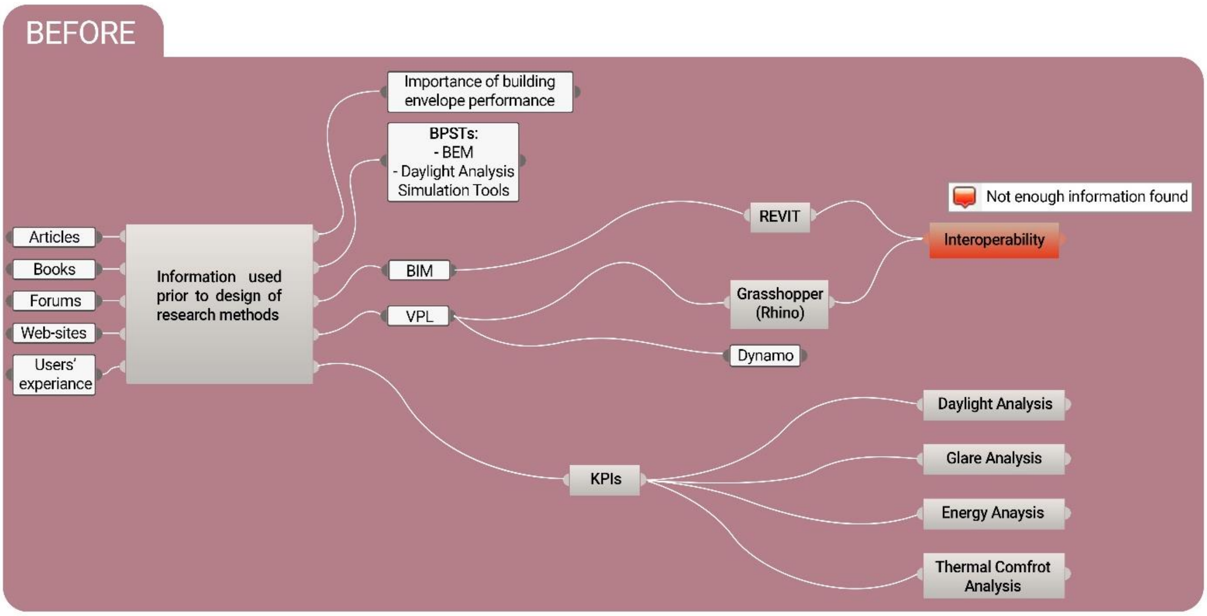


Figure 8.2 Collection of information available before practice implication of case studies

Once the workflows were established, it was time to test their strengths and limitations. The two case studies that were designed to test the possibilities that Grasshopper with its engines have to offer, were done in order to understand firstly, what the software programs have to offer and if the workflows that were constructed work, and next, with the second case study, to understand to how the constructed workflows correspond to a model with higher geometry and model properties complexity. This process is graphically represented in figure 8.1.

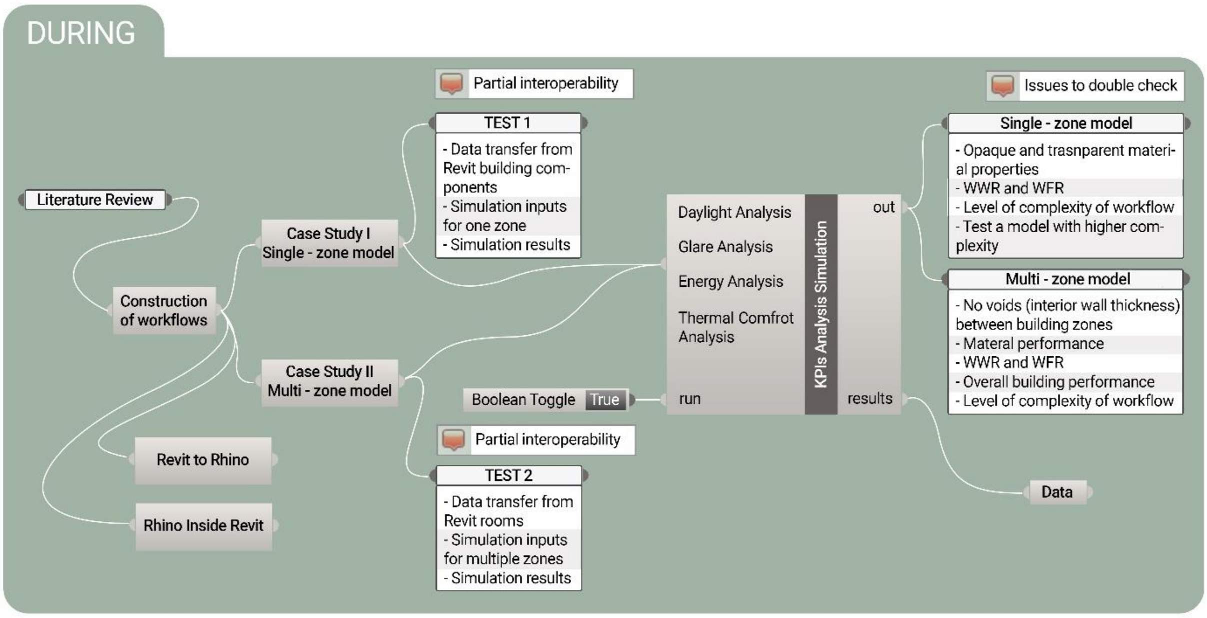


Figure 8.1 Collection of information available during practice implication of the case studies

The results from the simulations of the case studies were resulting in heatmaps, charts, tables and images which help the users understanw how the model corresponds to the information that was assigned to it. The overall experience with the programs and the results from the case studies lead to a conclusion of the overall research activity. The results from the traditional exportation process uding .DWG file format was easy to use and there was no need to implement a middle software connector, however, the model units might differ from Revit to Rhino, some of the Revit model families were not recognized, the possibility of backwards interoperability is not viable and the material properties cannot be transferred from Rhino onto the Grasshopper interface automatically. This workflow was the most time consuming out of the tree. Next, regarding the use of Speckle, it was concluded that Speckle is very simple to use and understand, it is free of charge, simple to download, gives the opportunity to connect many different BIM and softwares that use VPL, all of the model properties are stored onto the online stream and there is a possibility of semi-automated backwards interoperability. However, the data regarding the material properties of the model were not able to be transferred. Lastly, RIR allows the users to export the complete model geometry by component categories, thhe geometry modifications were quickly recognized and implemented on the opposite softwares, but, while using RIR only one project can be openet at a time and the material properties units from Revit were not recognized on Grasshopper (Figure 8.3).

Overall, all of the workflows had given results, it is just important for the user to chose which one complements their workflow the best. At this pont, the exportation process using RIR is the most developed and the most reliable for future practice, however, since Speckle is relatively new and not fully developed, it promises to fix most of the issues regarding interoperability that are present today. It is important to keep track of the development of Speckle since it could be a tool that will be of great benefit to the users of building simulation programs.

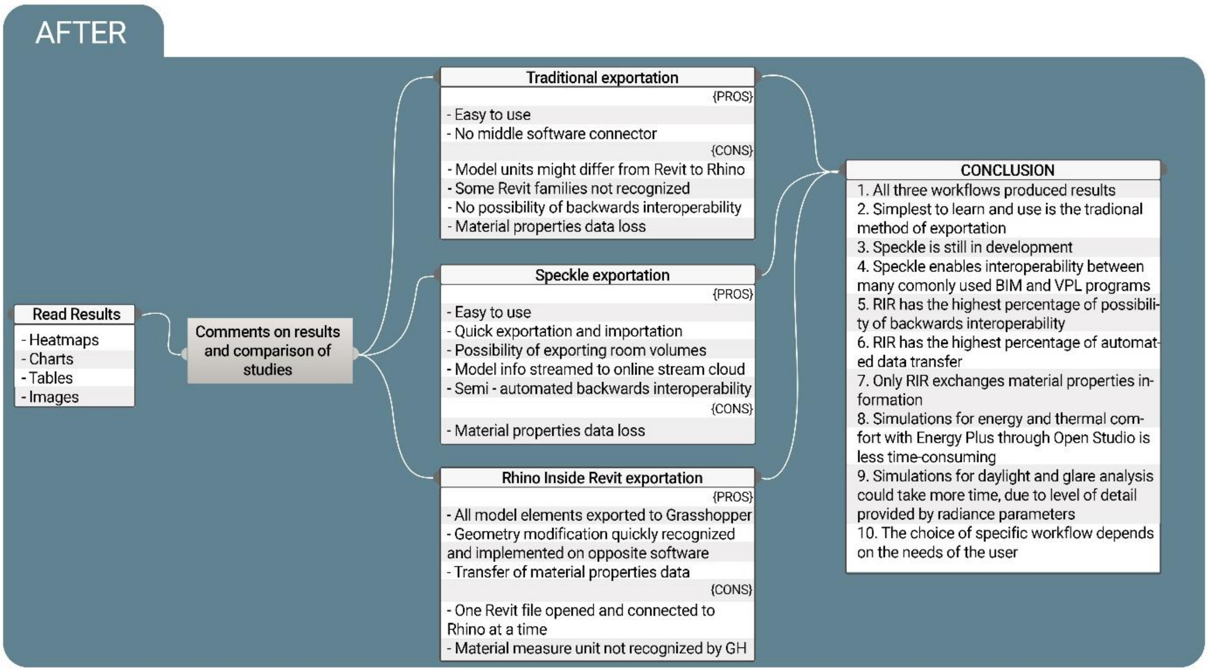


Figure 8.3 Collection of information available after practice implication of the case studies

9. References

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