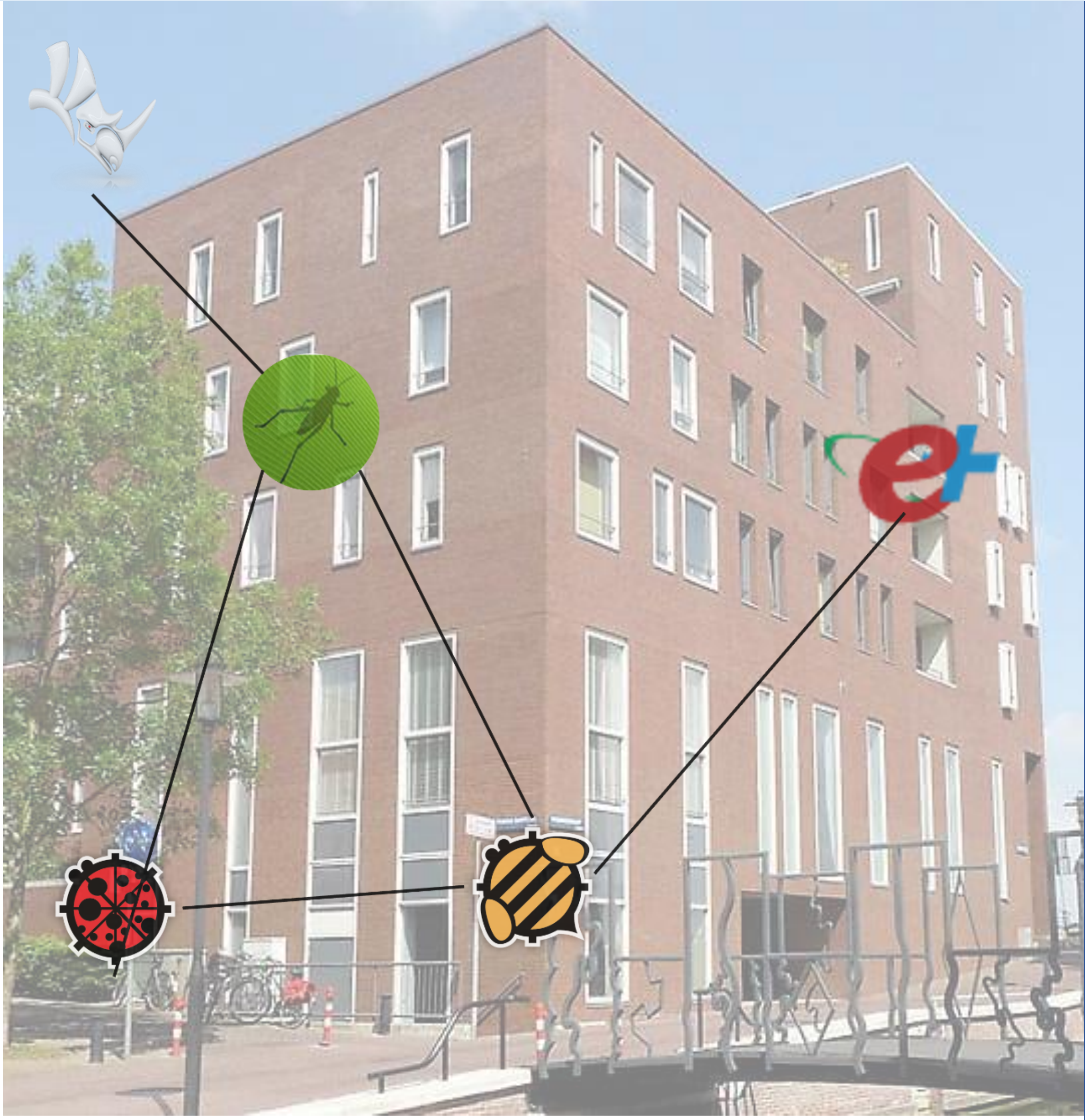
Ventilative Cooling in Midrise Residential Buildings in the Netherlands



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Ventilative Cooling in Midrise Residential Buildings in the Netherlands

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Abstract

This thesis investigates the potential for natural ventilative cooling strategies to improve the cooling and comfort of residential midrise buildings in the Netherlands. Ventilative Cooling is "*the application of the cooling capacity of the outdoor air flow by ventilation to reduce or even eliminate the cooling loads and/or the energy use by mechanical cooling in buildings, while guaranteeing a comfortable thermal environment*". The effect of Day and Night ventilation strategies on the indoor environment of two common typologies of midrise apartments seen in the Netherlands was evaluated. The project investigated window and stack ventilation using dynamic energy simulations coupled with airflow network (AFN) modelling. EnergyPlus airflow network model was used for simulations with Grasshopper and Rhino as the user interface. Honeybee and Ladybug plug-in for Grasshopper translated the model into the EnergyPlus-readable input format. Various performance indicators were used to evaluate the apartments' comfort and cooling. These included temperature limit exceedance hours, GTO hours, Cooling requirements reduction ratio, Climate Potential for Natural Ventilation (CPNV), Natural Ventilative Cooling Effectiveness (NVCE) and Climate Potential Utilization Ratio (CPUR). Ventilative cooling simulations yielded favorable results. There was a significant reduction in the peak temperatures and GTO hours within the rooms when the windows were opened, compared to when they were closed. Out of the tested two typologies of apartments, the number of hours when the temperature exceeds 28°C reduced by 50-70% when the windows were fully opened in typology 1 apartments and was reduced by 36-70% in typology 2. GTO hours reduced by 70-80% when the windows were opened for ventilative cooling in typology 1 apartments and reduced by 55-60% for typology 2 apartments in comparison to when they were closed. Apartments with the capability of cross ventilation performed better than those with only single-sided ventilation. The cooling effectiveness of the existing building designs was also evaluated. The results showed that there is room for improvement of design to utilize the site's potential for natural ventilation. When passive stack is used along with the opening of windows in an apartment, there was a slight reduction in temperature when compared to using only open windows for the same apartment. However, the reduction was not very significant. The findings are presented in a comparative and quantitative manner, providing valuable insight into the relevant field.

Acknowledgements

This thesis is completed as the final requirement of the Master of Science in Civil Engineering at the Delft University of Technology. I am happy to have finally completed this journey on a good note with a multitude of experiences which has helped me become the person I am today. This of course would not have been possible without the various people who helped me throughout this process.

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1. Introduction

1.1 Background Information

Buildings are responsible for about 40% of EU energy consumption and 36% of the greenhouse gas emissions making them the single largest energy consumer in Europe [1]. With the growing urban population and the demand for housing on the increase, there is an higher insistence for residential buildings. Moreover, the Dutch climate is likely to change with milder winters and more frequent heat waves which will result in an increased need for active cooling systems in buildings. Therefore, adequate measures to reduce the energy consumption and promote sustainable development without compromising on comfort is necessary.

With the projected increase in temperatures worldwide, there is a high risk of buildings being not just uncomfortable but also potentially detrimental to the health of its inhabitants due to high internal temperatures. Studies suggest that the global surface temperature can increase by 1.1 °C to 6.4 °C in the 21st century. In cities however, the temperature is expected to be higher than the surrounding countryside by 5 °C to 10 °C due to the urban heat island effect [2].

Overheating in buildings is an emerging problem. The high performance standard for energy reduction in heating dominated climatic regions also increases the risk of overheating. High insulation levels and low infiltration are beneficial for heating season but are responsible for increased indoor temperatures in cooling season. Dutch dwellings also follow a similar pattern of housing with focus on maintaining a warm temperature range during winter, resulting in large windows and high insulation combined with excellent air tightness [3].

In most post occupancy studies overheating is a frequently reported problem especially during the summer and shoulder seasons. It is recommended that steps are taken to decrease the risk of overheating in order to protect new and existing constructions. Various measures for passive cooling can be adopted for summer thermal comfort. This study will focus on the use of natural ventilative cooling principles to improve thermal comfort. Ventilative cooling refers to the use of natural or mechanical ventilation strategies to cool indoor spaces. Ventilative cooling can be defined as the application of the cooling capacity of the outdoor air flow by ventilation to reduce or even eliminate the cooling loads and/or the energy use by mechanical cooling in buildings, while guaranteeing a comfortable thermal environment. This effective use of outside air can reduce the energy consumption for cooling [4]. In this study the focus will be on natural ventilative cooling by day and night ventilation. This research is to identify the potential for cooling and improvement in comfort through the use of natural ventilative cooling in mid-rise residential buildings in the Netherlands.

1.2 Research Design

1.2.1 Research Objective

The main objective of the research is to identify the potential for cooling by using natural ventilation in mid-rise residential buildings in the Netherlands. It also aims to understand how the number of overheating hours in apartments can be reduced so that the indoor temperature is in a comfortable range for the users.

1.2.2 Research Questions

"What is the potential for cooling and comfort in mid-rise residential buildings in the Netherlands by adopting natural ventilative cooling strategies?"

Sub Questions

1. What is the common typology of buildings and the present state of ventilation design in mid-rise residential buildings in the Netherlands?
2. What strategies can be adopted for ventilative cooling in mid-rise residential buildings?
3. What percentage of time during summer season is it possible to maintain indoor temperature in a comfortable range with ventilative cooling?

1.2.3 Methodology

Initially, a background study is required to understand the existing ventilation design in mid-rise residential buildings. To select a representative building for testing the ventilative cooling concepts, a study into the common residential building typology in the Netherlands will be needed. Ventilative cooling strategies have to be explored on venticool.eu platform. Initially a base case scenario will be tested with the existing building components. By doing so, the daily operative temperatures can be obtained and compared to the thermal comfort range to determine the temperature deviation and percentage of time there is overheating. Then the day and night ventilation strategy using wind as well as buoyancy driven techniques can be evaluated. The Airflow Network (AFN) model from EnergyPlus will be used as an engine for energy analysis. Energyplus is a whole building energy simulation program. It reads input and writes output files, due to which it behaves more like a simulation engine rather than a user friendly interface. It is possible to use a graphical interface developed by third parties to perform the intended simulation. In this thesis, the graphical interface used is Rhino and grasshopper. Rhino is used as a 3D modeler and Ladybug and Honeybee are the plugins which connect to EnergyPlus in Grasshopper.

1.2.4 Thesis Outline

The information is divided into various chapters. Chapter 1 introduces the topic and also the research Question. Chapter 2 provides an extensive literature review pertaining to different topics of interest in this thesis: Ventilative cooling, natural ventilation, thermal comfort, airflow network modelling, the different ventilation systems and the performance indicators used in the study. It also introduces the two building typologies used in the simulation. Chapter 3 provides an insight in to the simulation parameters that are considered for modelling. It also gives information regarding the construction materials for the apartments and the windows. The various design variants studied are also discussed here. Chapter 4 introduces the grasshopper script used in the model as well as some components which are used in the script. Chapter 5 is a pilot study done to understand how the airflow network modelling works. It is a small chapter including simple simulations done and contains the results and discussions regarding the same. Chapter 6 includes the results obtained from the various simulations. Chapter 7 explains the validation check performed using VABI Elements. Chapter 8 is the concluding chapter where the research questions are answered and recommendations for future studies are given.

2. Literature Review

2.1 Ventilative cooling

Ventilative Cooling (VC) can be defined as "*the application of the cooling capacity of the outdoor air flow by ventilation to reduce or even eliminate the cooling loads and/or the energy use by mechanical cooling in buildings, while guaranteeing a comfortable thermal environment*" [5]. When there is an increase in air temperature, reducing the mean radiant temperature or enhancing convective transfer of heat exchange between the body and the nearby environment helps moderate the temperature and improve comfort. The latter is the basic idea of ventilative cooling [4]. The implementation of ventilative cooling principles varies depending on the climate and also the microclimate, building type, ventilation technique, and user expectations. Under unfavorable weather circumstances, ventilation cooling can be coupled with other natural cooling methods that utilize additional natural heat sinks in the environment, or with mechanical cooling systems. Table 2.1 shows the different strategies for ventilative cooling used in different climatic regions.

Table 2.1. Overview of typical ventilative strategies applied depending on outdoor climate conditions and type of ventilation system. (6)

Temperature difference[a]	Ventilative cooling	Supplementary cooling options
Cold (ΔT more than 10 °C)	Minimize air flow rate—draught free air supply	–
Temperate (2–10 °C lower than comfort zone)	Increasing air flow rate from minimum to maximum	Strategies for enhancement of natural driving forces to increase air flow rates Natural cooling strategies like evaporative cooling, earth to air heat exchange to reduce air intake temperature during daytime
Hot and dry (ΔT between − 2 and +2 °C)	Minimum air flow rate during daytime Maximum air flow rate during nighttime	Natural cooling strategies like evaporative cooling, earth to air heat exchange, thermal mass and PCM storage to reduce air intake temperature during daytime Mechanical cooling strategies like ground source heat pump, mechanical cooling
Hot and humid	Natural or mechanical ventilation should provide minimum outdoor air supply	Mechanical cooling/dehumidification

When ventilative cooling is achieved solely by natural driving forces (wind and stack), it is termed as natural ventilative cooling. When it is achieved by the use of fans alone it is termed as mechanical ventilative cooling. When both natural and mechanical means are used in combination or alternation, it is called hybrid ventilative cooling. This thesis focuses on the natural ventilative cooling of buildings.

There are numerous studies conducted showing the potential of natural ventilation in helping cool down buildings. A study was done by Li, Y. and Li, X. in 2014 to understand the natural ventilation potential of 6 common types of high rise residential buildings in northern China by combining the CFD model with a thermal and airflow coupling model. It was seen that for the particular climate, the annual cooling load saving ratio increased with the annual average ventilation rate following the logarithmic law. With the help of a logarithmic regression formula developed for 6 types of residential buildings in 10 cities under different internal heat conditions, a quick analysis can be performed for investigating the annual cooling load saving potential. The research findings are however valid only to the specific building types defined in the study [7]. The ventilative cooling capacity of a low energy dwelling based on the active house idea was investigated in Dutch climate. In the absence of active cooling, the dwelling was susceptible to overheating. The possibility of using ventilative cooling was considered. A computational model was developed and calibrated with actual field measurements in the house. The simulation results showed that when ventilative cooling was used along with other design elements (shading and thermal mass), there is significant reduction in overheating potential of the house. Even in the event of warm spells with relatively high nighttime temperatures, it was able to reach thermal comfort by increasing the ventilative cooling capacity.[5] Another research was conducted to determine the potential reduction in energy demand for cooling and mechanical ventilation by using natural ventilation during summer for a 21 storey office building of the Faculty of Electrical Engineering, Mathematics and Computer Science (EWI) at the Delft University of Technology. Six different design strategies with variations in façade type, size of air inlets/outlets and application of vertical shafts were designed and tested by CFD simulations and thermal calculations using the Design Builder and EnergyPlus software respectively . It was found that during 90% of the occupancy time during summer, natural ventilation was able to meet the requirements for fresh air and thermal comfort [8].

From the various studies present on the venticool.eu platform [6], the most commonly used residential ventilation components are discussed below.

Façade Windows: These are the most common type of component used for ventilative cooling. Openable windows are user friendly and also airflow can be regulated based on the opening percentage. Common ventilation strategies employed are cross ventilation and single sided ventilation.

Roof Windows: This is used to employ buoyancy or stack ventilation through circulation areas (stairs and landing). These are usually automated and controlled based on air temperature in the living zones or CO2 concentration. The operative temperature that considers the effect of air and surface temperature are also used as control.

Sliding Doors: This is used to increase the airflow rates and air velocity in indoor spaces. They are especially useful when the exterior spaces have some shading or balconies overhead which will help reduce the air temperature of incoming air.

Mechanical fans: They are generally used to maintain indoor air quality and minimum fresh air rates during heating season. However with an effective heat recovery bypass functionality, they can also be used to provide air supply for cooling when the passive ventilative cooling is low. It is important to make sure that mechanical fans support existing airflow regimes like stack ventilation rather than obstructing them and lowering the overall VC potential. Various inputs, ranging from interior air temperature to CO_2 concentration levels, are frequently used to control fan airflow rates.

External Shading: Although not a direct component of ventilative cooling, it is an integral part of the cooling system to ensure low solar gains and reduction of incoming air temperature. These can substantially extend the range of time when VC is suitable for cooling.

Chimneys: Used mainly for exhaust, Chimneys can be installed in residential homes or apartments using specially designed chimney components or by converting stairwells and other major circulation zones into airflow ducts. Chimneys can be built to improve the overall height producing flow as well as the pressure regime at the output.

Louvres and Grills: Louvres are less common components for ventilative cooling in residential buildings. However, they can provide some shading, protection against rain ingress and burglars which can help with night cooling strategy.

More components used for ventilative cooling are discussed in Appendix A.

2.2 Natural Ventilation

Natural ventilation has two driving forces, wind and buoyancy. Natural ventilation can occur as a result of combination of these forces or in alternation. When these forces work in unison, the ventilation rate increases, and when they act in opposition, it decreases. Air moves from regions of higher pressure to regions of lower pressure. The pressure difference created by natural wind allows the movement of air by using these pressure differences. When wind hits a building, a region of positive (high) pressure is created on the side facing the wind and a similar region of negative (low) pressure is created on the leeward side of the building. These pressure gradients created allows air to move through the openings. Pressure difference is also caused due to the difference in density of air which in turn depends on temperature and humidity. Hot air is less dense than cool air, due to which it rises while cold air sinks, creating a difference in pressure which induces movement of air. This is called thermal buoyancy or often referred to as stack effect. Figure 2.1 shows the two driving forces of natural ventilation acting on a building.

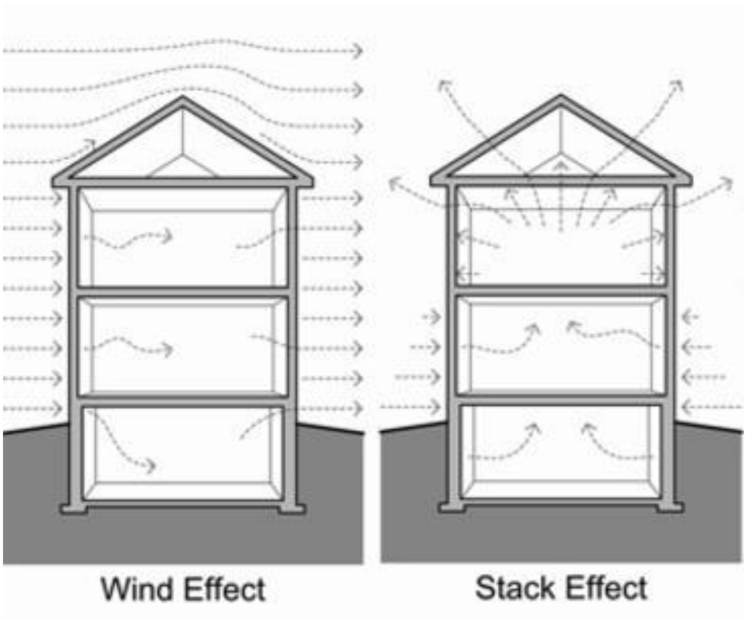


Figure 2.1. Picture showing airflow through buildings due to wind and stack [9]

The various forms of equation defining different relationships of airflow based on the above described driving forces is provided in the ASHRAE Fundamentals handbook [10]. Measuring airflows through openings can be performed using Bernoulli equation for steady, incompressible flow. This form of equation is valid for stack, wind and mechanical ventilation pressures across a building opening. This relationship is described in equation 2.1 below.

$$Q = C_D A \sqrt{2\Delta p/\rho} \tag{2.1}$$

Where,

Q = airflow rate, m^3/s

A = cross-sectional area of opening, m^2

ρ = air density, kg/m^3

C_D = discharge coefficient for opening, dimensionless

Δp = pressure difference across opening, Pa

The discharge coefficient C_D depends on the geometry of the building and the Reynolds number of the flow.

When the flow of air is caused by wind alone, the following equation 2.2 can be used to determine the airflow rate through the openings.

$$Q = C_v A U \tag{2.2}$$

Where,

Q = airflow rate, m^3/s

C_v= effectiveness of openings

A = free area of inlet openings, m^2

U = wind speed, m/s

When airflow is caused by thermal forces alone, equation 2.3 shows the relationship defining the airflow rate caused by stack effect.

$$Q = C_D A \sqrt{2g\Delta H_{\mathrm{NPL}}(T_i - T_o)/T_i} \tag{2.3}$$

Where,

Q = airflow rate, m^3/s

C_D = discharge coefficient for opening

ΔH_{NPL} = height from midpoint of lower opening to Neutral Pressure Level (NPL), m

T_i = indoor temperature, K

T_o = outdoor temperature, K

2.3 Thermal Comfort

Thermal comfort is defined as *“the condition of mind that expresses satisfaction with the thermal environment” [11].* The definition of thermal comfort demonstrates that comfort is based on mental perception. Consequently, it can vary significantly amongst individuals based on their cognitive processing of the many changes in the environment. People are constantly generating and exchanging heat with their surroundings. Thermal comfort therefore has a vital role to play in the energy consumption of buildings. As a result, a substantial amount of work has been made to determine techniques to evaluate and predict thermal comfort. There are two main approaches to evaluating thermal comfort. They are the heat balance model and the adaptive model [12].

The first heat balance model was developed by Fanger. He formulated a concept for human heat transfer and a thermal balance-based equation. He stated that for ensuring steady state thermal comfort, some factors have to be met: the body is in heat balance, the sweat rate and skin temperatures are within specified limits and there are no local discomforts [13]. The thermal environment was taken in to consideration by the air temperature, humidity, radiant temperature and the velocity of air. Through his numerous studies and experiments, he developed the Predicted Mean Vote (PMV) index which is especially significant because it serves as the foundation for the majority of national and international comfort standards. This index estimates the mean value of a large group's votes on a 7 point ASHRAE thermal sensation scale where -3 signifies cold, 0 signifies neutral and +3 signifies hot. Table 2.2 shows the complete scale of PMV index. This was expanded to measure the number of individuals who are dissatisfied with the environment by the Predicted Percentage Dissatisfied (PPD). The value of PPD is determined based on the value of PMV. The relationship between PPD and PMV can be seen in Figure 2.2. This comfort model has been used to evaluate thermal comfort for many years. However, there are also studies pointing out the discrepancies in the model largely due to the strict nature of conditions under which the PMV model was derived. The experiments were conducted in climate chambers assuming the clothing insulation and the metabolic rate. However, this was not the case under actual circumstances. Studies also found that, in naturally ventilated buildings, the perceived comfortable temperature increased in warmer climates and decreased in cold climatic zones [12].

Table 2.2. The thermal sensation scale [14]

PMV	**Comfort**
3	hot
2	warm
1	slightly warm
0	neutral
-1	slightly cool
-2	cool
-3	cold

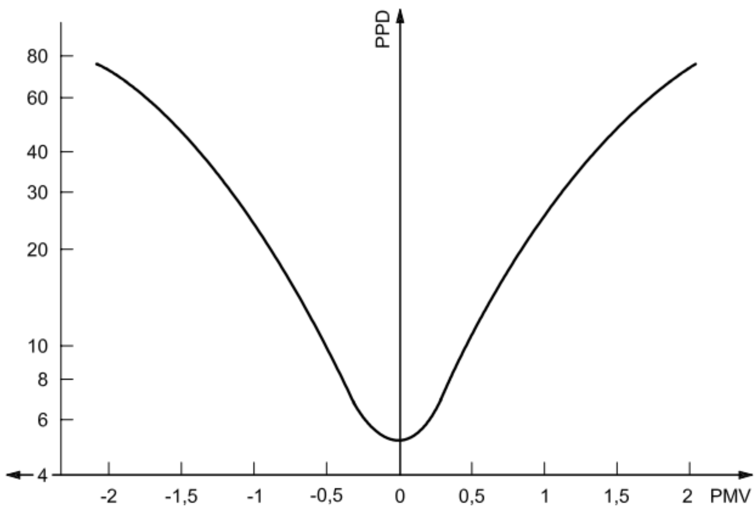


Figure 2.2. Relationship between PMV and PPD [14]

The adaptive comfort model approach is based on the statistical analysis of field surveys of people's responses to their surroundings. The main principle is "*if a change occurs such as to produce discomfort, people react in ways that tend to restore their comfort*" [15]. Field survey is the fundamental instrument of the adaptive method. Compared to Fanger's method, participants wore normal clothing and were doing their usual activities. From the surveys conducted it was found that indoor comfort temperature and the outdoor temperature were strongly related. The comfort temperature was not static, it was a result of the interaction between the people and the environment and changed based on the season, the weather and also the location of a person's work [15]. Different countries and regions have different standards for thermal comfort. For this study we will be looking at the adaptive comfort model as given in EN 16798. The optimal indoor comfort temperature is given in equation 2.4 as:

$$\Theta_c = 0{,}33\Theta_{\mathrm{rm}} + 18{,}8 \tag{2.4}$$

Where,

Θ_c is the operative temperature (°C);

Θ_{rm} is the running mean outdoor temperature

The running mean outdoor temperature is calculated using the following equation 2.5 :

$$\Theta_{\mathrm{rm}} = (1-\alpha)\cdot\{\Theta_{\mathrm{ed-1}} + \alpha\cdot\Theta_{\mathrm{ed-2}} + \alpha^2\Theta_{\mathrm{ed-3}}\} \tag{2.5}$$

Where,

α is a constant between 0 and 1, with a recommended value of 0.8;

$\Theta_{\mathrm{ed}-n}$ is the mean daily outdoor temperature for n days prior to the day being evaluated.

Based on the optimal temperature for comfort, the acceptable indoor temperatures are divided into the different categories as discussed in Appendix B. In this study, category II is used to determine the site conditions suitable for natural ventilation (discussed in section 2.7.3) Figure 2.3 shows the acceptable operative temperatures for buildings without mechanical cooling systems.

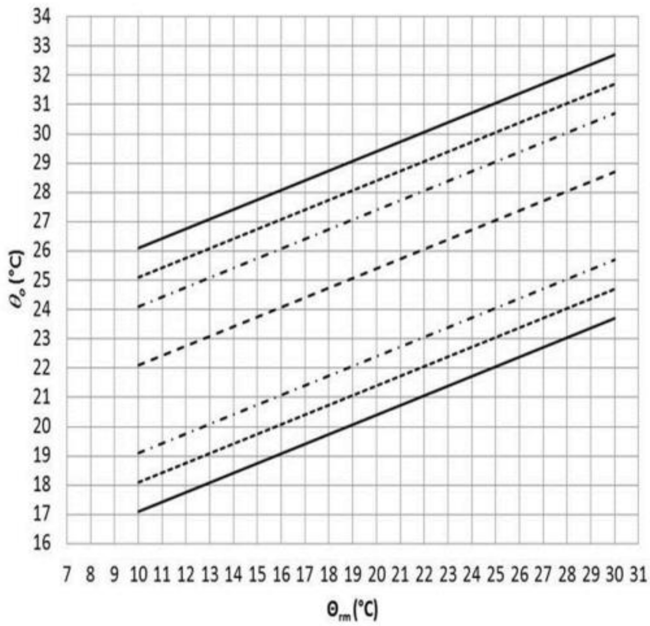


Figure 2.3. Acceptable operative temperature ranges for buildings without mechanical cooling systems [16]

In order to combat the changing climate and achieve the performance standards as per the climate goals set, it is necessary for new constructions both residential and non-residential to meet NZEB (Nearly Zero Energy Building) requirements as of January 2021. One of the requirements of NZEB is the TO_{juli}. Which is a number indicating the risk of temperature exceedance. Since TO_{juli} is an index indicator, a GTO calculation (more information in section 2.5.3) can also be chosen in place of TO_{juli}. Although for evaluation of free running buildings, it is advised to use adaptive method, in this thesis since dynamic calculations are done for evaluating overheating, GTO hours which is based on the PMV model will be used to check the comfort.

2.4 Airflow Network Modelling

There are a variety of tools available for evaluating and comprehending the advantages and disadvantages of using ventilative cooling in buildings. These tools range from empirical formulas to dynamic simulation engines. For early-stage modeling, empirical formulas and monozone models are sufficient to comprehend the design. Airflow network (AFN) modelling, a combination of building energy simulation (BES) and AFN, zonal models, Computational Fluid Dynamics (CFD), and a coupled CFN-BES-AFN are generally used when a detailed assessment is required. In this thesis, the focus will be on Airflow Network Modelling.

The airflow network model is a detailed model used to calculate the airflows within a building. In these models, the buildings are represented as well mixed zones which are connected to each other by one or more airflow paths. Figure 2.4 represents an airflow network model. The airflow paths are a collection of zones represented by nodes and airflow components represented by linkages. The variables at the nodes and linkages are pressure and airflow respectively. The airflow paths are defined mathematically using the Bernoulli equation. Figure 2.5 shows one of the many possible airflow paths connecting three zones when all the airflow components (windows and doors) are open [17].

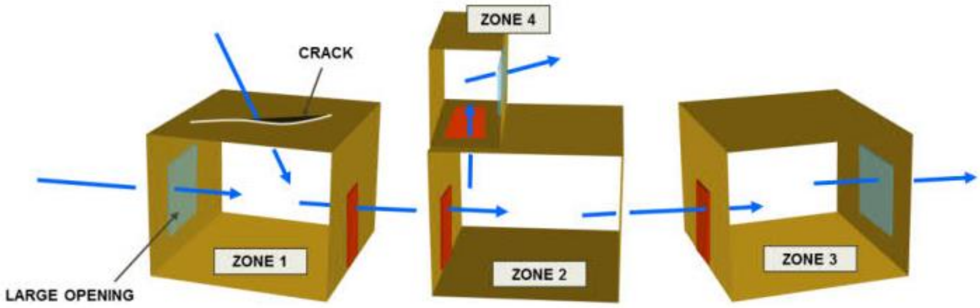


Figure 2.4. Airflow network schematic representation [6].

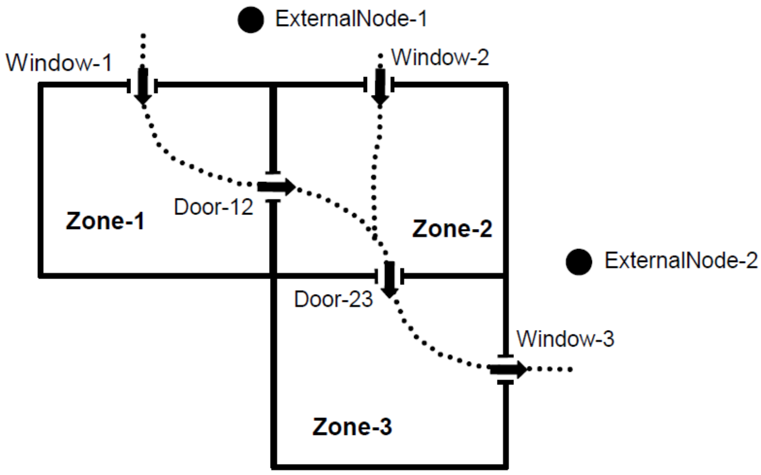


Figure 2.5.Representation of an airflow path in an airflow network diagram [17]

When combined with a dynamic simulation tool like Energyplus, Trynsis, ESP-r etc., users are able to couple thermal and airflow analysis. In this thesis, the airflow network model in EnergyPlus will be used for the simulation. Grasshopper with Ladybug and Honeybee is used as the user interface. In Energyplus airflow network model, the pressure and airflow are determined at each node and through each linkage respectively, given the wind pressures and forced airflows.

The wind pressure coefficients are determined by a surface average calculation provided by the simulation engine. This calculation is restricted to rectangular buildings and uses the following equation for low rise buildings [18].

$$C_{p,n} = 0.6^{*}\ln\begin{bmatrix}1.248 - 0.703\sin(\alpha/2) - 1.175\sin^2(\alpha) + 0.131\sin^3(2\alpha G) \\ +0.769\cos(\alpha/2) + 0.07G^2\sin^2(\alpha/2) + 0.717\cos^2(\alpha/2)\end{bmatrix} \tag{2.6}$$

Where $C_{p,n}$ is the wind pressure coefficient, α is the incident angle of wind measured from the surface normal, and G = ln(S) is the natural log of the side ratio S is the ratio of building length to width.

Figure 2.6. shows how the airflow network model is connected in Energyplus. It gives an idea of the various objects available in the airflow network and the associated objects in Energyplus.

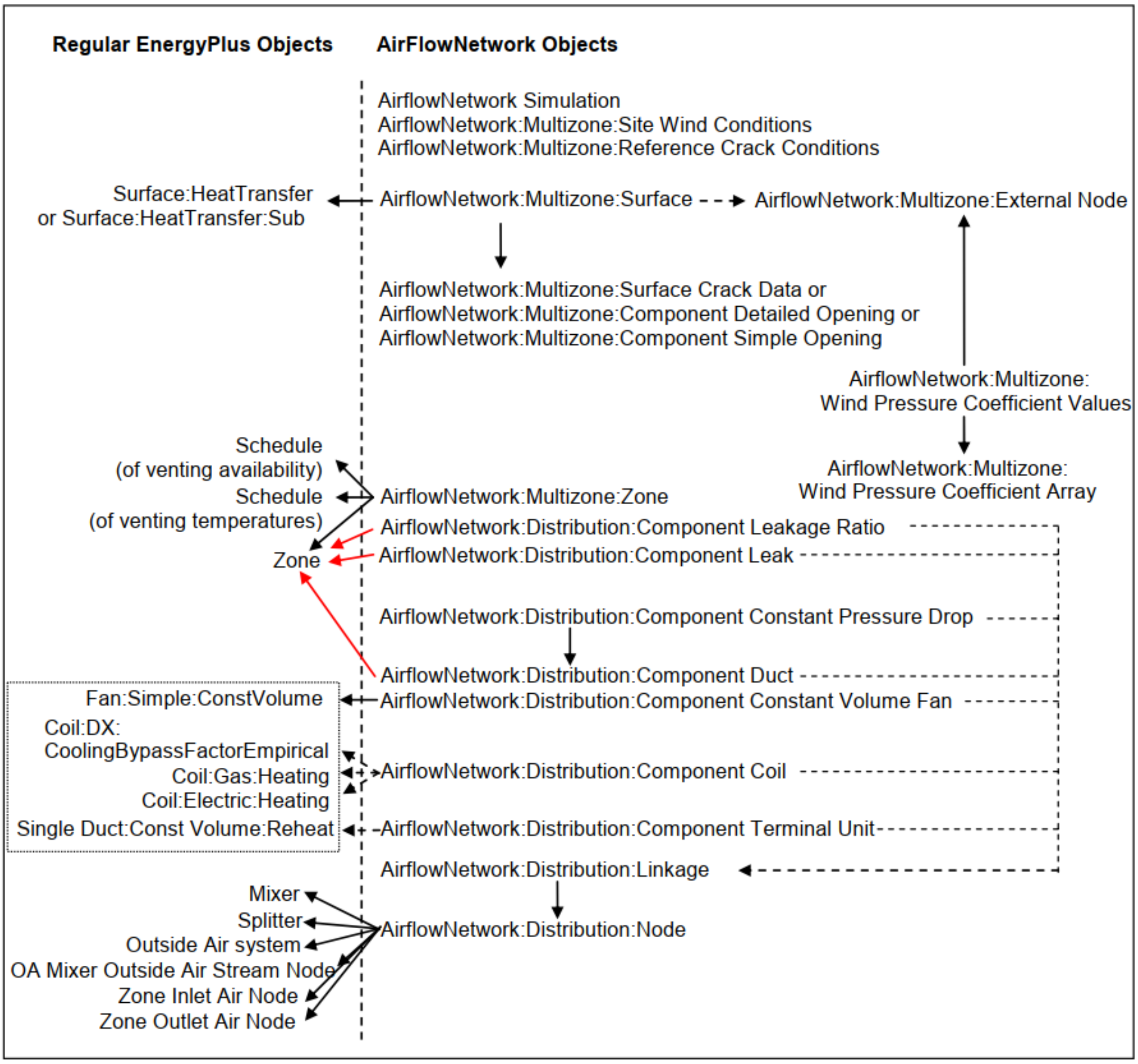


Figure 2.6. Energyplus objects and the associated airflow network objects. Arrows from object A to object B shows that object A references object B [17]

2.5 Midrise buildings common typology and characteristics.

The prevalent types of residential buildings were studied in the Dutch Reference Buildings Guide (Referentiegebouwen BENG) [19]. There are two common typologies of mid-rise residential buildings. The buildings are detailed such that the energy performance as per BENG requirements are possibly met. The first type of building is a mid-rise residential building of 6 floors with a total of 33 medium sized apartments. Figure 2.7 illustrates this type of building. These structures are designed so that the apartments surround the building's core. Each floor has five apartments except the ground floor which has three apartments and storage rooms. The construction details for the building is as shown in Table 2.3.

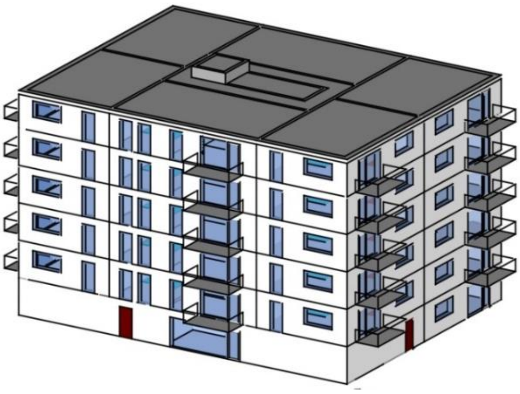


Figure 2.7. Mid Rise Residential Building type 1 [19]

Table 2.3. Construction and HVAC details of the Mid Rise residential Building

Thermal resistance of closed parts (R_c)(m^2K/W)	
floor	3.7
facade	4.7
roof	6.3
Thermal transmittance of open parts U_{total} (W/m^2K)	
Window	1
Front Door	1.4
Infiltration $q_{v10,spec}$ dm^3/sm^2	0.42
Cooling	free cooling
Ventilation	Mechanical Supply and discharge, ventilation with heat recovery, no zoning, no control and complete bypass (D2b2). (More info in section 2.6)

Due to the study's emphasis on apartment overheating, the building simulation is centered on individual apartments. Due to the fact that this structure contains two distinct apartment layouts, one in the center and one in the corner, two apartment models are included to represent each. Figure 2.9 shows the apartments in the building and Figure 2.9 shows how the two apartments are subdivided into various zones for the simulation. The living room and kitchen for these apartments are combined and considered to be a single zone.

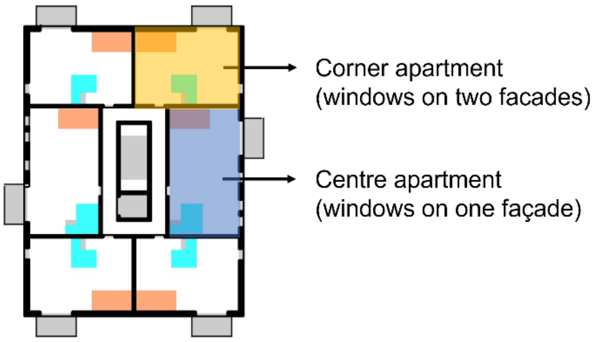


Figure 2.8. Picture showing the layout of the corner apartment and centre apartment in building typology 1.

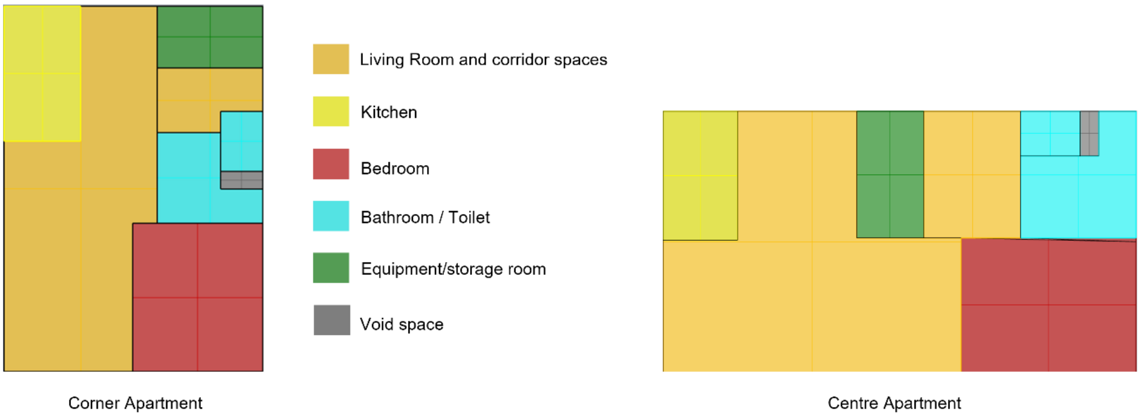


Figure 2.9. Building Typology 1 Corner and centre apartment illustration showing the different zones

The second type of commonly found midrise residential building is the gallery type building as shown in Figure 2.10. Unlike the previous apartment type, these buildings do not surround a core. In this building the ground floor has commercial functions. However, since this study is limited to understanding the thermal comfort in residential apartments, the commercial functions are not considered.

Table 2.4. shows the design characteristics of the building.

Figure 2.10.Mid-rise combination type building [19]

Table 2.4. Construction and HVAC details of Combination type Mid-rise building

Closed parts R_c (m^2K/W)	
floor	3,7
facade	4,7
roof	6,3
Open Parts U_{total} (W/m^2K)	
Window	1
Front Door	1,4
Infiltration $q_{v10,spec}$ (dm^3/sm^2)	0,4
Cooling	Free cooling
Heating	Electric Heat pump with soil as source

Ventilation	ventilation balanced ventilation with heat recovery, CO_2 regulation (C4c) natural supply, mechanical discharge. (More info in section 2.6)

The reference guide lacked a proper floor plan of the gallery apartments. Since the layouts of most gallery apartments are comparable. From among the ABT projects, a gallery apartment building plan was selected. Comparing it to the reference building guide and taking both into account, an appropriate plan was chosen. Figure 2.11 shows the various zones in the gallery apartment.

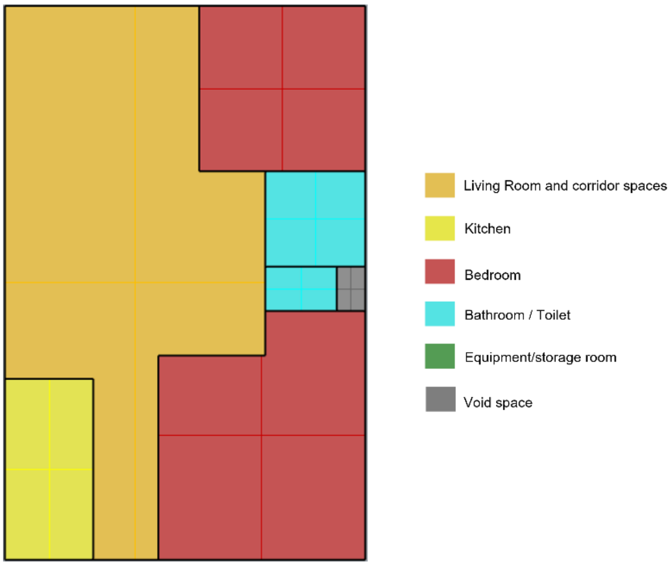


Figure 2.11. Building Typology 2 gallery apartment illustration showing the different zones

2.6 Ventilation Systems

In general, four fundamental ventilation system techniques have been identified (systems A, B, C and D). This design is based solely on how air is supplied and exhausted from the home, with no regard for energy efficiency, comfort, or air quality. System A relies entirely on natural pressure and temperature differences between the indoor and outdoor to supply and exhaust air. In system B, fans are used to deliver fresh air to the various living areas of the building. Thus, the old air is carried out of the house by overpressure. This system was utilized by (old) air heating systems. In system C, polluted air is expelled outside via exhaust grilles. This creates a negative pressure in the home, ensuring that fresh air is sucked in through the grilles. With system D, air is supplied mechanically to the living areas and exhausted mechanically from the kitchen, bathroom, and toilet. This is typically accomplished with a ventilation box that maintains a balance between air intake and exhaust in the home. Also referred to as balanced ventilation [20]. Figure 2.12. shows the ventilation systems A,B,C and D. Generally System C (mechanical extraction, natural supply) is widely seen in buildings. However, in the present day, system D (balanced ventilation with heat recovery) is increasingly preferred due to its higher energy efficiency.

The Building Decree specifies the ventilation capacity that must be installed and the air exchange that must be achieved per room. Table 2.5 displays the minimum ventilation capacity that must be installed in accordance with the Building Decree. In this thesis, for simplification the ventilation system for both the building typologies is assumed to have constant air supply of 0.9 l/s per m^2 in the living room and bedrooms.

Table 2.5. Building Decree 2012 requirements for minimum ventilation in homes [21]

	Minimum Ventilation Capacity to be Installed	
Room Type	**In the presence of residents**	**In the absence of residents**
Residence Area	0,9 $dm^3/s.m^2$	0,135 $dm^3/s.m^2$
Toilet	7 dm^3/s	1,05 dm^3/s
Bathroom	14 dm^3/s	2,1 dm^3/s
Kitchen	21 dm^3/s	3,15 dm^3/s

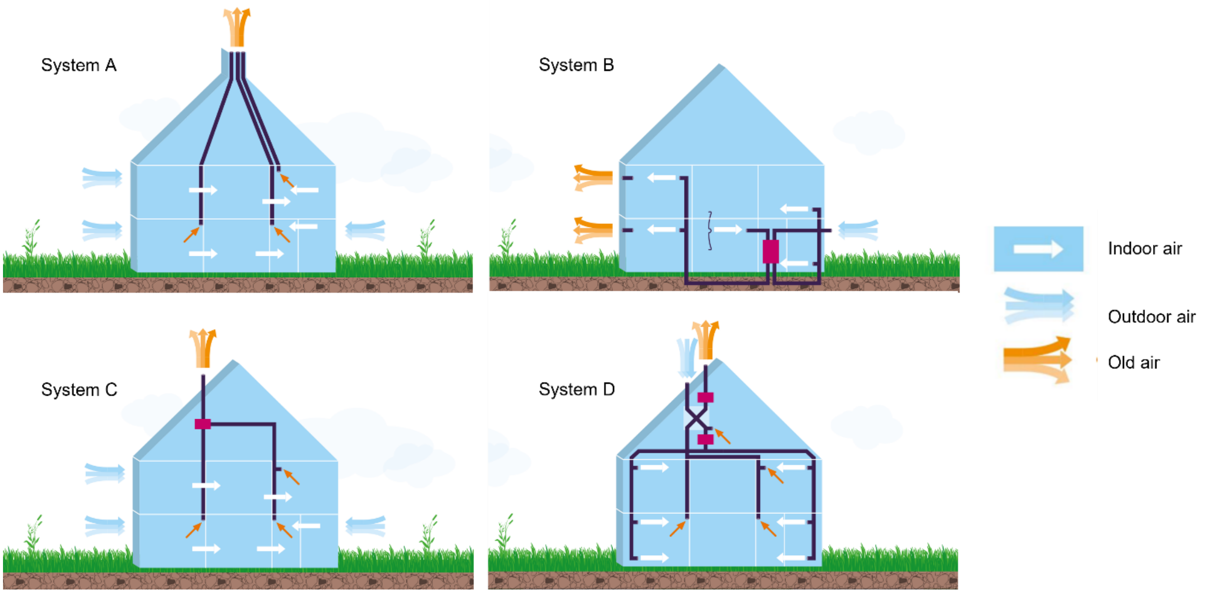


Figure 2.12. The four ventilation systems generally used in buildings [20]

2.7 Performance Indicators

In order to measure the thermal comfort and cooling, different indicators are used. They are explained in detail in this section.

2.7.1 Temperature Exceedance

The Government Buildings Agency along with the Government Occupational Health Agency in the Netherlands agreed in 1979 that a good thermal indoor climate had to meet the criteria of $-0.5 < PMV < 0.5$. This was based on the then reported PMV-PPD relationship [31]. These limits were permitted to be exceeded under certain conditions. They could be exceeded during 10% of the occupied time, or under unusual conditions for example during a heat wave or HVAC malfunction and also to a maximum of $-1.0 < PMV < 1.0$. Based on these considerations, the Government Buildings Agency developed the Temperature exceedance Hours (TO) approach that stated that 25°C may be exceeded for a maximum of 100 hours per year; 28°C may be exceeded for a maximum of 10 to 20 hours per year. The climate year data from 1964-1965 was selected as the standard year for simulating temperatures. This climate year was considered to be a moderate temperature year, so in warmer years it was acceptable for more hours to exceed the norm [31]

In this thesis, the temperature exceedance hours where the temperature is above 25°C and 28°C will be evaluated.

2.7.2 GTO (Weighted Overheating Hours)

GTO (Gewogen Temperatuur Overschrijdings-uren) stands for the weighted temperature exceedance hours. As temperatures are expected to be lower in structures with more thermal mass than in structures with less thermal mass, the level of discontent will be lower in heavier structures. The TO-method did not, however, account for this impact. Hence the GTO method was introduced. It is based on the Fanger's Comfort Model. In this method, the number of hours exceeded past a thermal threshold is measured and multiplied by a weighting factor before summation. The hours are counted when the PMV becomes greater than 0.5. The weighting factor is determined on the basis of the following equation 3.1 if $0.5 \leq PMV < 2.5$ and the weighting factor becomes 10 if $PMV \geq 2.5$ [32].

$$wf = 0{,}47 + 0{,}22 \cdot |PMV| + 1{,}3 \cdot |PMV|^2 + 0{,}97 \cdot |PMV|^3 - 0{,}39 \cdot |PMV|^4 \quad (3.1)$$

Where wf is the weighting factor and PMV is the predicted mean vote.

The climate year for GTO simulation is as per the reference year for temperature exceedance from NEN 5060:2018 with 5% chance of exceedance. The internal heat load is determined as per NTA 8800. It is assumed that the calculated heat load is maintained 24 hours a day. The calculation of the internal heat load is provided in Appendix C. In GTO calculation it is also assumed that there is no heat exchange between adjacent houses. The general specifications while performing dynamic simulation for GTO is provided in Table 2.6.

Table 2.6. GTO Calculation Specifications

Climate Year	2018:5%
Method	GTO (Weighted PMV)
	Living space: MET = 1,1 Clo = 0,5
Internal heat loads	Calculated for 24/7 internal heat
Sun protection	Calculated with values from NTA8800
	Sun protection from 150W/m^2
Ventilation capacity	Depending on the selected ventilation system
	C,2a: 83% (standard mech. vent.)
	C.4a: 80% (with CO 2 control WK)
	C.4c: 59% (with CO 2 control WK + HSK)
	D.2: 100% (balance with HRV)
	D.3 80% (with CO 2 control)
	With passive cooling: 100%
Calculation Period	30 April to 28 September

Although there are different ventilation systems with different capacities, in this thesis 100% capacity is assumed and a constant ventilation rate of 0.9l/s per m^2 is maintained in the living areas for buildings of both typologies.

2.7.3 CPNV, NVCE and CPUR

Yoon. N developed three metrics for evaluating the cooling performance of buildings [33]. These metrics can determine the building's potential to use natural ventilation as a source of cooling. It also indicates whether or not it is possible to make additional changes to improve the cooling.

Climate Potential of Natural Ventilation (CPNV) CPNV is used to determine the site's suitability for natural ventilation based on air temperature and relative humidity. The CPNV can be computed by dividing the total number of hours for which the climatic conditions meet the ventilation criteria by the total number of hours the simulation is run [33]. Equation 3.2 shows the calculation of CPNV.

$$CPNV = \frac{\sum_{i=1}^{n} h_{\mathrm{NV},i}}{h_{\mathrm{tot}}} \tag{3.2}$$

where h_{tot} is total number of hours in a year or the simulation period, and $h_{NV,i}$ is 1 if the climate condition at the i^{th} hour of the year meets thermal criteria, and 0 otherwise. The adaptive model in EN 16798 was used to determine the lower and upper temperature criteria to evaluate the hours during which the climate criteria was appropriate for natural ventilation.

Natural Ventilation Cooling Effectiveness (NVCE) determines the cooling effectiveness of the natural ventilation design within a timestep. The NVCE is influenced by the internal heat gain and losses, the building material, the intake airflow rate and also the local climate. Equation 3.3 illustrates the NVCE calculation.

$$NVCE_{\mathrm{ts}} = \frac{q_{\mathrm{avail}}}{q_{\mathrm{avail}} + q_{\mathrm{sup}}} = \frac{-\rho c \dot{V}_{\mathrm{avail}} \left(T_{\mathrm{target}} - T_{\mathrm{out}}\right)}{-\left\{q_{\mathrm{gain}} - UA\left(T_{\mathrm{target}} - T_{\mathrm{out}}\right)\right\}} \tag{3.3}$$

where ρ is air density, c is the specific heat of air at constant pressure, $\dot{V}_{\mathrm{avail}}$ is intake airflow rate through natural ventilation obtained by simulations, calculations, or measurements, and T_{target} and T_{out} are target and outdoor temperatures. U is the thermal transmittance of the building envelope and A is the area of the building envelope.

$NVCE_{ts}$ = 0 when no cooling power is available from natural ventilation (q_{avail} = 0), and $NVCE_{ts}$ = 1 when no supplemental cooling is needed (q_{sup}= 0). If NVCE is between 0 and 1, it indicates the partial cooling capacity that natural ventilation can provide relative to the required cooling capacity to meet the target temperature [34]. The NVCE for a particular time period (a year, season, or a month) is defined as the average of the NVCE simulated for each time step during the specified period. It is shown below in equation 3.4.

$$NVCE = \frac{\sum_{n_{ts}} NVCE_{ts}}{n_{ts}} \tag{3.4}$$

n_{ts} is the number of time steps in the given simulation period.

Climate Potential Utilization Ratio (CPUR) is used to compare the site and the building potential to use the natural ventilation capacity of the climate. It gives a measure of how much of the site's natural ventilation potential has been utilized by the building. This provides an indication of how much the building design can be improved to maximize the site's potential. The time duration, time step, and thermal conditions of NVCE and CPUR must be the same to make correct use of the metrics. To calculate CPUR, NVCE is divided by CPNV as shown in equation 3.5.

$$CPUR \equiv NVCE/CPNV \tag{3.5}$$

Figure 2.13 illustrates how NVCE and CPUR can be interpreted for interactive energy modeling. A high design NVCE and a high CPUR indicate that natural ventilation has a high potential to cool the building, and that the design has achieved adequate natural ventilation performance by utilizing the climate effectively. A low NVCE and a low CPUR indicate that natural ventilation cannot provide as much cooling power as the building requires, but there is room for improvement in the design NVCE because it does not make the most of the climate potential. A combination of a low NVCE and a high CPUR may not be reassuring, as it suggests that the building has poor performance despite a high utilization ratio of its climate resources.

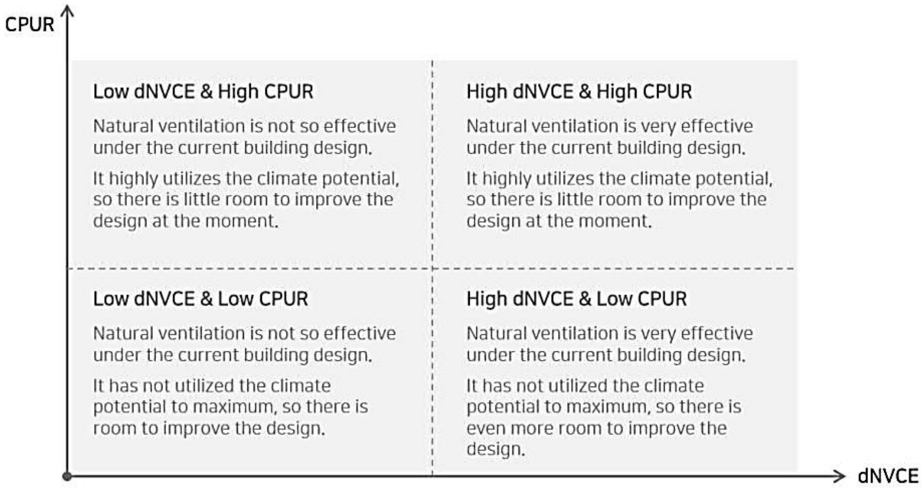


Figure 2.13. Relationship between CPUR and NVCE [35]

For evaluating the cooling performance, CPNV,NVCE and CPUR will be used and for evaluating the comfort parameters, GTO and temperature exceedance parameters.

2.7.4 Cooling Requirements Reduction - CRR

This energy performance indicator expresses the ratio of cooling requirements saved of a scenario with respect to the one of the reference scenario.

$$CRR = \frac{Q_{t,c}^{\text{ref}} - Q_{t,c}^{\text{scen}}}{Q_{t,c}^{\text{ref}}} \qquad (3.6)$$

Where $Q_{t,c\ ref}$ is the cooling requirements of the reference scenario and $Q_{t,c\ scen}$ is the cooling requirements of the ventilative cooling scenario. CRR can range between a negative value and +1. If CRR is positive, it means that the ventilative cooling system reduces the cooling requirements of the building. If CRR is equal to 1, the ventilative cooling scenario has no cooling requirements. If CRR is zero, the ventilative cooling scenario does not reduce the cooling requirements of the building and if it is negative, ventilative cooling increases them (increased ventilation induces more heat that the one it extracts from the building). CRR calculates cooling effectiveness of any ventilative cooling scenario, mechanical or natural.

Table 2.7 shows the overview of the indicators used in the study.

Table 2.7. Performance indicators used in the study

	Cooling	**Comfort**	**Energy**
Indicators	• Climate Potential Natural Ventilation (CPNV) • Natural Ventilative Cooling Effectiveness (NVCE) • Climate Potential Utilization Ratio (CPUR)	• Temperature exceedance hours (TO) • Weighted Temperature Exceedance hours (GTO) [hour]	• Cooling Requirement Reduction (CRR)

3. Methodology and varying Parameters

3.1 Building Characteristics

3.1.1 Apartment orientation

For this simulation, each apartment is simulated separately, as opposed to the building as a whole. This is because in this thesis, we are interested in the temperature variations at the apartment level. The simulation is run with each apartment model with the façade having the largest glass surface facing the south orientation.

The apartments are considered to be on the top floor. As per a field study undertaken on a student dormitory in Delft to assess thermal comfort, it was found that height and orientation are important parameters. Using CFD simulations, it was determined that there was a significant variation in temperature based on the floor level. The temperature was highest on the top floor and lowest on the ground floor while the middle floors had an intermediate temperature. The temperature and wind pattern inside rooms were strongly related to the weather and ventilation systems [22]. Another study by S. Sharifi indicated that the upper floors of apartment buildings had higher temperatures and longer periods of overheating than the lower floors. When temperatures on the lower floors met comfort standards, the air temperature in the apartments on the upper floors was warmer by an intensity of 3.5°C [23]. For simulations involving chimneys, apartment is modelled on the ground floor to check the maximum effect of stack. If there is temperature variation observed by the use of chimney, then apartment will also be modelled on the middle and top most floor to check the variation in temperature with the variation in stack height.

According to GTO calculation requirements, It is required that the walls of apartments that are adjacent to other apartments in the building do not allow heat to transfer between them. As a result, these adjoining walls are considered to be adiabatic.

3.1.2 Building Construction

In order to understand the differences in the thermal comfort in different building constructions of varying thermal mass while employing ventilative cooling strategies, distinction is made between light, medium heavy and heavy constructions.

The following construction elements were defined to account for the thermal mass. The material definition is based on a paper which defined materials that are in conjunction with the energy efficient housing standards in housing [24]. The construction details are as shown in Table 3.1.

Table 3.1. Construction details of light, medium heavy and heavy thermal masses

Construction Type	Building Component	Material	Density [kg/m³]	Specific Heat Capacity [J/Kg K]	Thickness [m]	Heat Capacity [kJ/m²K]
Light Weight Construction	External Wall	Brick	1700	800	0.1	136
		Air Gap	1.28	1000	0.1	0.1
		Insulation	130	840	0.17	18.6
		Plaster Board	800	1089	0.01	8.3
	Internal Wall	Plaster Board	800	1090	0.013	11.1
		Plaster Board	800	1090	0.013	11.1
	Ceiling and Floor	Tile	368	590	0.02	4.3424
		air gap	1.28	1000	0.1	0.128

Construction Type	Building Component	Material	Density [kg/m³]	Specific Heat Capacity [J/Kg K]	Thickness [m]	Heat Capacity [kJ/m²K]
		Lightweight concrete	1280	840	0.1	107.52
	Roof	Roof Membrane	1120	1460	0.01	16.4
		Insulation	130	840	0.23	25.1
		Air Gap	1.28	1000	0.1	0.1
		Tile	368	590	0.02	4.3
Medium Heavy Weight Construction	External Wall	Brick	1700	800	0.1	136
		Air Gap	1.28	1000	0.1	0.1
		Insulation	130	840	0.17	18.6
		Normal Weight Concrete	2322	832	0.1	193.2
		Gypsum Board	800	1089	0.013	11.1
	Internal Wall	Plaster Board	800	1090	0.013	11.1
		Normal Weight Concrete	2322	832	0.1	193.2
		Plaster Board	800	1090	0.013	11.1
	Ceiling and Floor	Carpet				
		Normal weight concrete	2322	832	0.1016	196.2814
	Roof	Roof Membrane	1120	1460	0.01	16.4
		Insulation	130	840	0.23	25.1
		Air Gap	1.28	1000	0.1	0.1
		Tile	368	590	0.02	4.3
Heavy Weight Construction	External Wall	Brick	1700	800	0.1	136
		Air Gap	1.28	1000	0.1	0.1
		Insulation	130	840	0.17	18.6
		Heavy Weight Concrete	2240	900	0.2	403.2
		Gypsum Board	800	1089	0.013	11.1
	Internal Wall	Gypsum Board	800	1089	0.013	11.1
		Heavy Weight Concrete	2240	900	0.2	403.2
		Gypsum Board	800	1089	0.013	11.1
	Ceiling and Floor	Carpet				
		Heavyweight concrete	2240	836.2	0.1016	190.3057
	Roof	Roof Membrane	1120	1460	0.01	16.4
		Insulation	130	840	0.23	25.1
		Air Gap	1.28	1000	0.1	0.1
		Tile	368	590	0.02	4.3

3.1.3 Window Construction

The windows have a triple glazed glass surface with a U value of 1.2 W/m^{2}K and a solar heat gain coefficient of 0.36. Internal white diffusing shades are provided having a thickness of 0.0002m and a transmittance of 40% of solar radiation and visible light through the shade. For the simulation, the window shades are switched on when the solar radiation through the window reaches a setpoint value of 150 W/m^2.

The reference buildings guide provides insufficient information regarding window construction. As a result, assumptions were made to satisfy the requirements. Although there is a high ratio of glazing surface to building area, the majority of houses have only a proportion of that as operable windows while the remaining is fixed. In this simulation, fifty percent of the windows in apartments of typology 1 were considered operable, while the remaining windows were considered fixed. It was assumed that these operable windows were tilt-and-turn windows. The operable windows in the corner apartment had a height of 1,10m and width of 1.10m. The operable windows in the center apartments had a height of 1.30m and width of 1.25m. Figure 3.1 and Figure 3.2 shows the windows that are considered operable (green) and non-operable (red) for the simulation in typology 1 apartment models.

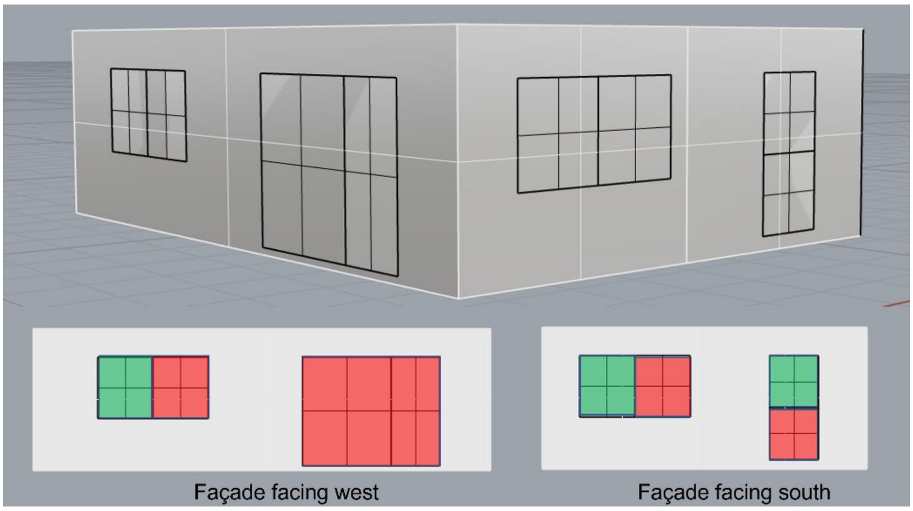


Figure 3.1. Illustration of the corner apartment and the considered operable (green) and fixed (red) windows.

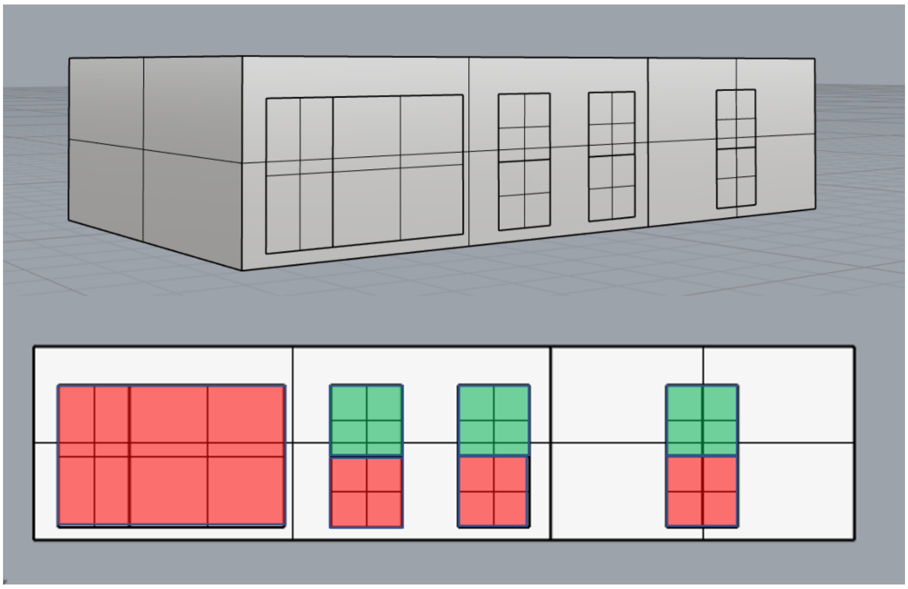


Figure 3.2. Illustration of the center apartment and the considered operable (green) and fixed (red) windows.

Since proper construction details of the facade were provided for the gallery apartments, only 18% of the total glazing surface had operable windows. Typically, gallery-style apartments feature small awning windows. The awning windows generally had a dimension of 0.32m by 0.9m. there was also a bigger window which could be turned ad opened at the back façade of the apartment which had dimensions of 1.40m in height and 0.77m in width. Figure 3.3 shows the operable and fixed windows in gallery apartment.

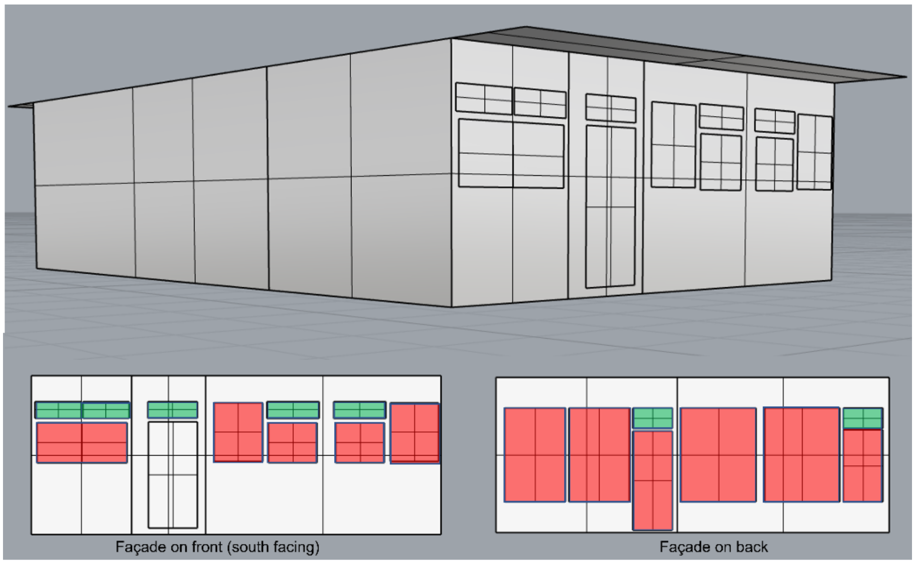


Figure 3.3. Illustration of the gallery apartment and the considered operable (green) and fixed (red) windows.

In Energyplus simulation, windows are distinguished based on their operable area, which is a required user input. The openable window area is "*the geometric free ventilation area created when a ventilation opening is open to its normal operational fully designed extent for ventilation purposes*" [25]. The free area for a bottom hung window can be seen in Figure 3.4.

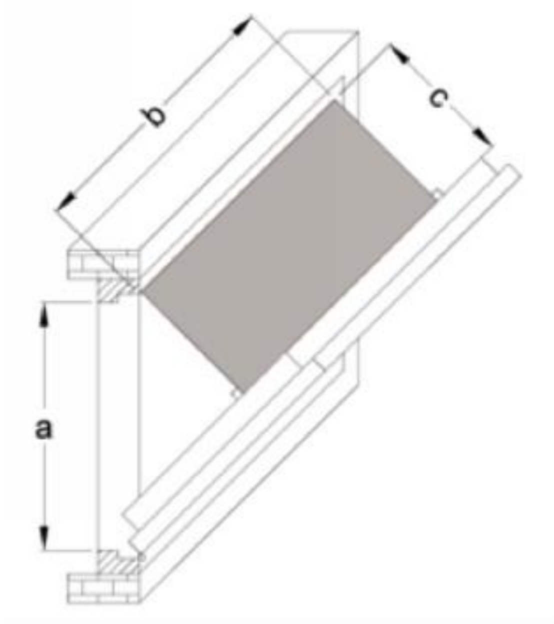


Figure 3.4. Operable free area for a bottom hung window [26]

Unless it is a fully-opened casement window, the operable window area does not cover the full glazed surface of the facade. S. Bliss in his book Best Practices Guide to Residential Ventilation had provided the free area available for various types of windows. This was used as the operable area for the simulation of natural ventilation through windows. Figure shows the operable areas available for different window types. For tilt and turn windows, the operable area was considered 10% of the total area of the glazed surface when the window was opened in the tilt position and 90% when the window was turned to open. Similarly, for the awning windows in the gallery type building, the operable area was assumed to be 75% of the total glass area [27]. Literature indicates that the discharge coefficient for windows is typically between 0.6 and 0.65 [36]. These windows are not equipped with insect screens. With the addition of insect screens, the discharge coefficient value is reduced to 0.45.

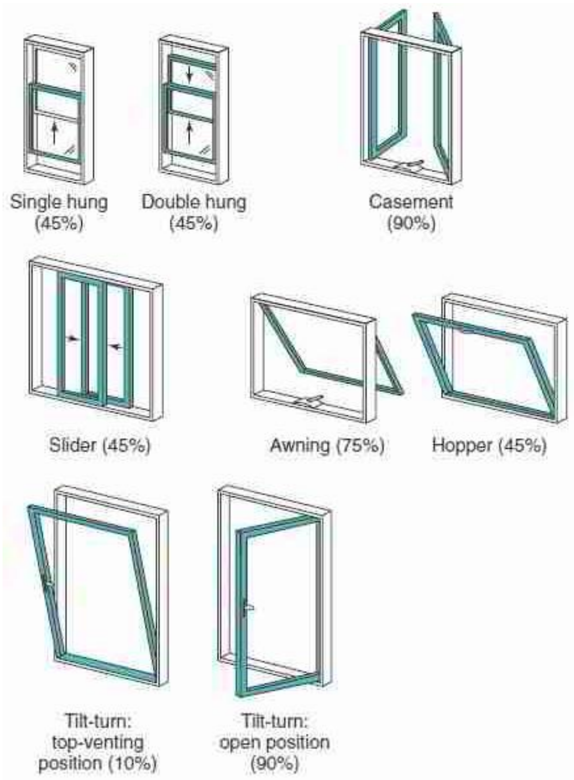


Figure 3.5. Operable window areas for natural ventilation for different window types [27]

3.2 Chimney Characteristics

Passive stack enhances ventilation through the use of natural driving forces. Stacks are typically used to extract air from rooms, particularly the kitchen and bathroom. Fresh air is supplied through windows or vents located at a lower level. Passive stack is reliant on difference in temperature and outlet wind pressure. Given that stack provides a very low driving force, it is important to ensure that the design has minimal resistance. If the stack ductwork passes through non-conditioned spaces (spaces without heating), it must be adequately insulated to prevent heat loss. Practice indicates that a separate stack each room from which air must be extracted is more efficient in terms of design. Typically, the diameters of stack system ducts range between 100mm and 150mm [28].

3.3 Weather Data

For the building simulation, the climate data of De Bilt is chosen as per the standard NEN 5060:2018. In accordance with the 2012 Building Decree, the NEN 5060:2018 reference year for temperature exceedances with a 5 percent chance of exceeding is considered as the outdoor climate for GTO calculation. The simulation is run for the summer period which is specified as the last Monday in April until the last Monday in September. This begins on Monday, 30th April at 00:00 and concludes on Sunday, 28th September at 23:59.

3.4 Ventilative Cooling Strategies

In accordance with CIBSE Guide A, 25°C is an acceptable operative temperature for the living area of a dwelling, while 23°C is acceptable for the bedrooms [29]. According to the 2012 Building Decree, summer night ventilation can occur between 22:00 and 06:00 or 24 hours a day if the windows have an automatic temperature control. In addition, the outdoor temperature must be above 13°C and the indoor temperature must be above 24°C. For the simulation, the windows are considered open when the temperature in the living area exceeds 24°C and for the bedrooms the temperature setpoint is 23°C throughout the whole day.

There are windows on both facades of the corner apartments of Typology 1 and the gallery apartments of Typology 2, allowing for cross ventilation. There should be two or more openings on more than one exterior wall for cross ventilation. There is a significant pressure gradient that would facilitate the performance of natural ventilation when cross ventilation is provided. However, apartments of type 1 in the center have windows on only one side of the facade, allowing for only single-sided ventilation. When there is a significant height difference between the inlet and outlet, stack ventilation is enhanced.

3.5 Design Variants

For a quick overview, Table 3.2 below illustrates the design variants examined in this study.

Table 3.2. Overview of design variants

Design factors	**Variables**
Building Typology	Midrise building around a core (typology 1) Midrise building gallery type (typology 2)
Apartment	Typology 1.1: Corner apartment Typology 1.2: Centre apartment Typology 2: Gallery apartment
Climate	De Bilt weather file with 5% temperature exceedance from NEN 5060:2018
Simulation Period	Summer (30th April to 28th September)
Thermal Mass	Light Medium-Heavy Heavy
Window	Typology 1: Tilt and turn windows Typology 2: Awning windows
Chimney	Diameter 0.2m

Design factors	Variables
Ventilation rate	minimum ventilation rate of 0.9 l/s per m^2 of floor area
Ventilative Cooling Strategy	Day & Night ventilation
Orientation	The façade with largest glazing ratio facing South

All the apartment models were assumed to be on the top most floor. Hence, these models were created at a height of four floors above the ground. Each floor had a height of 3m. The general parameters for the study are shown in Table 3.3. The main difference in the two typologies apart from the geometry are the window type and the opening area for each window type as defined in section 3.1.3. For the apartments in typology 1, i.e. the corner apartment and the center apartment simulations were run with tilt and turn windows. Hence, simulations were run for operable areas of 10% and 90% of glazing surface. The kitchen and living room for typology 1 apartments are combined and they are treated as a combined zone. For typology 2 gallery apartment, the simulations were run with awning type windows having an operable area of 75%. Ideal systems are used for heating and cooling of the apartments. Hence the heating and cooling energy obtained from the simulations is equal to the amount of heat that has to be added and removed from the zones to reach the respective temperature setpoints respectively. For maintaining the minimum ventilation rate, ideal air supply of a constant minimum ventilation rate of 0.9 l/s per m^2 is assumed and is included in the simulation. Simulations were run for changing multiple factors. They are as follows:

1. Simulation with all operable windows closed for all apartments and cooling system turned off for all thermal masses.
2. Simulation with all operable windows closed for all apartments and cooling system turned on for all thermal masses.
3. Simulations with window open and cooling system turned off for all thermal masses. The window opening area as per the window type.
4. Simulations with window open and cooling system turned on for all thermal masses. The window opening area as per the window type.
5. Simulation with chimney for an apartment on ground floor.

Table 3.3. General Parameters and setpoints for the simulation of the three apartments.

Parameters	Typology 1		Typology 2
	Corner Apartment	Centre Apartment	Gallery Apartment
Total Floor Area (m^2)	76	89	89
Volume (m^3)	228	267	267

<table>
<tr><th rowspan="2">Parameters</th><th colspan="2">Typology 1</th><th>Typology 2</th></tr>
<tr><th>Corner Apartment</th><th>Centre Apartment</th><th>Gallery Apartment</th></tr>
<tr><td>Mechanical ventilation rate (l/s per m^2)</td><td colspan="3">0.9</td></tr>
<tr><td>Window type</td><td>tilt and turn</td><td>tilt and turn</td><td>awning</td></tr>
<tr><td>Window Discharge coefficient C_d</td><td colspan="3">0.45 (with insect screens)</td></tr>
<tr><td>Window Opening Temperature Control</td><td colspan="3">Living Room
$T_{in,LR} > 24°C$
$T_{out} > 13°C$
$T_{in,LR} – T_{out} > 1°C$
Bedroom
$T_{in,BR} > 23°C$
$T_{out} > 13°C$
$T_{in,BR} – T_{out} > 1°C$
where $T_{in,LR}$= Temperature in Living Room, $T_{in,BR}$ = Temperature in Bedroom, T_{out} = Temperature outside</td></tr>
<tr><td>Ventilative Cooling Principle</td><td>Cross Ventilation</td><td>Single sided Ventilation</td><td>Cross Ventilation</td></tr>
<tr><td>Total area of facade (m^2)</td><td>53.1</td><td>38.1</td><td>45.6</td></tr>
<tr><td>Glazed surface area (m^2)</td><td>18.5</td><td>15</td><td>18.7</td></tr>
<tr><td>Heating set point (°C)</td><td colspan="3">20</td></tr>
<tr><td>Cooling set point (°C)</td><td colspan="3">Living room: 26
Bedroom: 23</td></tr>
<tr><td>Shading control setpoint (W/m^2)</td><td colspan="3">150W/m^2 of solar radiation</td></tr>
</table>

4. Modelling

Three apartment models were created for simulation purposes. The geometries were first modelled in rhino and then imported into grasshopper. Except for the differences in geometry, the workflow for configuring the models in the simulation was identical for all three. Honeybee converted the model into an Energyplus-compatible Input Data File. The rhino models of the apartment and the grasshopper script can be seen in Figure 4.1 and Figure 4.2.

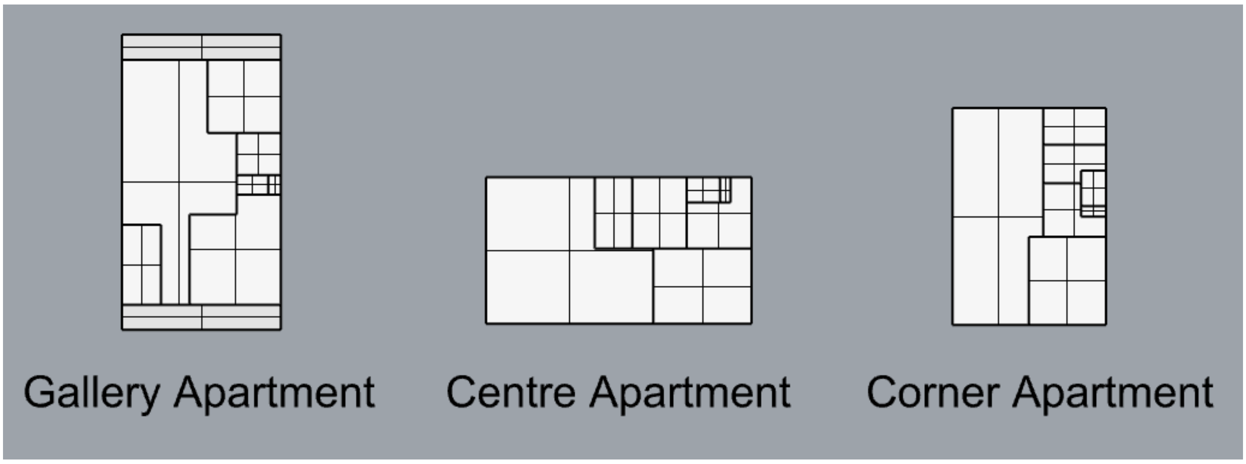


Figure 4.1. Top view of the apartments as modelled in Rhino.

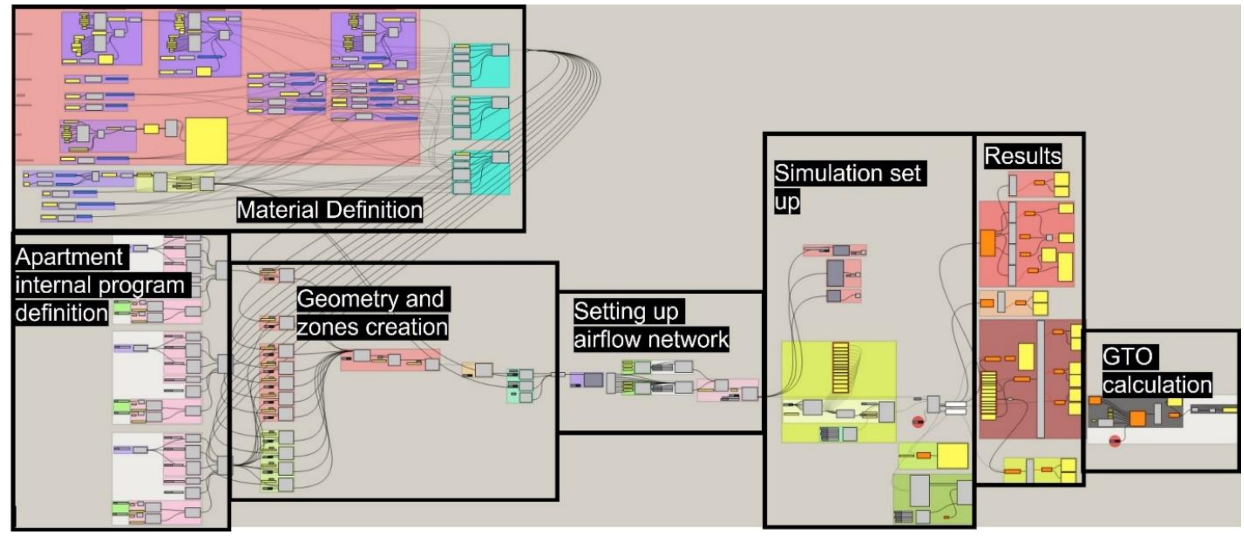


Figure 4.2. Grasshopper Script overview

Rooms and Construction Material Definition

The materials are defined as explained in section 3.1.2. The grasshopper script for material definition can be seen in Figure 4.1. The materials are custom defined to consider the different thermal masses. The different zones are defined as honeybee rooms and the construction set is applied for the simulation. For the corner and center apartments of typology 1, the living room and kitchen is combined as a single zone. Also, to ensure that the doors between rooms are always open, some wall surfaces were made as air boundary.

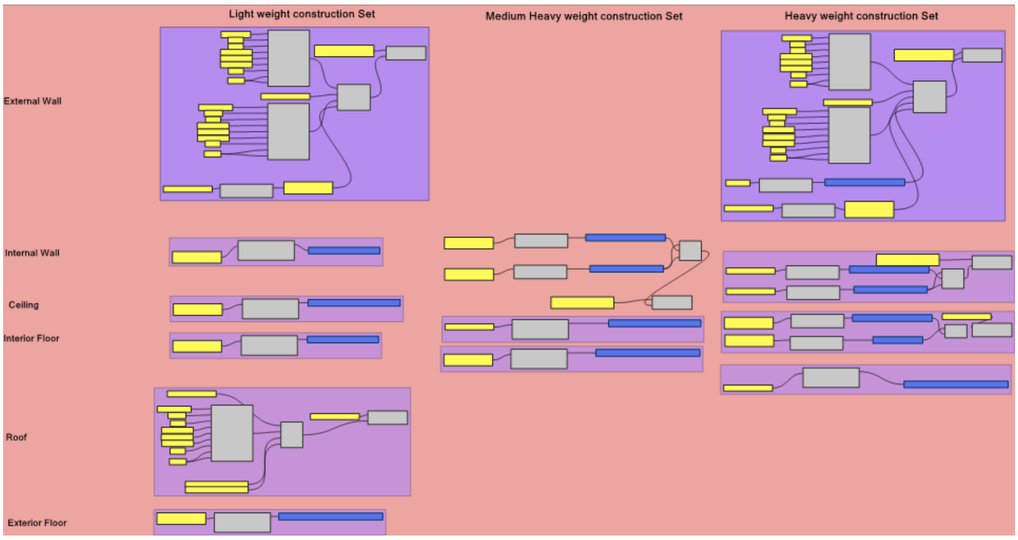


Figure 4.3. Grasshopper script showing the material definition for light, medium heavy and heavy constructions

Definition of Program types

A custom program type was defined for the simulation in order to input the internal heat gains calculated with NTA 8800. Since the NTA calculation provided the sum of all the internal heat gains from people, lighting, and equipment, the program type was defined such that the sum of all the internal heat gains was constant for 24 hours and matched the previously calculated value. Figure 4.4 illustrates the script that defines the program type. The mechanical ventilation rate is defined as 0.0009 m^3/s per m^2 in this program type as discussed in section 2.6. For GTO calculations, the heating set point temperature is 20°C as the temperature in the apartments should not fall below 20°C. The infiltration rates were estimated to be 0.0001 m^3/s, to make the building airtight. In order to prevent the cooling system from activating during the simulation of the natural ventilation, the temperature setpoint for cooling was kept high. However, when calculating the cooling energy, the setpoint temperatures for cooling were maintained at 26°C for living rooms and 23°C for bedrooms. This was in accordance with ISSO 32 [38], which states that for category 2 buildings, the living room and bedroom temperatures should not exceed 26°C and 23°C, respectively. The defined program types and construction sets are connected to the room geometry component on honeybee as shown in Figure 4.5.

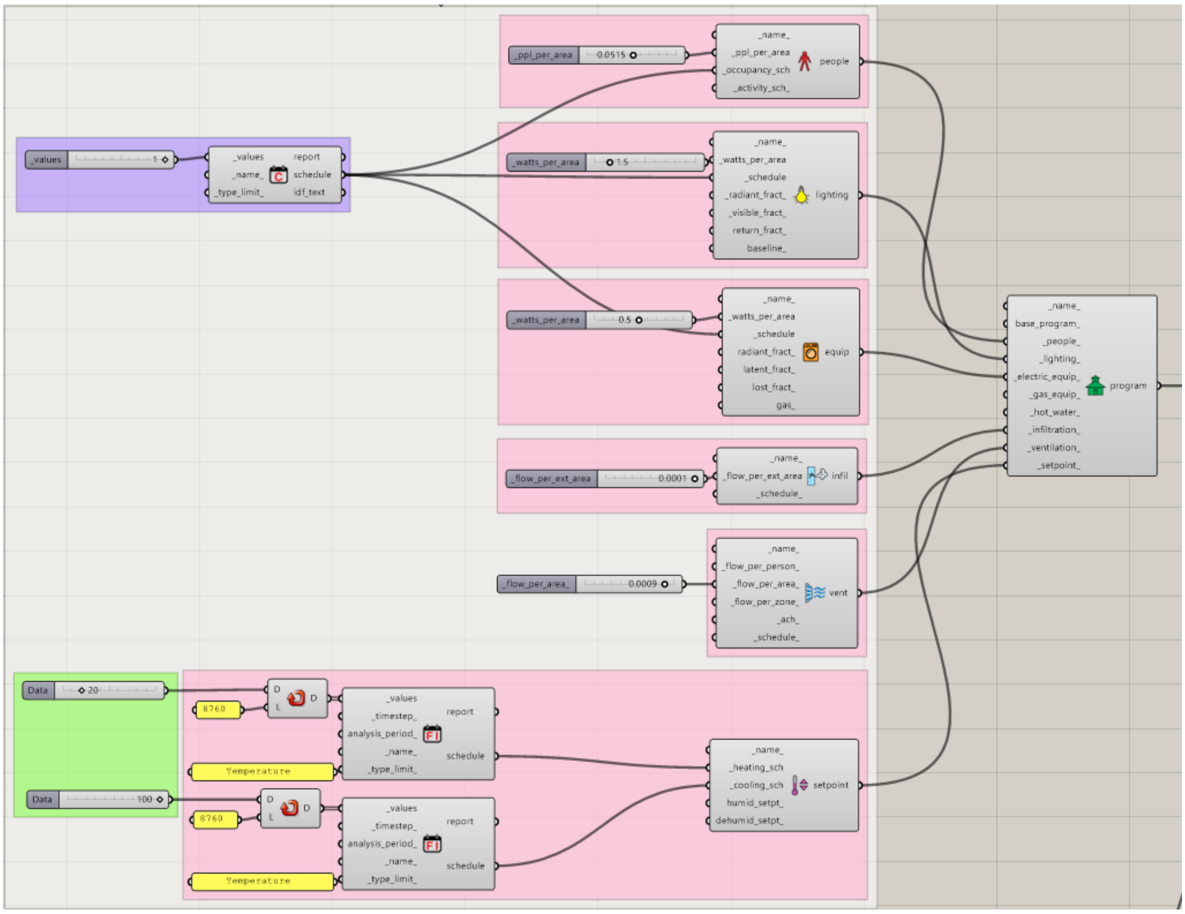


Figure 4.4. Program type definition for internal heat loads, mechanical ventilation rate and heating and cooling setpoints.

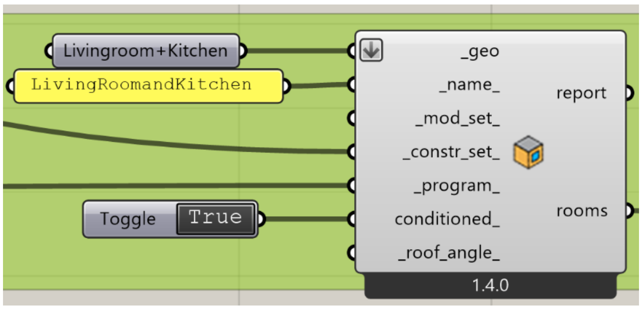


Figure 4.5. Script showing how rooms are defined in honeybee. All the components for the construction set and program types are connected to the room.

Setting up Airflow Network model

The ventilation controls are as described in section 3.4. The temperature setpoints for the bedroom and living room are 23°C and 24°C, respectively, as shown in Figure 4.6. The windows only open when the indoor and outdoor temperatures differ by 1 degree. Below this difference temperature, the windows are closed. This is to prevent the windows from opening when the outside temperature is higher than the interior temperature. After defining the ventilation controls and the operable areas of the windows based on the window type, the airflow network component is connected. This component enables the use of the airflow network model in Energyplus. It converts the infiltration objects defined into AFN crack objects assigned to each opaque face. The air boundaries defined in the model will be changed to AFN crack objects with very high pressure coefficients which are derived using orifice equation and the area of the air wall. The operable windows in the model will be changed to AFN simple opening objects.

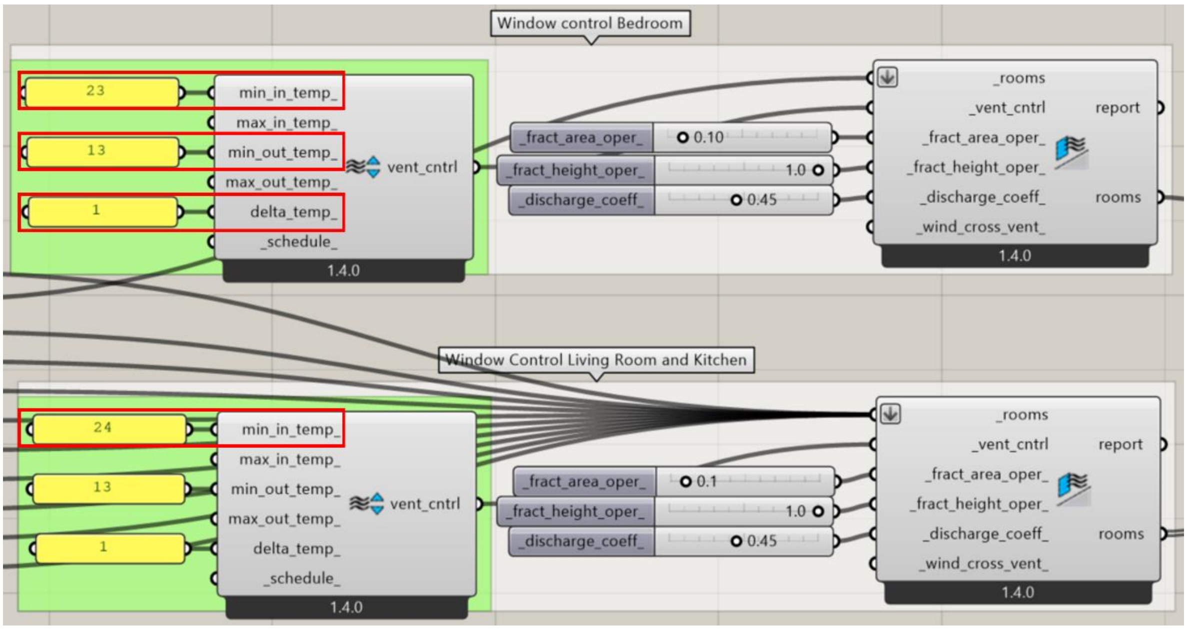


Figure 4.6. Grasshopper script showing the ventilation control for the rooms.

The simulation is run for the summer period. The dates are set for the simulation period in summer and an hourly data for the simulation is requested from the simulation as shown in Figure 4.7.

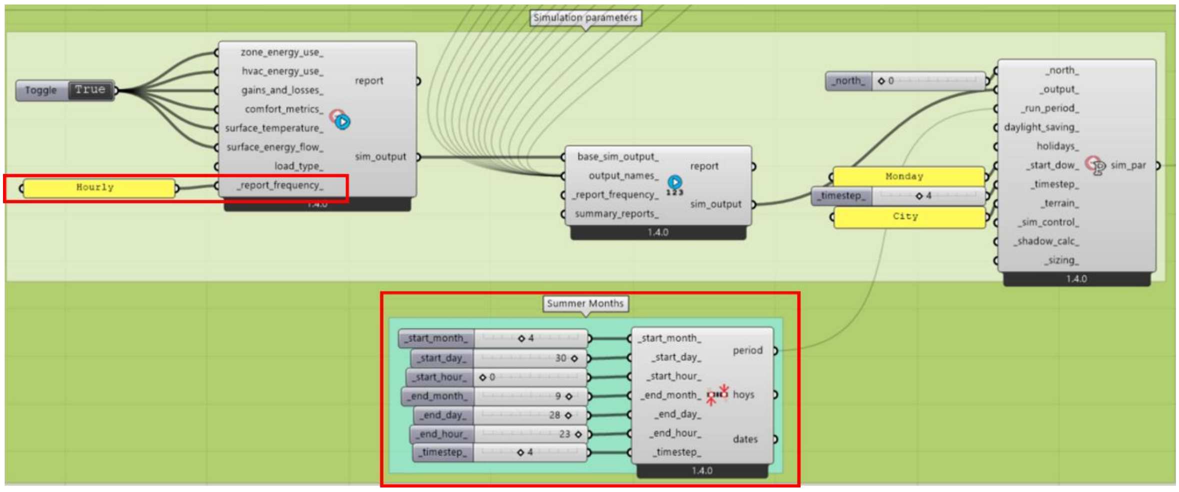


Figure 4.7. Script showing the simulation controls including the simulation period and the output report frequency

GTO Calculation

For the GTO calculation, the PMV calculation was done as per the Fangers comfort model provided in ladybug tools. The PMV comfort model parameters are set as per the requirements for GTO calculation (Figure 4.8). A simple python script was made to calculate the GTO as per equation 3.1. The python script is shown in Figure 4.9.

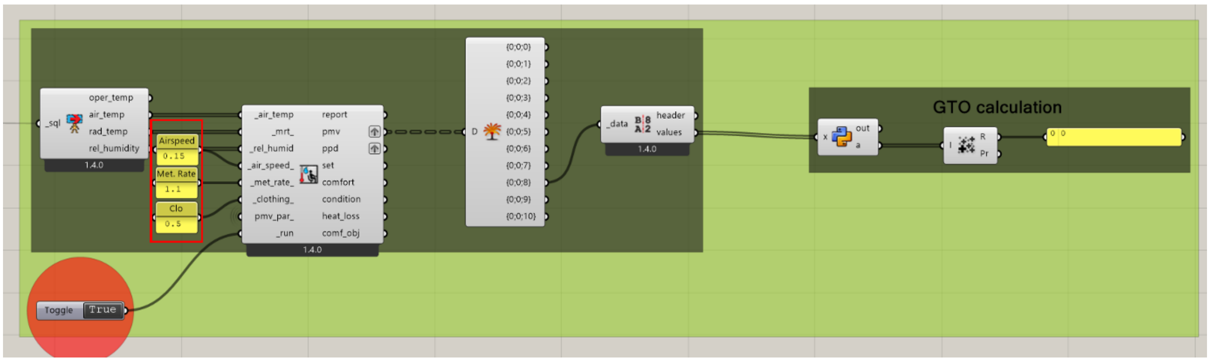


Figure 4.8. Grasshopper script for PMV comfort model

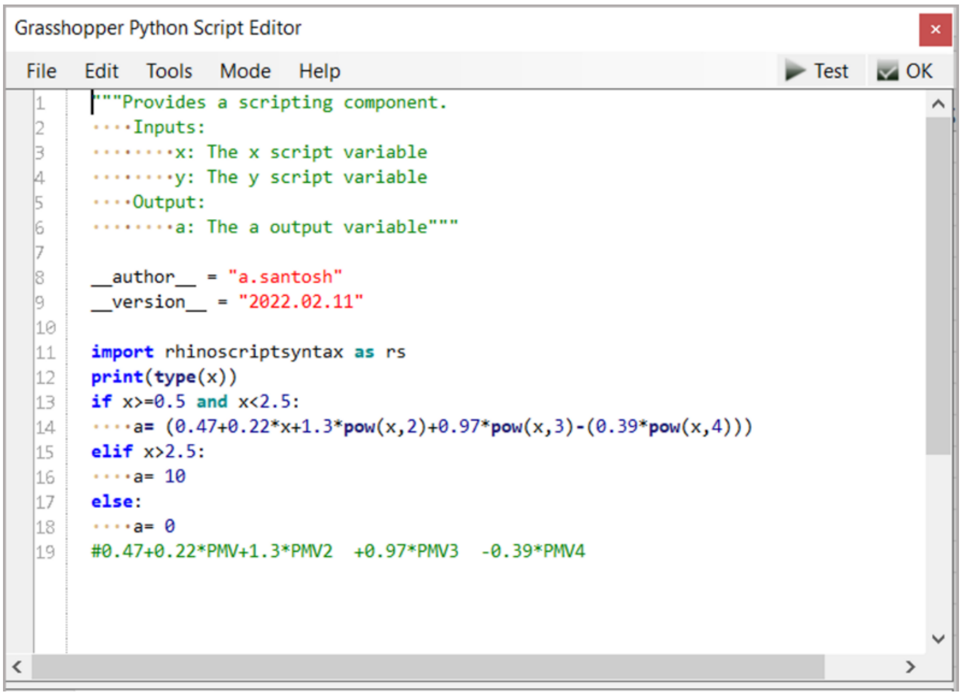


Figure 4.9. Python script for GTO calculation.

5. Pilot Study

In general, honeybee utilizes zonal methods to determine ventilation and infiltration. This is accurate for single zones. When additional zones with operable windows are added, inconsistencies emerge. However, the airflow network component can be used to model a multizone airflow with operable windows. The honeybee airflow network model is relatively new. Since there are very few models that have been created utilizing the airflow network which are available for study, simple single-zone, multi-zone and chimney models were tested to determine how it performs.

5.1 Single Zone Model

A relatively simple model consisting of a single room was developed as shown in the Figure 5.1. The length, breadth and height of the model is 4m, 3m and 3m respectively. It has a total volume of $36m^3$ and a floor area of $12m^2$. Two windows of size 1.5m X 1m were provided on opposite facades.

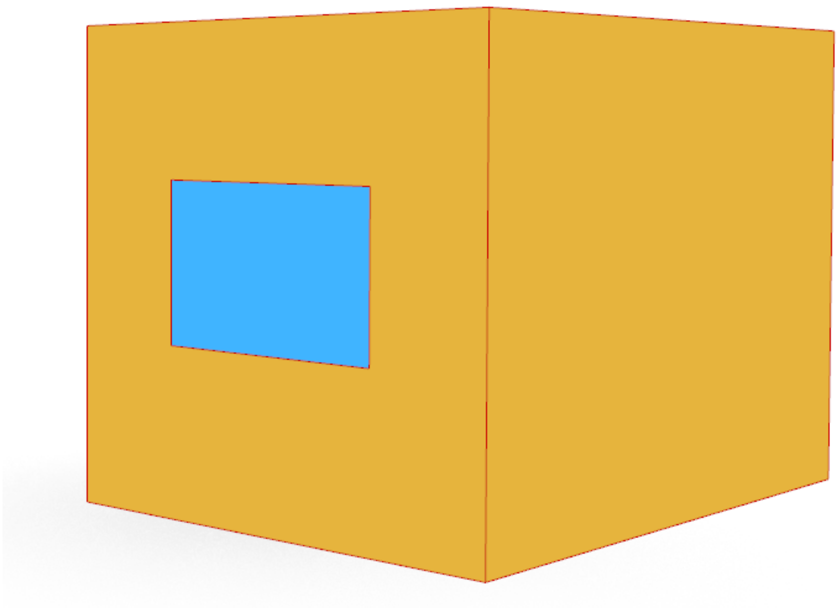


Figure 5.1. Single Zone model developed for testing

The discharge coefficient of the windows were set to 0.45. The simulation was run and the windows were allowed to open when the temperature inside was higher than 24°C and the outside temperature was above 13°C. Only 50% of the window area were set to be operable.

The airflow was simulated after defining the room as a zone. The zone in the simulation behaves like a node in the airflow network model. The outdoor environment also has a representative node. These nodes are connected to each other through linkages, which in this case would be the window. The volumetric flow rate between the two nodes i.e., node 1 (interior zone node) to node 2 (outside node) and vice versa were obtained from the simulations. The table below shows the data obtained for volumetric airflow through the windows at four different time steps. Figure 5.2 shows how the airflow through the different apertures for one of the timesteps shown in the table. Each time step is one hour. The model shows that there is balance of air coming in and air going out during each time step.

Table 5.1. Volume air flow rate through the apertures for a single zone test model with two operable windows

	Aperture 1		**Aperture 2**			
Timestep	**Volume Flow Rate from node 1 to node 2 [l/s] {1}**	**Volume Flow Rate from node 2 to node 1 [l/s] {2}**	**Volume Flow Rate from node 1 to node 2 [l/s] {3}**	**Volume Flow Rate from node 2 to node 1 [l/s] {4}**	**Volume of air coming in [l/s] {2+4}**	**Volume of air going out [l/s] {1+3}**
1	13.7	7.0	7.0	13.7	20.7	20.7
2	27.4	8.4	8.3	27.4	35.7	35.7
3	23.5	23.5	23.5	23.5	46.9	46.9
4	22.6	22.6	22.5	22.5	45.1	45.1

Figure 5.2. Diagram representation showing the plan of the single zone model with airflow through the apertures

5.2 Multizone Model

For Multizone modelling, 4 individual zones were modelled as shown in Figure 5.3. Each individual zone had length, breadth and height of 4m, 3m and 3m respectively. Four windows of size 1.5m X 1m were provided for each zone.

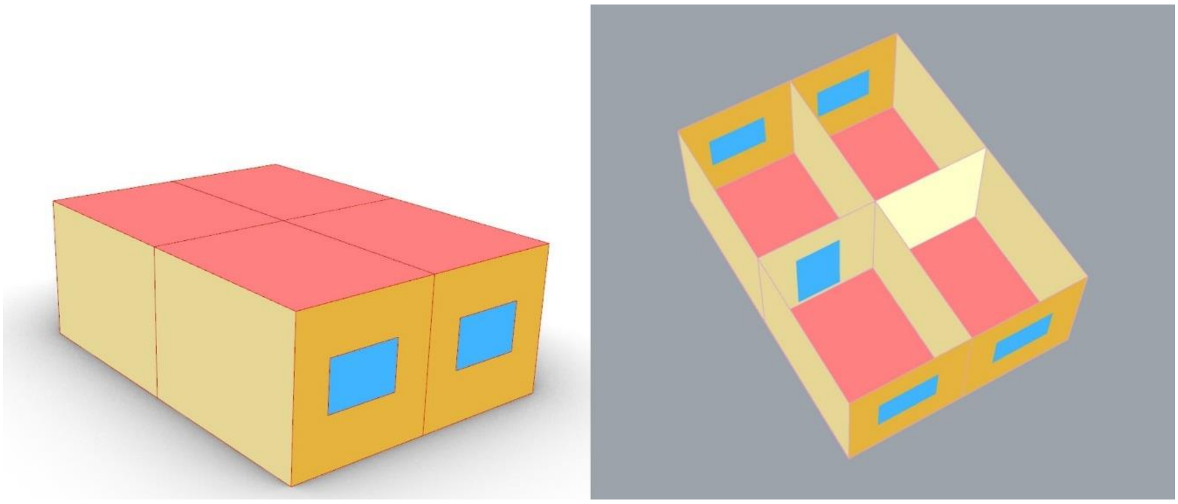


Figure 5.3. Multizone model with four zones for testing. Each zone having an exterior window. Two zones are connected by an internal aperture and the other two zones are connected by airwall.

The opening schedule for the apertures were similar to the single zone model. To study the air boundaries and interior apertures, two zones were connected with air boundary while the remaining two zones were connected with an interior aperture as shown in the figure. The air boundary feature is to ensure that there is an open boundary between zones. When an air boundary is used in the honeybee model, it is defined as a crack on the zone surface acting as an air boundary with large pressure coefficients. These pressure coefficients are determined using the orifice equation and the area of the surface to ensure mixing between the zones.

The volumetric airflow through the apertures were obtained from the simulations. Table 5.2. Volume air flow rate through the apertures for a multi zone test model with four operable exterior windowsTable 5.2 shows the results for a set of time steps of one hour each. It shows that there is balance in air coming in and going out of the zones. A schematic representation of the same for the first and the last timesteps from the above table can be seen in Figure 5.4.

As a user input, the percentage of the window's operable area is specified. When simulations are executed, Energyplus also multiplies the operable window area by an opening factor. Energyplus determines the opening factor based on a combination of multiple factors when the ventilation schedule is activated. The opening factor for this simulation is provided in Table 5.3 below.

Table 5.2. Volume air flow rate through the apertures for a multi zone test model with four operable exterior windows

Connected by interior aperture				**Connected by airwall**					
Aperture 1		**Aperture 2**		**Aperture 3**		**Aperture 4**			
Vol. Flow Rate from node 1 to node 2 [l/s] {1}	**Vol. Flow Rate from node 2 to node 1 [l/s] {2}**	**Vol. Flow Rate from node 1 to node 2 [l/s] {3}**	**Vol. Flow Rate from node 2 to node 1 [l/s] {4}**	**Vol. Flow Rate from node 1 to node 2 [l/s] {5}**	**Vol. Flow Rate from node 2 to node 1 [l/s] {6}**	**Vol. Flow Rate from node 1 to node 2 [l/s] {7}**	**Vol. Flow Rate from node 2 to node 1 [l/s] {8}**	**Volume of air coming in [l/s] {2+4+6+8}**	**Volume of air going out [l/s] {1+3+5+7}**
9.3	9.3	3.1	3.1	6.3	6.2	9.3	9.3	28.1	28.0
8.8	8.7	0.0	0.0	8.8	8.9	5.9	5.7	23.4	23.3
16.7	16.6	11.3	11.2	13.6	13.8	11.1	11.0	52.7	52.7
46.5	8.7	0.0	37.7	46.1	2.8	0.0	43.2	92.6	92.5

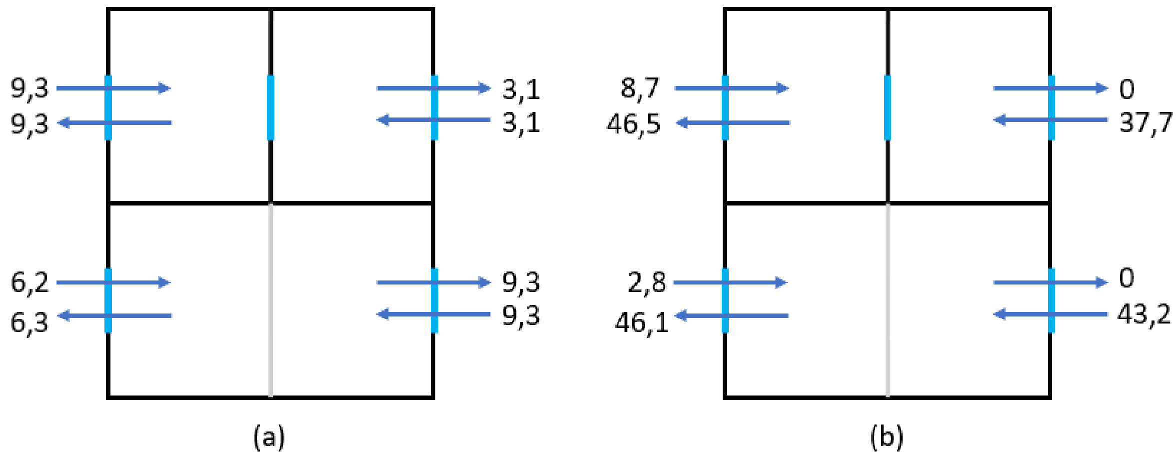


Figure 5.4. Top view diagram representation of airflow through the apertures for a multizone mode where two zones are connected by a window and two zones are connected by an airwall. (a) represents the first timestep from table 4.2 and (b) represents the last timestep from the table 4.2.

Table 5.3. Opening Factor of the apertures for two zones connected by interior aperture in the multizone model

Opening factor for Interior aperture	Opening factor for Aperture 1	Opening factor for Aperture 2
0.0	0.0	0.1
0.1	0.1	0.1
0.1	0.1	0.2
0.2	0.2	0.2

Since the control for the windows are zone based and not surface based, it is not possible to assign separate controls for the windows through Honeybee unless additional codes are added to edit the Input Data Format (IDF) file of EnergyPlus which requires advanced knowledge in EnergyPlus simulations. Hence all apertures in the zones are given the same control based on temperature as mentioned.

5.3 Chimney Model

For the purpose of understanding stack modeling in honeybee, a chimney was modeled over the zone with a single window on the facade. The zone had the same dimensions as the single zone model. The chimney cannot be modelled as a cylinder. Hence it was also modelled as a rectangular zone assuming that the material has a very low conductivity to ensure there is no heat exchange between the chimney and the surrounding. The chimney had dimnesions of 0.2m by 0.2m. The roof and chimney are joined by an airwall. Two models were evaluated, one with windows on all four walls of the chimney, as depicted in Figure 5.5, and the other with windows on only one wall of the chimney. The initial approach was to add skylights to the top, but the skylights couldn't be installed on the roof's horizontal surface. Energyplus restricts the installation of windows on horizontal surfaces. However, if the surface is slightly sloped, windows and skylights can be placed. By placing a skylight on a tilted surface, the results showed lower values than the expected values as calculated using equation 2.2. Hence it was decided to run the simulation replacing the skylight on the roof of the chimney with small windows of 0.19m x 0.19m on the walls of the chimney at the top.

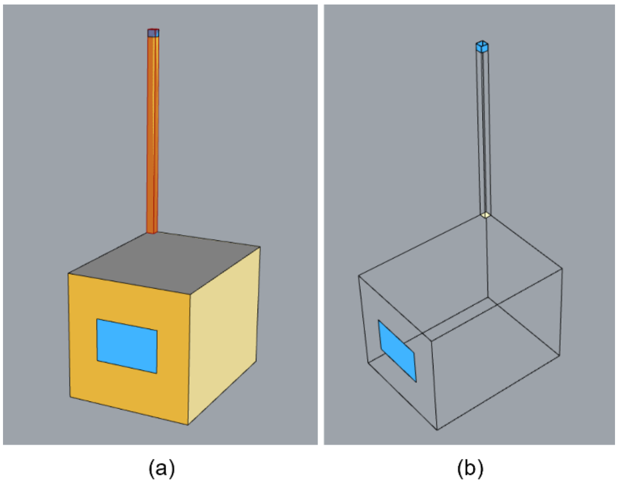


Figure 5.5. (a) Chimney with four windows connected to a zone with a single window on the facade. (b) shows the airwall connection with the roof and the apertures on the zone and the chimney.

With each model, simulations were conducted. In one test, only 10% of the window in the room was opened, whereas in the other, 90% of the window was opened. To examine the effects of stack alone, these simulations were executed with the same weather file, but without wind.

Simulations were run initially with the operable area of the window set to 10% of the total glazed surface. It was found that the air change rate had increased when the chimney with 1 window was used. Further, when the chimney with four windows were used, there was a greater air change rate as shown in Figure 5.9. The temperature also reduced when the chimney with 1 window was added. The lowest temperatures were visible with the chimney having four windows at the outlet. These temperature variations can be seen in Figure 5.7

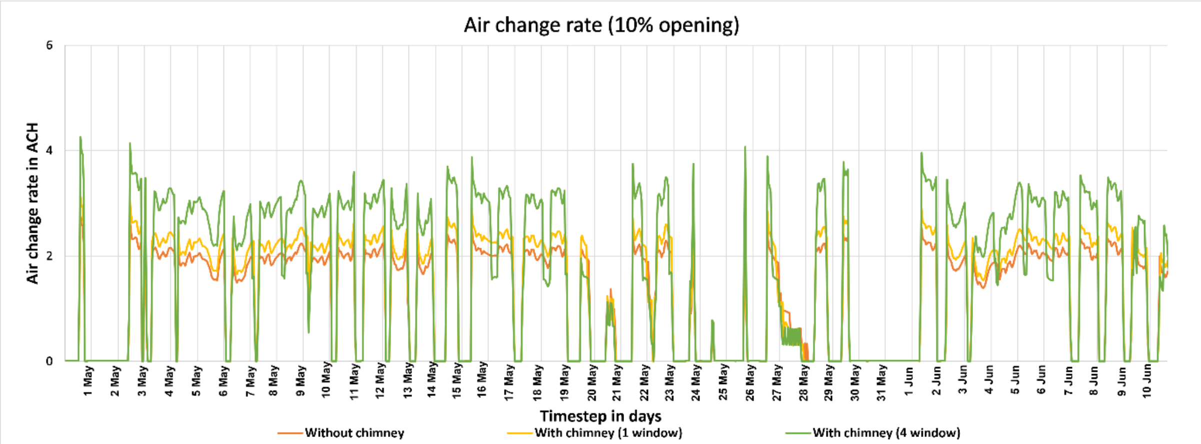


Figure 5.6. Graph showing the variation in the air change rate when simulations were run with chimney and 10% of the window in the room was considered operable.

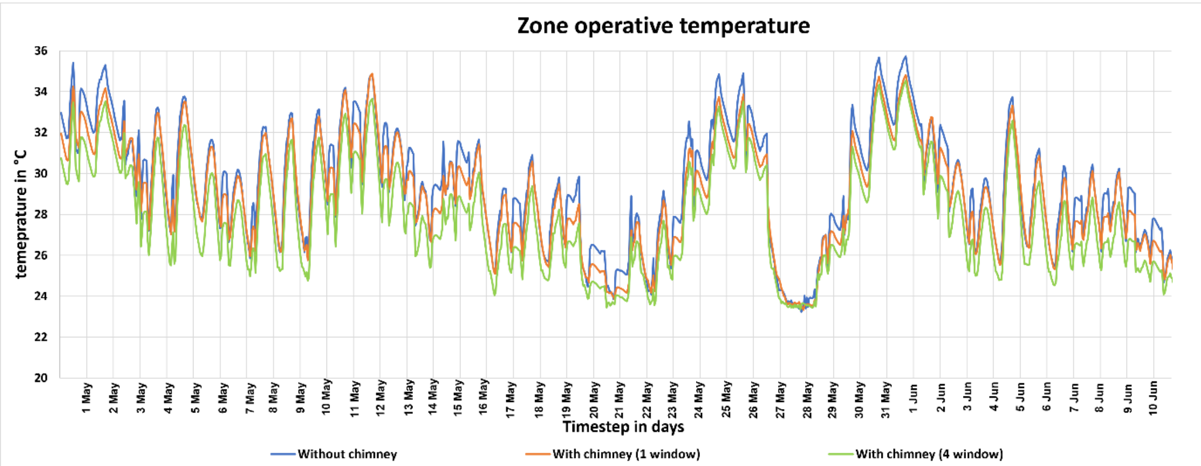


Figure 5.7.Graph showing the variation in the zone temperature when simulations were run with chimney and 10% of the window in the room was considered operable.

When the operable area of the window in the room was 90%, the results for the temperature and air change rate obtained from the simulation are as shown in Figure 5.8. The airflow through the window in the room dominated the flow through the chimney, hence not much effect of the chimney was visible. The results showed that chimney is most effective when paired with the simulation were the windows in the room had only 10% of the total glazed surface as operable. The number of hours when the temperature is greater than 28°C was calculated for all cases. It can be seen in Table 5.4.

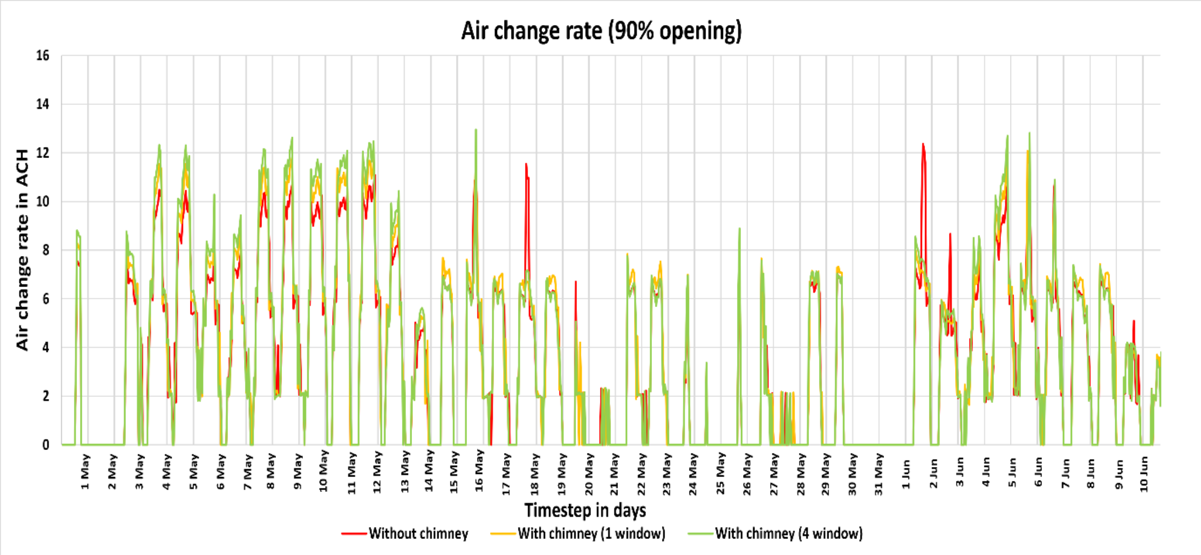


Figure 5.8. Graph showing the variation in the air change rate when simulations were run with chimney and 90% of the window in the room was considered operable.

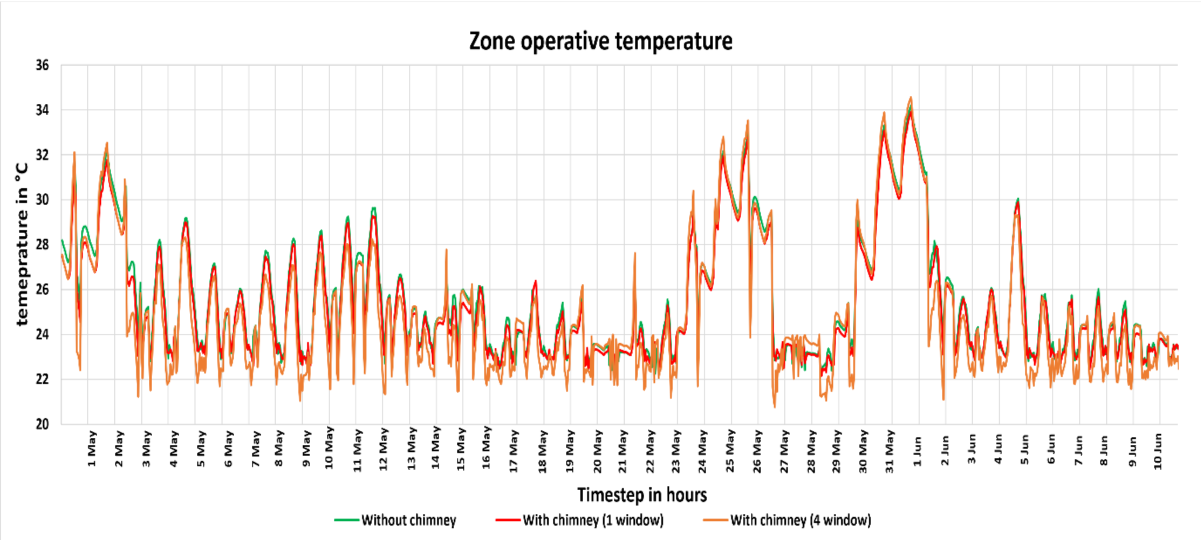
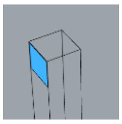
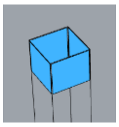


Figure 5.9. Graph showing the variation in the zone temperature when simulations were run with chimney and 90% of the window in the room was considered operable.

Although the simulations were run without wind, there was significant airflow happening through the window in the room. This could be because Energyplus considers the pressure difference caused by the wind and also that by stack while calculating the airflow. Since the window in the room was considerably large (1.5m x 1m), there was also stack effect coming in to play while considering the airflow.

Table 5.4.Test Model chimney calculation results showing the number of hours the temperature in the room was above 28 for the different simulation cases involving chimney

No. of hours the temperature rose above 28°C (all values in this table are in hours)	**no chimney**	**chimney with 1 window** 	**chimney with 4 windows** 	**% reduction achieved with chimney having one window**	**% reduction achieved with chimney having four windows**
zone windows open 10%	2233	819	629	63.3	71.8
zone windows open 90%	429	395	387	7.9	9.8

6. Results and Discussion

6.1 Window Ventilation

6.1.1 Indoor Temperature

The simulations performed to assess the impact of opening windows on indoor temperature yielded the following results. The operational temperature decreased in all three apartment cases. The simulation results obtained for medium heavy construction will be discussed here. Similar pattern was also noted for light and heavy building types. The temperature results obtained for living rooms are discussed in the results since it has the highest internal heat loads and in most cases larger glass ratio leading to higher temperatures inside. For the corner and center apartments of type 1, tilt-and-turn windows are utilized. Therefore, there are two window-opening positions. Each position has been simulated. The gallery apartments feature awning windows with one opening position. As can be seen in Figures 7.1 and 7.2, the decrease was more pronounced in the corner and center apartments of typology 1. Additionally, the gallery apartments had a lower operative temperature than the other two apartments. When numerous instances of temperatures exceeding 24°C were recorded in Typology 1 apartments, the gallery apartment experienced comparatively less temperature increases above 24°C. This could be because the gallery apartments have an overhanging roof that provides significant shading, resulting in less solar energy penetrating the interior and, consequently, a lower internal heat gain and temperature. The temperature setpoint for opening windows was 24°C and this requirement was not met most of the time, hence, it is only fitting that the temperature reduction from opening windows in the gallery apartments is lower than the other apartments.

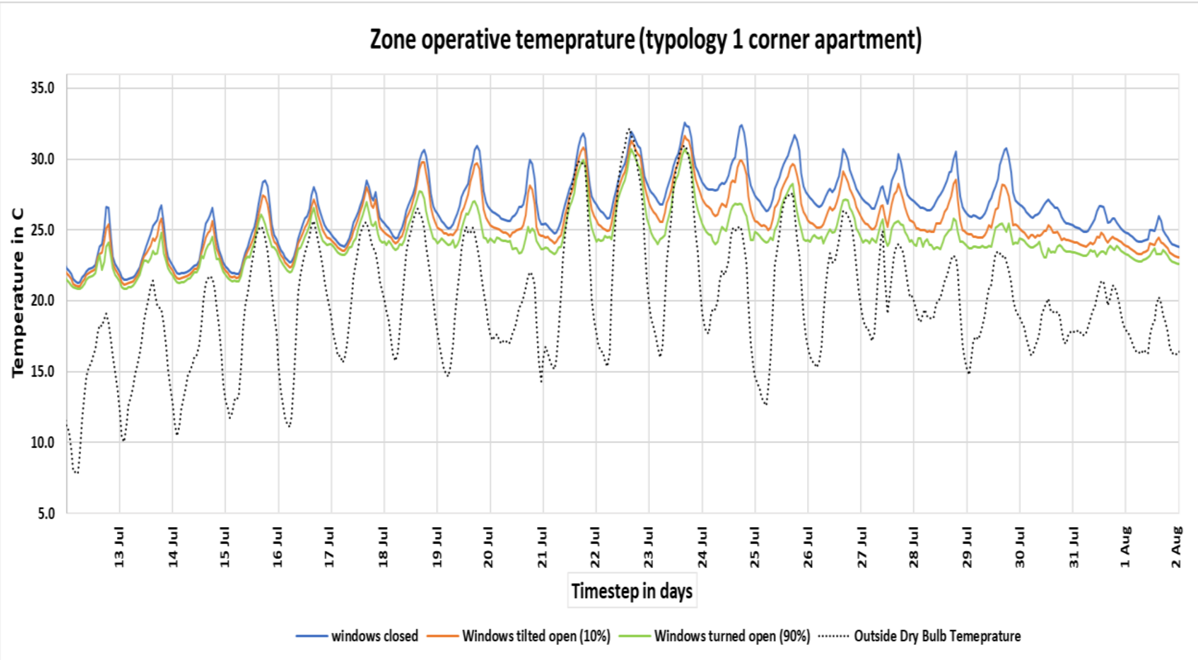


Figure 6.1. Zone operative temperature of corner apartment for three cases. The blue line represents the zone temperature when the windows are closed for the whole time. The orange line represents the zone temperature when the windows are opened in the tilt position where only 10% of the glazed surface is open. The green line represents the window open in turned position where 90% of the glazed area is available for ventilation. The dotted grey line represents the outdoor temperature. (full graph in Appendix D)

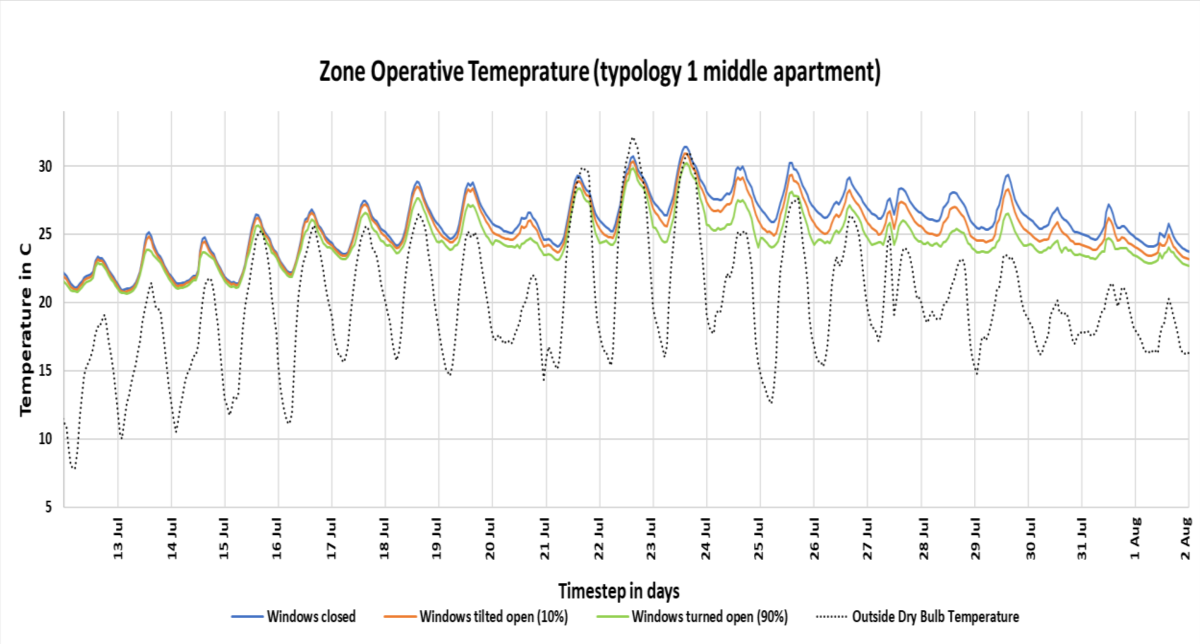


Figure 6.2. Zone operative temperature of center apartment for three cases. The blue line represents the zone temperature when the windows are closed. The orange line represents the zone temperature when the windows are opened in the tilt position where only 10% of the glazed surface is open. The green line represents the window open in turned position where 90% of the glazed area is available for ventilation. (full graph in Appendix D)

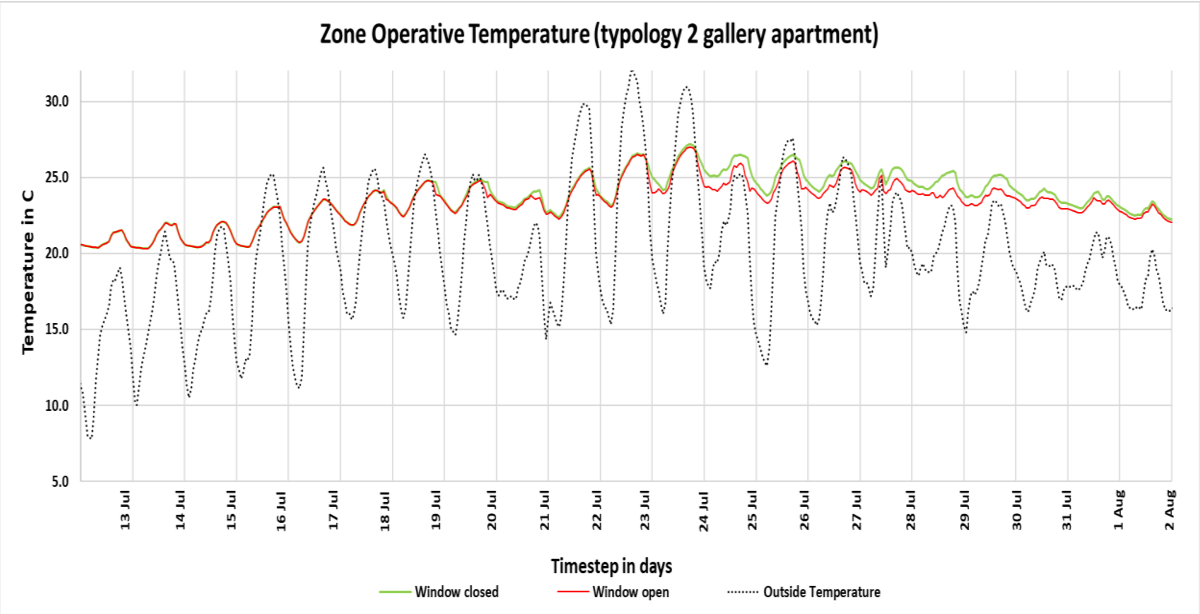


Figure 6.3. Zone operative temperature of gallery apartment for three cases. The blue line represents the zone temperature when the windows are closed for the whole time. The orange line represents the zone temperature when the windows are opened. (full graph in Appendix D)

6.1.2 Air change rate in apartments

The windows were opened in accordance with the temperature thresholds. The simulation revealed that the temperature control setpoints refer to the air temperature of the zones rather than the operational temperatures. The rate of air change obtained in the living room by opening windows in various simulations is discussed here. When the corner apartment's windows were opened in the tilt position, the air exchange rate was below 5 ACH, indicating a healthy ventilation rate. When open in the turn position, a greater air change rate was observed. The value occasionally reached 33 ACH. This is visible in the graph depicted in Figure 7.4. According to England and Wales' building regulations, there should be enough openable windows to allow for 4 air changes per hour [39]. For various levels of window opening, the UK Standard Assessment Procedure (SAP) for rating the energy performance of dwellings gives details about the air circulation rates that can be assumed [40]. When windows are fully open in rooms in two or more storey dwellings where cross ventilation is possible, the maximum effective air change rate is 8 ACH.

In general, the air change rate observed in the apartment in the center was lower than in the apartment in the corner. When the windows were opened in the tilt position, the air change rate was extremely low, less than 0.5 ACH. During certain days, a maximum of 3 to 3.5 ACH is obtained when windows are opened in the turn position. Although both apartments have the same number and almost same size of windows, this difference in ACH values may be due to the following factors discussed here. Firstly the volume of the zone in the corner apartment is 228 m^3 and the center apartment is 267 m^3. Furthermore, cross ventilation is possible in the corner apartment due to windows on both the south and west-facing facades. While only single-sided ventilation is possible for the center apartment in the building. This is the important distinction between the apartment models. Furthermore, in De Bilt, the wind comes primarily from the south and southwest. These two variables may have affected the natural ventilation air flow rate into the model apartment. Figure 7.5 depicts the wind direction and speeds, as well as the simulated apartment models for the analysis.

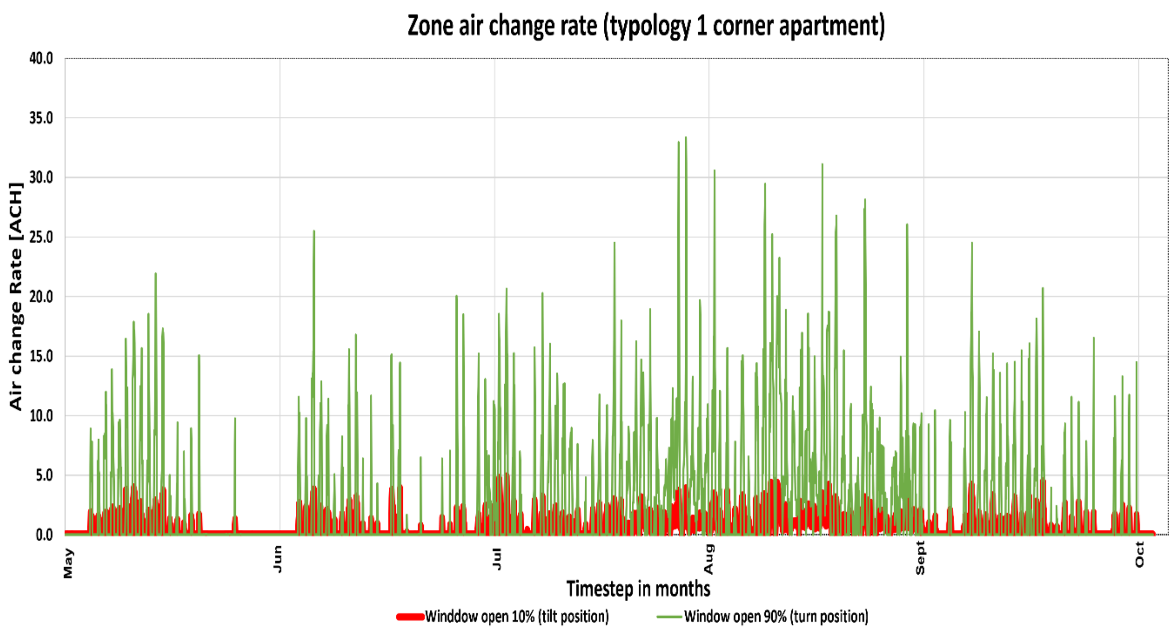


Figure 6.4. Graph showing the air change rate in the living room for the corner apartment when the windows are opened in the two positions.

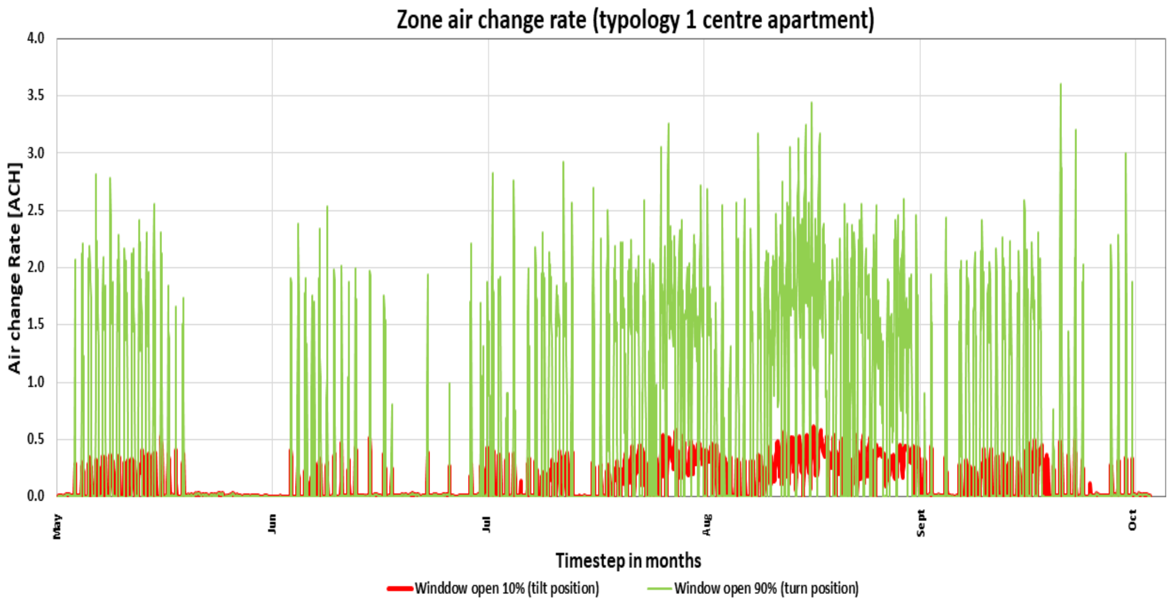


Figure 6.5.Graph showing the air change rate in the living room for center apartment when the windows are opened in the two positions.

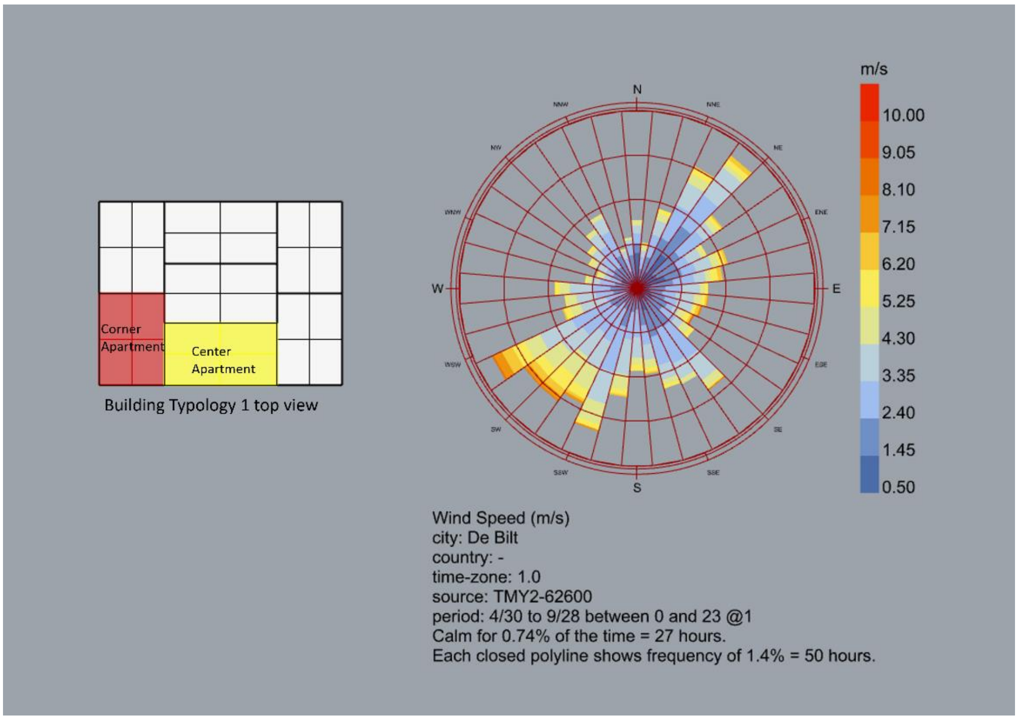


Figure 6.6. Wind rose diagram for the DE Bilt site along with the building typology 1 apartments used for simulation shown.

As previously mentioned, the gallery apartments had already lower indoor temperatures. Consequently, windows were only opened intermittently throughout the duration of the simulation. This is demonstrated by the graph in Figure 7.7. When windows were open, an average air change rate of 13 ACH was observed.

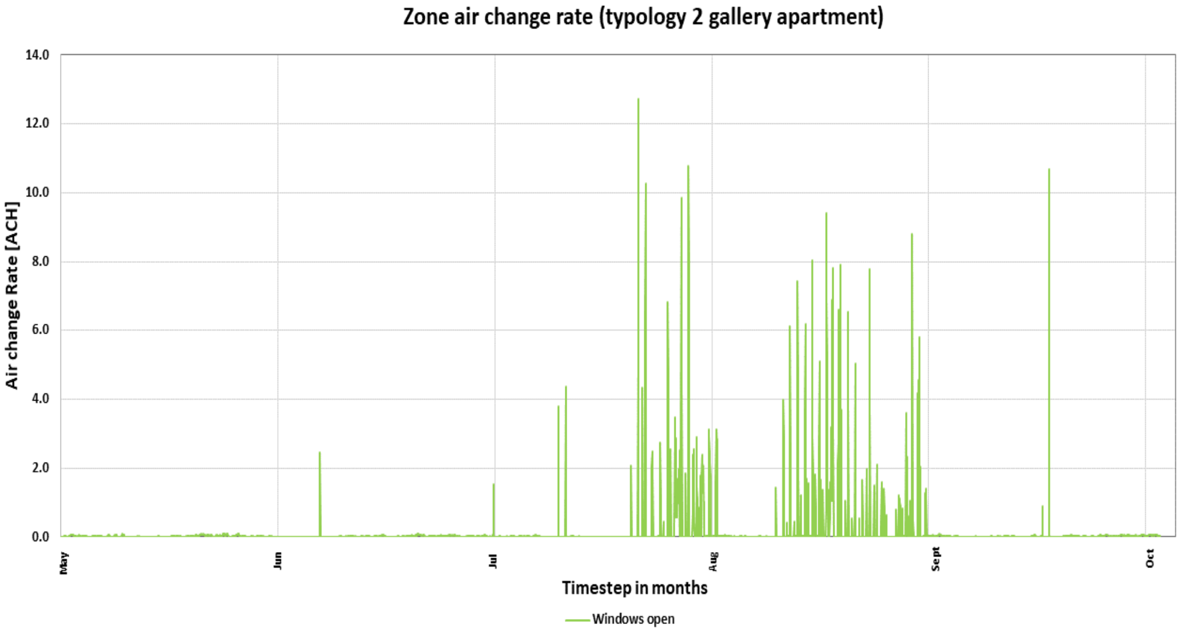


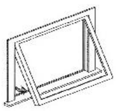
Figure 6.7. Graph showing the air change rate in the living room for the gallery apartment when the windows are opened.

6.1.3 Temperature exceedance

For the calculation of temperature exceedance, the living room air temperature results from multiple simulations for all three apartments are examined. The living area and the kitchen have the greatest heat gain (people, lighting and equipment). Table 7.1 provides an overview of the obtained results . As can be seen, when the windows in the corner apartment were opened in the tilt position, the number of hours exceeding 28°C decreased by approximately 40 to 50 percent compared to when the windows were completely closed for all thermal masses. When the windows were fully opened, there was a 70 percent reduction. When the center apartment's windows were opened in a tilted position, there was a 20 percent reduction and when they were opened fully, there was a 50 percent reduction. T the gallery apartments on the other hand had fewer than 100 hours of temperatures exceeding 28°C. Another observation made was that, with the increase in thermal mass there was a general decrease in the hours of temperature exceedance. Temperature exceedance hours for bedrooms in these apartments can be seen in Appendix E.

Table 6.1. Table showing the number of hours the temperature exceeds 25°C and 28°C in the living room.

		Window type	Thermal mass	Window opening (free area in m^2)	No. of hours with temperature above 25°C	No. of hours with temperature above 28°C
Typology 1	Corner Apartment	Tilt and turn 	Light	Closed	1510	658
				Open tilt position (0.121 m^2)	897	389
				Open turn position (1.1 m^2)	489	165
			Medium heavy	closed	1355	515
				Open tilt position (0.121 m^2)	794	311

		Window type	Thermal mass	Window opening (free area in m²)	No. of hours with temperature above 25°C	No. of hours with temperature above 28°C
				Open turn position (1.1 m²)	473	152
			Heavy	closed	1336	485
				Open tilt position (0.121 m²)	905	213
				Open turn position (1.1 m²)	474	146
	Center Apartment	Tilt and turn 	Light	closed	1389	552
				Open tilt position (0.121 m²)	1067	428
				Open turn position (1.1 m²)	648	230
			Medium heavy	closed	1245	436
				Open tilt position (0.121 m²)	961	316
				Open turn position (1.1 m²)	603	176
			Heavy	closed	1253	319
				Open tilt position (0.121 m²)	958	288
				Open turn position (1.1 m²)	592	164
Typology 2	Gallery Apartment	Awning window 	Light	closed	536	81
				Open (0.216 m²)	312	53
			Medium heavy	closed	352	16
				Open (0.216 m²)	235	5
			Heavy	closed	304	4
				Open (0.216 m²)	219	0

6.1.4 GTO hours

Buildings must have a TO_{July} or GTO calculation to ensure that the number of overheating hours is well below the allowed maximum. The weighted overheating hours calculated by the GTO should not exceed 450 hours. The Table 6.2 below displays the simulation-based GTO calculated values. Prior to this chapter, the validity of the GTO hours was discussed. The GTO hours decreased significantly when the windows were opened for day and night ventilation. It also decreased as the thermal mass of the structure increased. When the windows in the corner apartments were fully opened, the GTO hours decreased by approximately 70-80% compared to when they were closed. Already, the gallery apartments appeared to be doing well, as the GTO hourly values were well below 450 even in the scenarios when the windows were closed. With the opening of the windows, the GTO hours decreased even further.

Table 6.2. GTO calculation results from the simulations

Apartment Type	Thermal Mass	Window opening condition	GTO [hours]
Corner Apartment	Light	closed	3800
		tilt open	1860
		turn open	728
	Medium heavy	closed	2307
		tilt open	1064
		turn open	465
	Heavy	closed	2068
		tilt open	956
		turn open	420
Middle Apartment	Light	closed	2910
		tilt open	1895
		turn open	895
	Medium heavy	closed	1815
		tilt open	1057
		turn open	498
	Heavy	closed	1578
		tilt open	932
		turn open	432
Gallery Apartment	Light	closed	336
		open	153
	Medium heavy	closed	35
		open	13
	Heavy	closed	6
		open	0

6.1.5 CPNV, NVCE and CPUR

As described in section 3.6, the parameters used to determine the cooling effectiveness of natural ventilation are simulated. This performance indicator measures the amount of cooling accomplished via natural ventilation. Since this equation represents a steady state (Equation 3.3), thermal mass variations are disregarded. The only significant variable is the amount of air that enters through the windows. Variations in thermal mass have no impact on the Natural Ventilation Cooling Effectiveness value (NVCE). The NVCE parameter is primarily impacted by the volumetric airflow rate from the windows, the internal heat gains, and the local climate. Climate Potential for Natural Ventilation (CPNV) is calculated in accordance with the adaptive comfort model in EN 16798 for this thesis. Utilizing the model, the optimal temperature range for natural ventilation was determined. The minimum outside temperature for comfort with natural ventilation was calculated to be 17°C, and the maximum was estimated to be 25°C. Consequently, all hours of the simulation period in which the outdoor temperature was within the specified limits were deemed suitable for natural ventilation cooling. The CPNV was calculated using equation 3.2 . As thermal criteria, only temperature limits were established; humidity limits were not factored into the CPNV calculation. CPNV value was calculated to be 0.4 indicating that the site conditions are suitable for natural ventilation for approximately forty percent of the time.

After determining the site conditions, the design of the structure is evaluated by calculating the NVCE, which measures the ventilation potential of the building. The CPUR, on the other hand compares how much of the site's potential the building design is utilizing. The building had a very low NVCE of 0.1, with the value rising to 0.2 in some cases (corner apartment with 90 percent of its windows open). Comparing NVCE and CPUR for the gallery apartment, the building design is only able to utilize 10% of the site's Natural ventilation potential. It is possible to modify the design to improve the CPUR by increasing the airflow rate. For the corner apartments, however, the design makes use of fifty percent of the site's natural ventilation potential. This indicates that although the NVCE is 0.2, the site is already utilizing fifty percent of its potential since the CPUR is 0.5. It is still possible to modify the design to increase the NVCE. Even though the corner and center apartments have the same number and type of windows, the NVCE is significantly different. This is because the volumetric airflow rate through the corner apartment's windows is considerably greater than that of the middle apartment. One of the reasons for this is that the corner apartment has two facades, one facing south and the other west. With windows on both facades, cross ventilation is also attainable. While the entire facade of the apartment in the center faces south and all windows are on one facade, leading to only single-sided ventilation.

A value of 1 for the NVCE indicates that cooling can be achieved through natural ventilation alone. So an effort should be made to achieve an NVCE value of 1 However, if the site's potential is limited, there will be limitations on how much NVCE can increase in value.

Table 6.3. Results for CPNV,NVCE and CPUR from the simulation.

Apartment Type	Thermal Mass	Window operable area	NVCE	CPUR
Corner Apartment	Light	tilt open	0.1	0.2
		turn open	0.2	0.5
	Medium Heavy	tilt open	0.1	0.2
		turn open	0.2	0.5

Apartment Type	Thermal Mass	Window operable area	NVCE	CPUR
	Heavy	tilt open	0.1	0.2
		turn open	0.2	0.5
Centre Apartment	Light	tilt open	0.1	0.2
		turn open	0.1	0.3
	Medium Heavy	tilt open	0.1	0.1
		turn open	0.1	0.3
	Heavy	tilt open	0.1	0.1
		turn open	0.1	0.3
Gallery Apartment	Light	open	0.1	0.2
	Medium Heavy	open	0.1	0.1
	Heavy	open	0.1	0.1

6.1.6 Cooling Requirements Reduction Ratio

The cooling energy computed for this simulation was the amount of heat energy that must be removed from the zone to achieve the desired required temperature. A cooling system was not included in the simulation. The temperature at which the living room's cooling system is assumed to be activated was set to 26°C. The following Table 6.4 illustrates the varying cooling energy requirements. Generally, there was a reduction of 18-20% in the cooling energy requirement for corner apartments when the windows were fully opened. Similarly, the cent apartments showed a decrease of around 11% and the gallery apartments showed a decrease of 5-8% in the cooling energy requirement.

Although the values in the table provide an indication of how cooling energy requirement varies, it was observed during simulations that when the window was open and the temperature inside the living room was above 26°C, the cooling energy required to remove that extra heat to bring down the temperature to 26°C was also calculated. In these instances, the outdoor temperature was lower than the indoor temperature, but both were above 26°C. This is because during the simulation, windows are permitted to open as long as the difference in temperature between the interior and exterior is greater than +1°C (positive one to ensure that there is no situation when the window opens when the temperature inside is lower than the temperature outside), the outdoor temperature is above 13°C and the indoor temperature is above 24°C.

Table 6.4. The cooling energy requirement for the living rooms in the apartment simulations

Apartment Type	Thermal Mass	Window operable area [%]	Cooling Energy living room [kWh]	% reduction from the closed scenario
Corner Apartment	Light	closed	507.1	
		tilt open	479.5	5.4
		turn open	404.5	21.4
	Medium	closed	442.5	
		tilt open	421.0	4.9
		turn open	360.8	18.5
	Heavy	closed	430.5	
		tilt open	410.2	4.7
		turn open	352.4	18.1
Middle Apartment	Light	closed	436.0	
		tilt open	429.2	1.5
		turn open	386.9	11.3
	Medium	closed	377.7	
		tilt open	372.4	1.4
		turn open	333.9	11.6
	Heavy	closed	361.6	
		tilt open	356.9	1.3
		turn open	319.7	11.6
Gallery Apartment	Light	closed	37.9	
		open	35.8	5.5
	Medium	closed	15.9	
		open	14.6	8.2
	Heavy	closed	10.0	
		open	9.3	6.6

6.2 Stack Ventilation

Simulations were performed after fitting a chimney of size 0.2m by 0.2m on the center apartment with single sided ventilation for checking if there was any difference in the temperature. For this simulation, the apartment was modelled on the ground floor so that the chimney can have a good height difference between the inlet and outlet.. Due to the fact that the building has five stories, the stack was constructed at a height of 12 meters in order to cover the entire building and have an outlet just above the roof. All four walls of the chimney had windows at the top of size 0.19m by 0.19m acting as outlet. The temperature control for window openings of the chimney was similar to that of the living room. The window opening temperature setting was 24°C. The windows of the chimney could not be controlled based on the temperature of the living room. The control was based on the air temperature in the chimney. The connection between the apartment roof and the chimney was an airwall, so there is little flow resistance. As previously performed simulation on the shoe box model in section 4.3 showed that the effect of chimney reduces when the windows are completely open, the simulations were conducted with the windows open in the tilted position (10% of the total glazing area is operable). This was done to ensure that airflow through the windows does not dominate the stack effect. After running simulations, it was found that the chimney did reduce the indoor temperature but the reduction was not very significant. Table 6.5 below shows the number of hours the temperature was above 28°C with and without the use of chimney. Figure 7.8 depicts a graph showing the indoor temperature variations with and without chimney displaying the same information. If the diameter of the chimney is increased, the flow rate will increase and temperature reduction will be enhanced. However, this is impractical and therefore not particularly useful for apartment models.

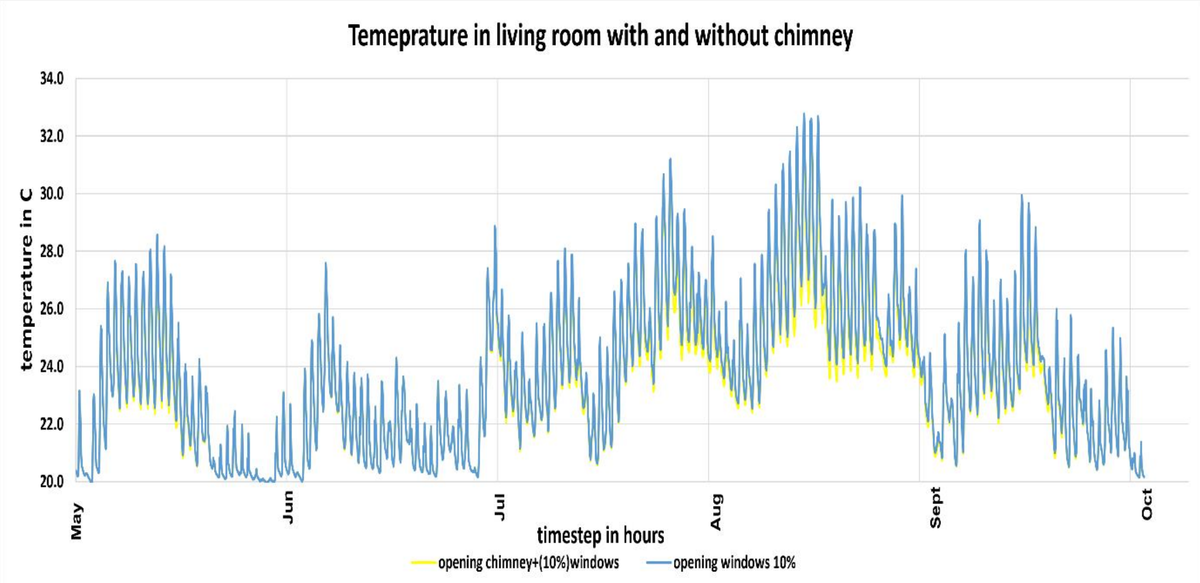


Figure 6.8. Temperature in the living room when the chimney of 0.2m by 0.2m in size is used.

Table 6.5. Shows the number of hours during which the temperature rose above 28°C

No. of hours temperature is above 28°C when opening windows 10%	349
No. of hours temperature is above 28°C when opening windows 10% and using chimney	298
% reduction while using chimney	14.6

7. Validation

The GTO calculations were used for the validation check. The GTO hours simulated using Grasshopper was checked with the GTO values obtained from VABI Elements simulation. VABI is generally used for performing GTO calculations in projects across the Netherlands. Since the grasshopper script remains largely the same with variations in the geometry for different apartments, only one model was checked to see if the results obtained from VABI are close to the results obtained by airflow network simulation. Since dynamic simulation of window opening as per criteria definition is not possible to do in VABI, the simulation was tested for a corner apartment with light mass and having all windows closed. Figure 7.1 shows the geometry as created in VABI.

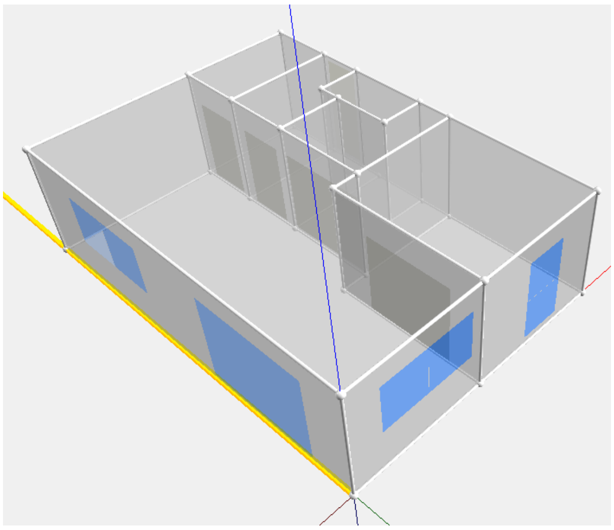


Figure 7.1. VABI geometry for corner apartment

The building simulation was set up to calculate as per TO_{July} and the weather file for GTO calculations from NEN 5060:2018 with 5% chance of exceedance was used. The simulation period was as defined earlier for the summer months also shown in Figure 7.2.

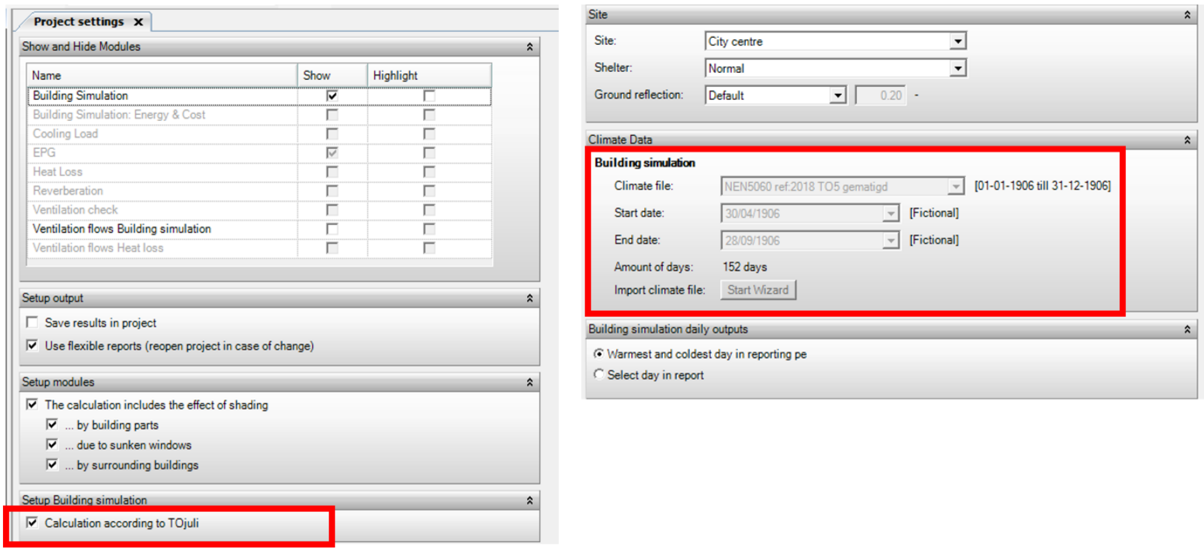


Figure 7.2. Weather file and TOjuly settings for VABI

The construction material layer for the VABI simulation and the Grasshopper simulation were slightly different. The material definition in VABI for the roof can be seen in Figure 7.3. The thermal resistance value was changed to match the grasshopper materials. The material definition for the exterior wall can be seen in Figure 7.4.

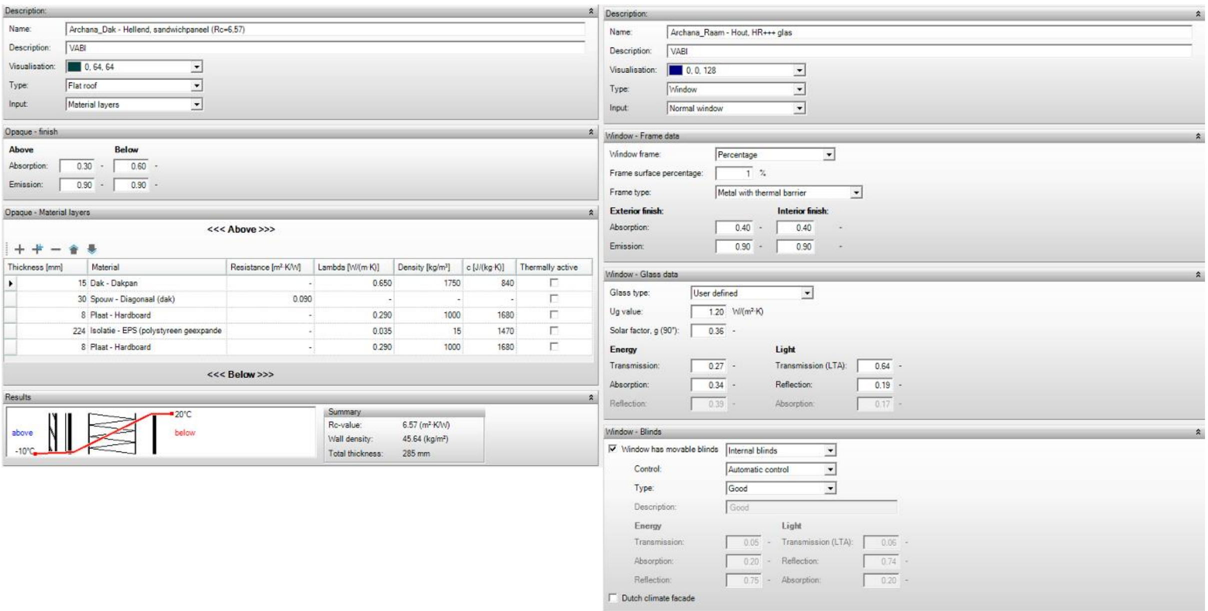


Figure 7.3. Roof material definition on VABI

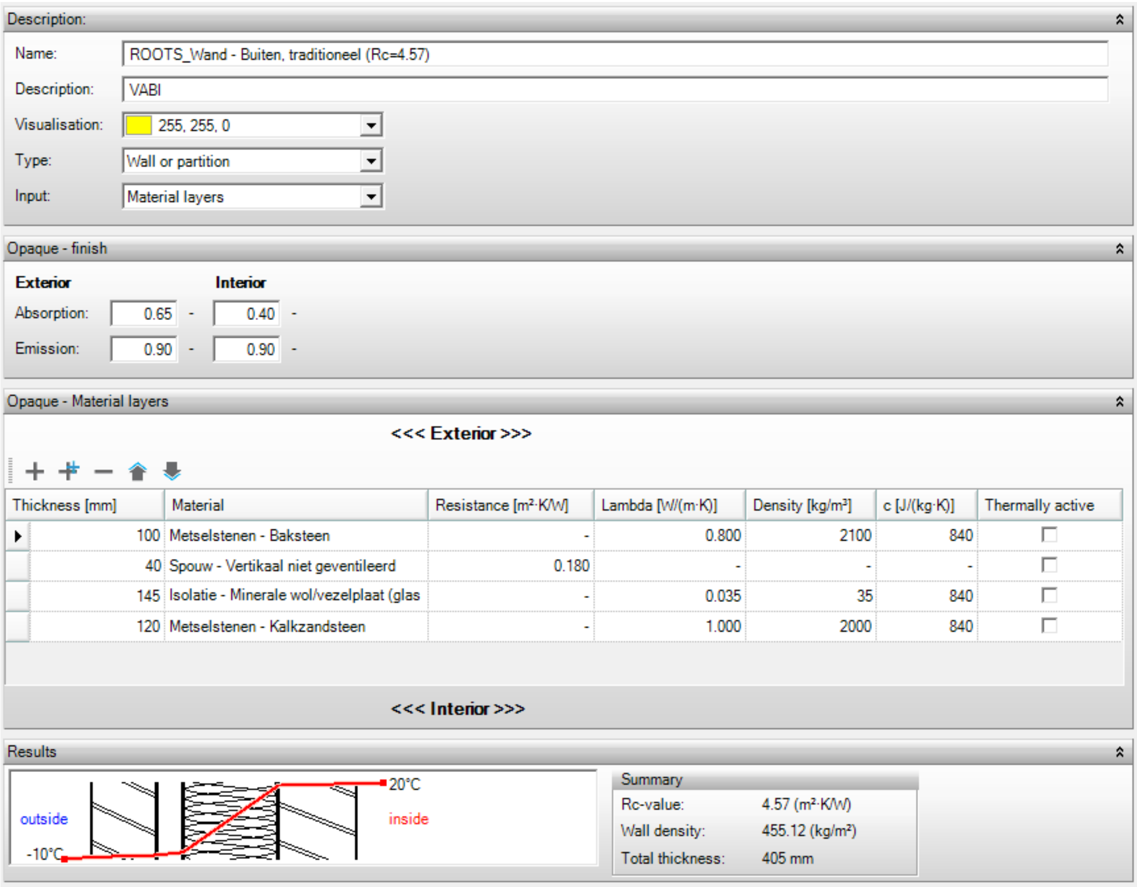


Figure 7.4. Facade material definition on VABI

A low temperature heating was provided from an external source in VABI. A constant ventilation rate of 0.9l/s was maintained in the VABI simulation as shown in Figure 7.5 which is similar to the Grasshopper simulation. This was maintained in all rooms. After running the simulation, the GTO hours obtained in the living room was 3914 hours as shown in Figure 7.6. The GTO hours obtained from grasshopper simulations were 3800 hours. The results are within a 3% range of validated software used in consultancy. The difference in values could be due to the difference in the material definition and also the interior walls defined in VABI. In grasshopper the airwalls are defined instead of doors and the airflow rate through the airwalls is based on the pressure difference between the two zones sandwiching the airwall. It is not possible to model the air walls in VABI. However, the value obtained from grasshopper simulation is very close to the values obtained from simulation.

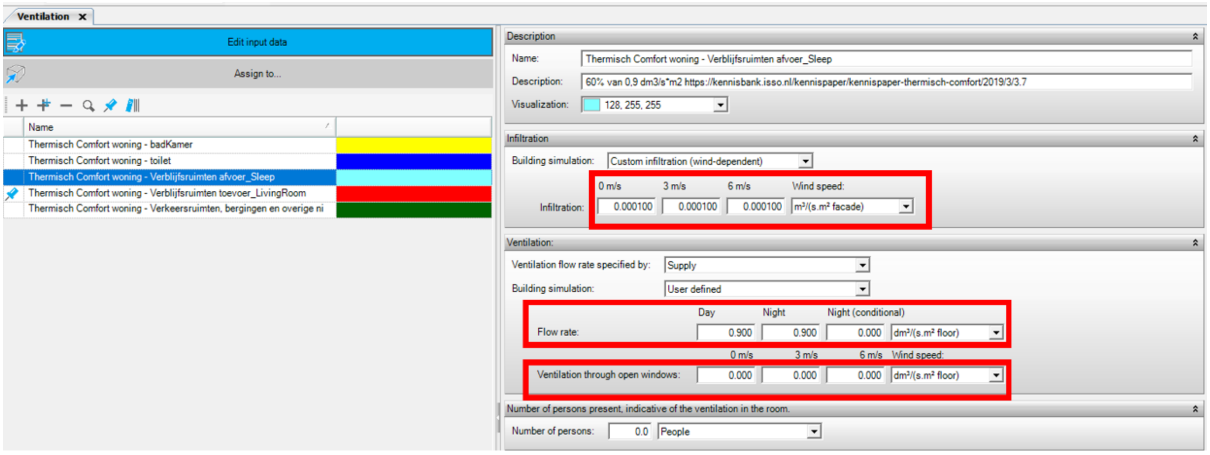


Figure 7.5. Constant mechanical ventilation rate of 0.9 l/s

Number room	Name room	Air temperature number of hours > 25 °C counted period [h]	Air temperature number of hours> 28 ° C counting period [h]	Comfort temperature number of hours> 25 ° C counting period [h]	comfort temperature number of hours> 25 ° C counting period [h]	GTO overheating number of weighting ho [h]
39	LivingRoom	2617	936	2660	925	3914
27	SleepingRoom	2230	577	2286	622	2354
49	BathRoom	1894	364	1973	414	1446
1	Entrance	1532	211	1628	242	1069
75	Storage	1457	188	1549	216	1006
71	Shaft	1124	47	1172	56	612

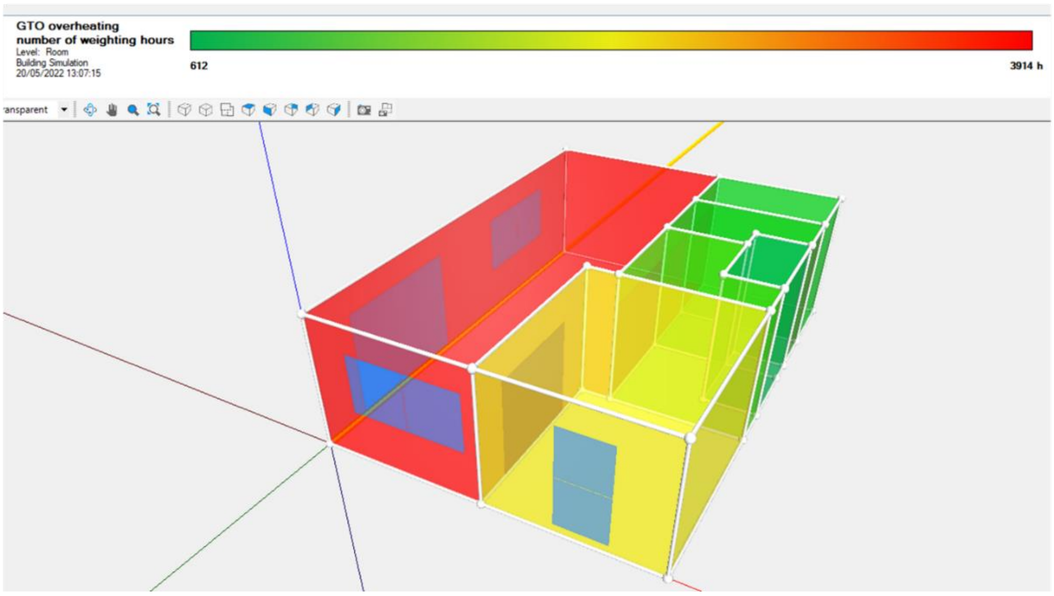


Figure 7.6. GTO hours calculated in VABI

The validation could be compared only for the condition when operable windows were closed for the apartments. When windows are opened on grasshopper, they are not completely open as per the conditions given by the user alone, but also based on certain modulation factors considered by EnergyPlus which keeps varying. However VABI doesn’t have these factors of modulation. Hence the results obtained from VABI and Grasshopper for simulation with open windows will not give comparable results for GTO hours.

8. Conclusions, Limitations and Recommendations

8.1 Answering Research Questions

The primary objective was to assess the viability of natural ventilative cooling strategies to enhance comfort and provide cooling in mid-rise apartments. This brings us back to the main research question

"What is the potential for cooling and comfort in mid-rise residential buildings in the Netherlands by adopting natural ventilative cooling strategies?"

To answer this question, two midrise apartment models in the Netherlands were modelled and evaluated for their ability to achieve better indoor temperatures through ventilative cooling strategies. The tested strategies primarily involved natural ventilation via windows and passive stack. The simulations were conducted for various thermal masses using a day-and-night ventilation strategy. The findings were encouraging:

When windows were opened, there was a significant reduction in temperature across all apartments. A decrease of number of hours exceeding 28°C in all apartments was noted when windows were used for ventilative cooling. A decrease by 70% was observed in apartments in typology 1 for all thermal masses compared to when the windows were completely closed. For typology 2 apartments, the number of hours exceeding 28°C decreased by around 30% and 70% based on the light and medium heavy thermal mass constructions used respectively. The comfort was also relatively better as there was a significant reduction seen in the GTO hours calculated when the windows were opened. GTO hours reduced by 70% to 80% when the windows were opened for apartments in typology 1 and reduced by 55% to 60% for apartments in typology 2 when the windows were opened for ventilative cooling compared to when they were closed. There was also a significant decrease in the cooling energy perceived by various apartments. The cooling requirements ratio reduced by 20% for corner apartments, 11% for centre apartments and 5% for gallery apartments. The type and size of the windows had a substantial impact on the indoor temperature. An observation made during a simulation without wind showed that when large windows are provided, the stack effect at the window opening alone provides a sufficient amount of airflow into the apartment even without the action of wind, an effect also known from literature.

Chimneys do provide a temperature reduction, but it is comparatively discreet. In the simulations performed, the resistance in the chimney was extremely low, whereas in reality it could be significantly higher. Moreover, this stack effect is not very useful for apartments in the top floor as they will not have a good height difference between the inlet and outlet to obtain good airflow rates. In addition, since different apartments will need to be connected to the stack pipe, proper calculations will be needed to measure the resistance and pressure difference in the stack to ensure proper flow through the chimney or a different stack pipe would have to be provided for different apartments which does not seem practical. The chimney dimensions are also small to induce substantial flow or air change rate.

Using the CPUR indicator, it is evident that the site has greater potential to provide natural ventilative cooling, and by modifying the window's parameters, such as its size and placement, better cooling can be achieved. None of the apartment models appeared to fully utilize the climate potential of the site for natural ventilation, indicating that the building design could be improved to further enhance the cooling effect. It is safe to conclude from these observations that natural ventilation can improve comfort and provide cooling in apartments.

Sub questions

1. What is the common typology of buildings and the present state of ventilation design in mid-rise residential buildings in the Netherlands?

There were two common residential building types for midrise structures. One where the apartments are surrounded around the core of the building and the other, gallery type buildings which have apartments arranged along a line. For buildings surrounding the core, ventilation system D with balanced ventilation and heat recovery is typically used. Thus, mechanical supply and mechanical extract are employed. Ventilation system C is frequently found in gallery apartments. This ensures natural fresh air supply and mechanical exhaust, as well as CO_2 emission control for discharge per occupied space. Ventilation system D is increasingly preferred these days due to its greater energy efficiency.

2. What strategies can be adopted for ventilative cooling in mid-rise residential buildings?

Providing operable windows for ventilation clearly improves the temperature inside the apartments. The thermal mass also plays an important role in ensuring that the temperature remains lower even when the temperature outside is shifting. Another option found in literature review, was the usage of louvres or grills for letting in fresh air. Another option is to use good external shading devices. External shading provided by the overhanging roofs in the gallery apartments significantly reduced the GTO hours. These are the natural ventilative cooling options for midrise apartment buildings.

3. What percentage of time during summer seasons is it possible to maintain indoor temperature in a comfortable range with ventilative cooling?

To evaluate this, we will consider all overheating hours as uncomfortable and the rest of the hours as comfortable. The heating system maintains the temperature at 20°C. Hence it is safe to assume that apart from the overheating hours, the remaining hours are comfortable for the residents. Overheating is defined by CIBSE as conditions in which the comfortable internal temperature threshold of 28°C is exceeded. Since the simulation is run for the summer period from 30th April to 28th September, the total number of hours the simulation is run is 3648. The table below gives the percentage of time the indoor temperature is comfortable. This table only includes the situations where the windows are fully opened. That is, the tilted open position for the tilt and turn windows has been omitted in this table.

Table 8.1. Table showing the percentage of time it is comfortable inside the buildings with the windows open

	Thermal mass	**No. of hours with temperature above 28°C**	**% of time the temperature inside is comfortable**
Corner Apartment	Light	165	95.5
	Medium heavy	152	95.8
	Heavy	146	96.0
Centre Apartment	Light	230	93.7
	Medium heavy	176	95.2
	Heavy	164	95.5

	Thermal mass	No. of hours with temperature above 28°C	% of time the temperature inside is comfortable
Gallery Apartment	Light	53	98.5
	Medium heavy	5	99.9
	Heavy	0	100.0

8.2 Limitations

The simulations carried out are applicable to the set of apartments from the discussed two typologies of buildings. For the simulations, there are simplifications done. The ventilation rates are assumed to be constant with a ventilation rate of 0.0009 m^3/s per m^2 and not a specific ventilation system (like system C or system D) is used. To implement the condition that doors between zones are always open, air boundaries are made between zones instead of internal openings. This is to ensure that the doors stayed open irrespective of the temperature within the zones.

The difference in the types of windows are based in the operable area that is available for ventilation. Tilt and turn windows had different percentages of glazed surface considered to be operable based on their opening positions (tilt open – 10% glazed surface is operable, turn position – 90% is operable).Similarly, for awning windows, the free vent area considered when the windows are completely open is only 75% of the total area of glass.

For chimney simulations, windows could not be provided on the roofs connecting the room and chimney, instead air walls are provided. Hence there is no control for the air flowing into the chimney and there is no means to control air flowing through airwall based on temperature of the room. It is assumed to be always open.

From a practical point of view, opening windows also poses the risk of burglary attack. Although insect screens are considered, the problem of dust accumulation from outside could also discourage users from opening windows.

8.3 Recommendations

Future investigations can also include the following areas:

1. This thesis focused on the natural ventilative cooling aspect. It is also possible to improve comfort by increasing the mechanical ventilation flow rate only by the use of fans. This aspect can be a good influencing factor in the thermal environment. Combining both mechanical and natural ventilative cooling can be studied

2. The windows in this model were controlled at the zone/room level. Butterfly, a new grasshopper plug-in enabling surface control of windows has been released. This enables the user to input control parameters at the window level. So different windows in the same room can have different set of controls. This is beneficial in study especially if different window types are used in the same room.

3. The influence of the changing temperature and the limitations it will impose on the use of outside air for ventilative cooling is an intriguing area of study as the global temperature continues to rise.

4. CPNV, NVCE, and CPUR are used as performance indicators in this thesis. These indicators can be used to evaluate the effectiveness of a design for cooling by natural ventilation. Applying these to check different window types and sizes and their effective cooling would be helpful to come up with better designs for window construction for apartment buildings.

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Appendix A: Ventilative Cooling Building Components

There are a variety of components available in the market for ventilative cooling design. They have been grouped into the following for better understanding. The ventilative system design is a combination of the various components available to enhance the cooling in the building.

Table A.0.1. Ventilative cooling components

Functionality	**Component**
Airflow Guiding Components	Windows, Roof lights, Doors Dampers, Flaps, Louvres Special Effect Vents
Airflow Enhancing Ventilation Components	Chimney, Atria Venturi Ventilators, Wind Towers, Wind Scoops
Passive Cooling Building Components	Convective Cooling Components, Evaporative Cooling Components, Phase Change Cooling
Control and automation	Chain Actuators, Linear Actuators Rotary Actuators, Sensors

Table A.0.2. A few advantages and Disadvantages of using the airflow guiding components and airflow enhancing components

	Components	**Advantage**	**Disadvantage**
Air Flow Guiding Components	Windows, Roof lights, Doors	Familiar to Occupants High ventilation Capacity Night Flush Ventilation which requires air change rate of 5 or higher are easier to attain	Issues of particle and noise Security issues Careful consideration for conflict free integration of actuator options and blinds
	Damps, Flaps, Louvres, Grills	Useful to control airflow within building	Heat loss and draft problems when used on facades Can cause excessive air infiltration

	Slot Vents	Provides Minimum fresh air rate	Draft risk at lower outdoor temperatures during winter and excessive air flow in connection with wind occurrence Night Ventilation: challenges to attain a high airflow Noise protection issues
Air Flow Enhancing Components	Ventilation Chimneys	Can be combined with venturi shaped capping/ electric exhaust ventilators	Buoyancy driven chimneys performs best in combination with lowest flow resistance ventilation
	Atria	Useful as an exhaust zone	Extensive glazing can result in overheating
	Wind Catchers and Wind scoops	High airflow velocity can be achieved	Proper functioning depends on air flow driving forces, wind and temperature differences
	Double Facades, Ventilated walls	Protected space usable for moving sun blinds and blinds	High Cost
		Enhances cross ventilation	

Appendix B: Categories of Adaptive Comfort

The categories of different acceptable operative temperature ranges in a building without mechanical cooling systems as per EN 16798 is given as follows:

Category I

upper limit: $\theta_o = 0{,}33\Theta_{\mathrm{rm}} + 18{,}8 + 2$

lower limit: $\theta_o = 0{,}33\Theta_{\mathrm{rm}} + 18{,}8 - 3$

Category II

upper limit: $\theta_o = 0{,}33\Theta_{\mathrm{rm}} + 18{,}8 + 3$

lower limit: $\theta_o = 0{,}33\Theta_{\mathrm{rm}} + 18{,}8 - 4$

Category III

upper limit: $\theta_o = 0{,}33\Theta_{\mathrm{rm}} + 18{,}8 + 4$

lower limit: $\theta_o = 0{,}33\Theta_{\mathrm{rm}} + 18{,}8 - 5$

Appendix C: Internal Heat Gain Calculation

The total internal heat load is determined in accordance with paragraph 7.5.2.1 of NTA 8800 as per the formula: $180 \times N_{\text{woon;zi}}$ W.

The number of residents per calculation zone per living area $N_{\text{woon;zi}}$ can be determined using the following equations if

$$\mathrm{A_{g,zi}/N_{woon,zi}} \leq 30\mathrm{m}^2\!: N_{\text{P, woon;zi}} = 1$$

$$30\mathrm{m}^2 < \mathrm{A}_{g\ \text{zi}}\,/N_{\text{woon;zi}} \leq 100\mathrm{m}^2\!:\ N_{\text{p; woon:zi}} = 2{,}28 - 1{,}28/70 \times \left(100 - \frac{\mathrm{A}_{g;zi}}{N_{\text{woon;zi}}}\right)$$

$$\mathrm{A}_{g,zi}/\mathrm{N_{woon,zi}} > 100\mathrm{m}^2\!: N_{p,woon;zi} = 1{,}28 + 0{,}01 \times \frac{\mathrm{A}_{g;zj}}{N_{\text{woon:zi}}}$$

Where,

$Q_{H/C=int,dir;zi;mi}$	is the internal heat gain in calculation zone z_i, for heating/cooling, in kWh;
$N_{\text{woon;zi}}$	is the number of residential functions in calculation zone z_i
$N_{p,woon;zi}$	is the average number of residents per calculation zone per residential function;
$\mathrm{A}_{g,zi}$	is the usable area of the considered calculation zone,

The calculation value of the internal heat load is then determined with the following formula:

calculation value = total internal heat load / (2 x floor area living room and kitchen + sum of the floor area of the other bedrooms).

The internal heat load is distributed as follows:

- Living room and kitchen are given 2 times the calculation value times the floor area as internal heat load (W);
- Other living spaces are given 1 times the calculation value multiplied by the floor area as internal heat load (W).

The heat load calculated above is maintained 24 hours a day.

Table C.0.1. Internal heat load calculations for gallery apartment

GBO [m2]	89	
N;P;woon;zi [-]	2.07886	
Interne warmtelast	Totaal [W]	374.194
	Rekenwaarde [W]	3.0

	Vloeroppervlak [m2]	Interne warmtelast [W]
Woonkamer	42.5	254
Keuken	7.1	42
Slaapkamer 1	20.82	62
Slaapkamer 2	12.25	37
Totaal		395

Table C.0.2. Internal heat load calculated for the center apartment

GBO [m2]	89	
N;P;woon;zi [-]	3	2.07886
Interne warmtelast	Totaal [W]	374.194
	Rekenwaarde [W]	3.6

	Vloeroppervlak [m2]	Interne warmtelast [W]
Woonkamer	40	288
Keuken	6.9	50
Slaapkamer 1	16.92	61
Slaapkamer 2	-	-
Totaal		399

Table C.0.3. Internal heat load calculated for corner apartment.

GBO [m2]	89	
N;P;woon;zi [-]	3	2.07886
Interne warmtelast	Totaal [W]	374.194
	Rekenwaarde [W]	3.5

	Vloeroppervlak [m2]	Interne warmtelast [W]
Woonkamer	42	292
Keuken	8.3	58
Slaapkamer 1	15.5	54
Slaapkamer 2	-	-
Totaal		403

Appendix D: Living Room Indoor Operative Temperature complete Graphs

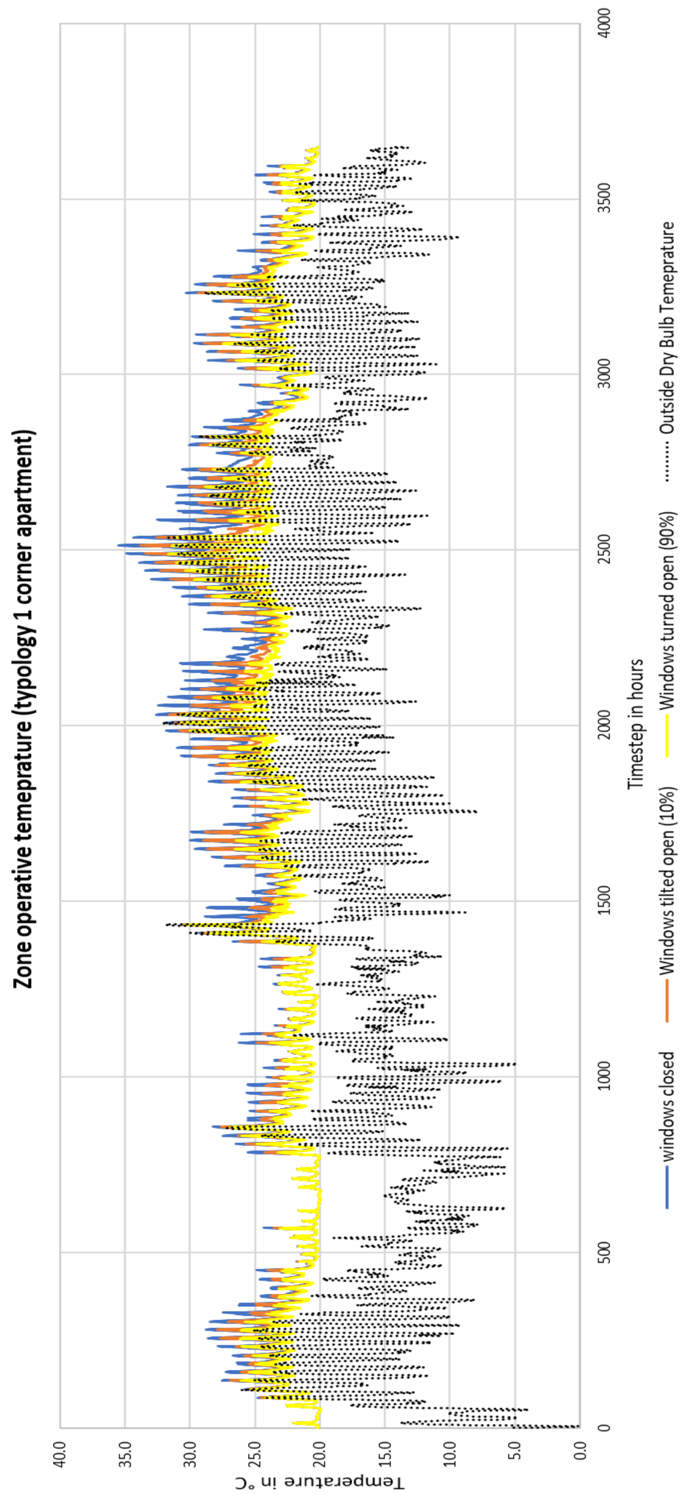

Figure D.0.1. Zone operative temperature of corner apartment for three cases. The blue line represents the zone temperature when the windows are closed for the whole time. The orange line represents the zone temperature when the windows are opened in the tilt position where only 10% of the glazed surface is open. The yellow line represents the window open in turned position where 90% of the glazed area is available for ventilation. The dotted grey line represents the outdoor temperature.

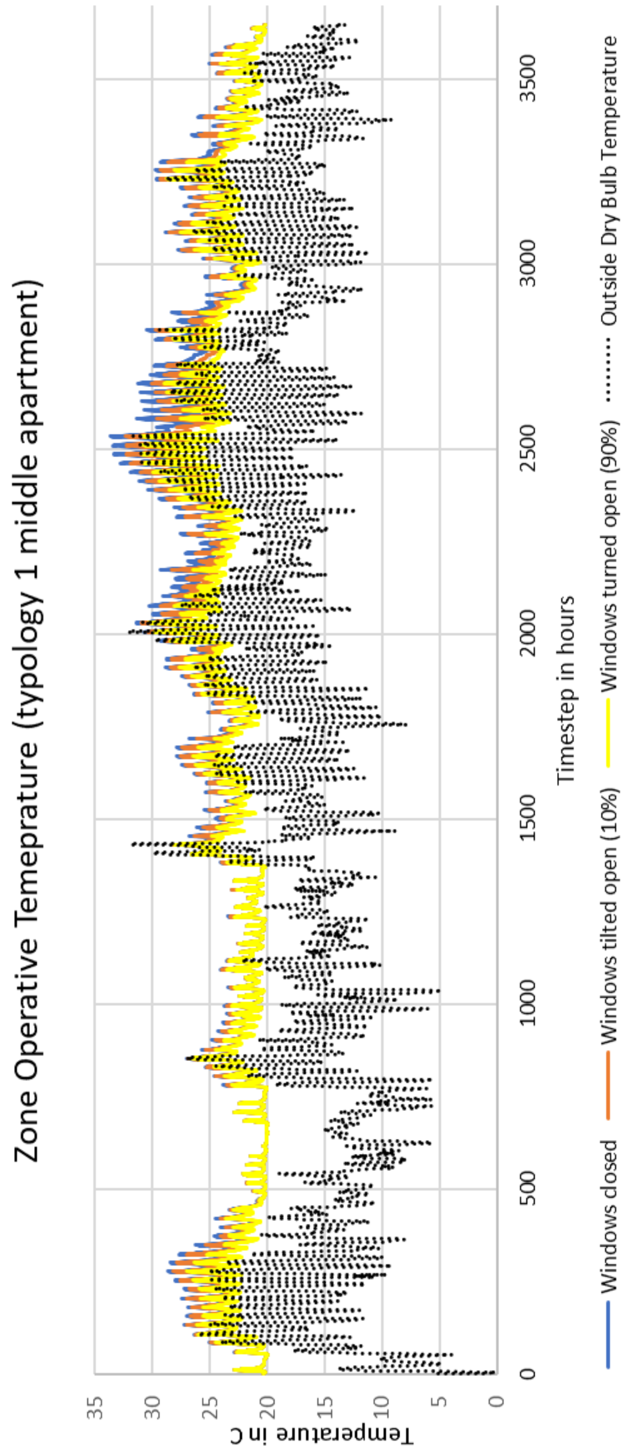

Figure D.0.2. Zone operative temperature of center apartment for three cases. The blue line represents the zone temperature when the windows are closed. The orange line represents the zone temperature when the windows are opened in the tilt position where only 10% of the glazed surface is open. The yellow line represents the window open in turned position where 90% of the glazed area is available for ventilation.

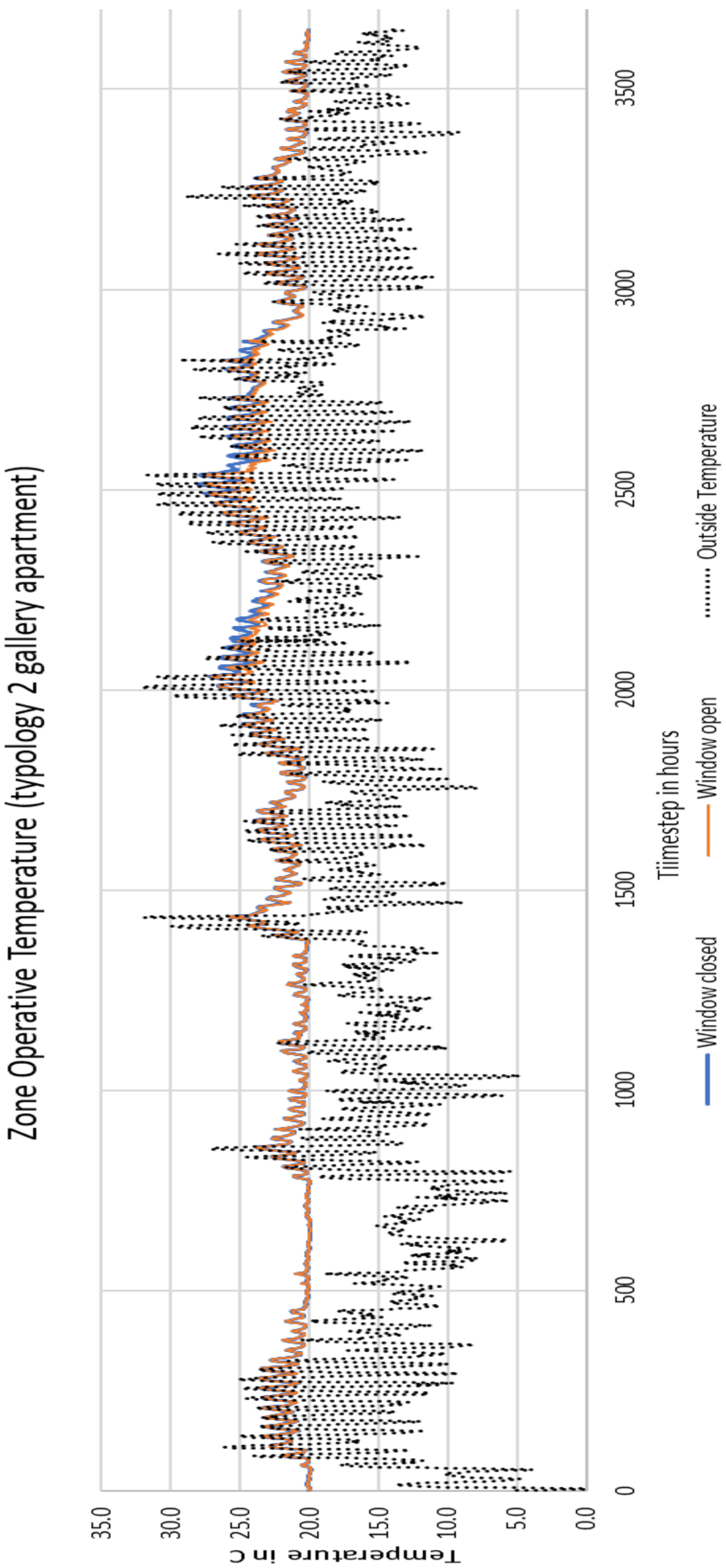

Figure D.0.3. Zone operative temperature of corner apartment for three cases. The blue line represents the zone temperature when the windows are closed for the whole time. The orange line represents the zone temperature when the windows are opened.

Appendix E: Bedroom Indoor Temperature, Temperature Exceedance Hours and CRR ratio

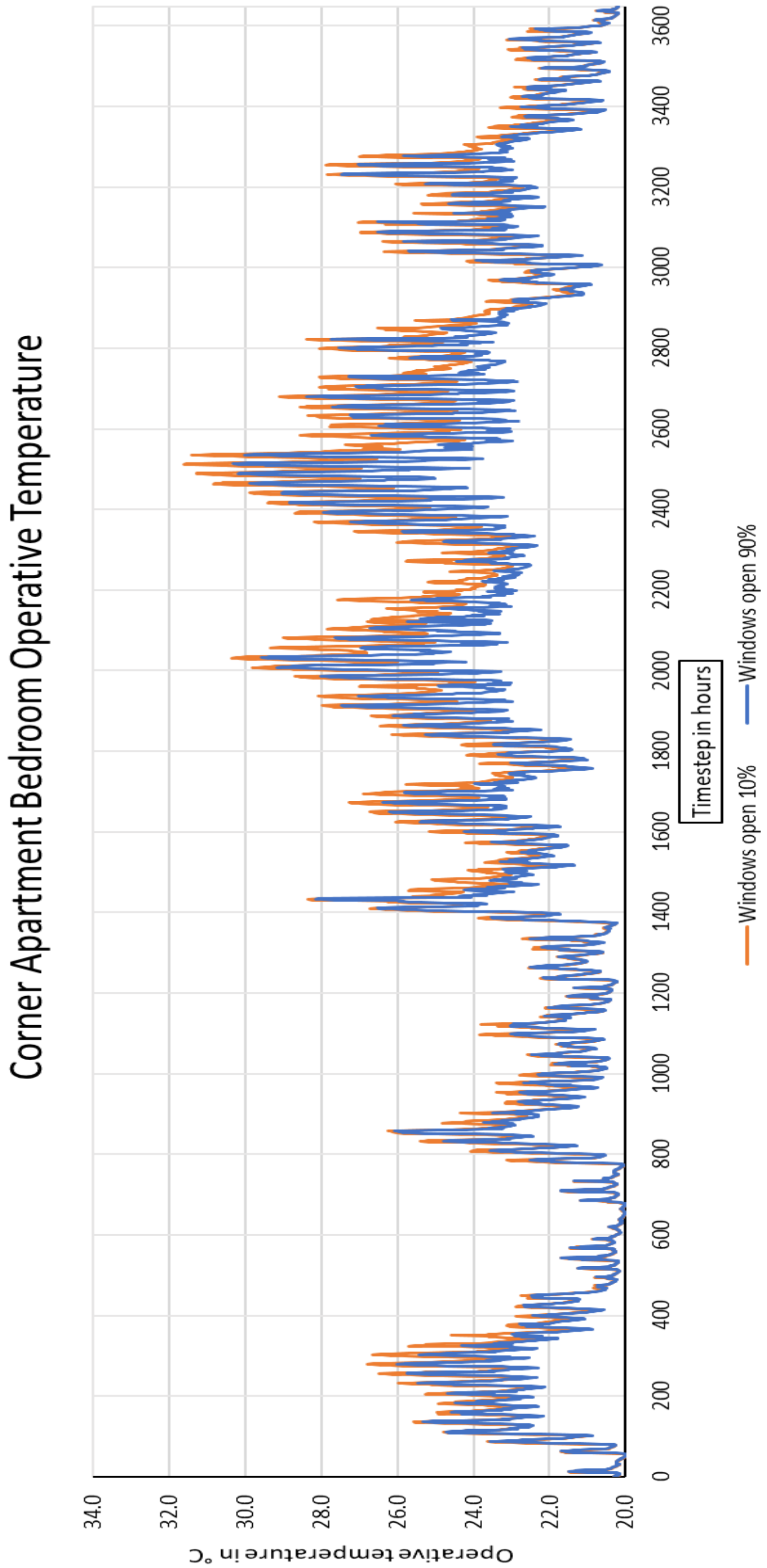

Figure E.0.1. Indoor temperature variation in bedroom in corner apartment of typology 1 building when windows are opened

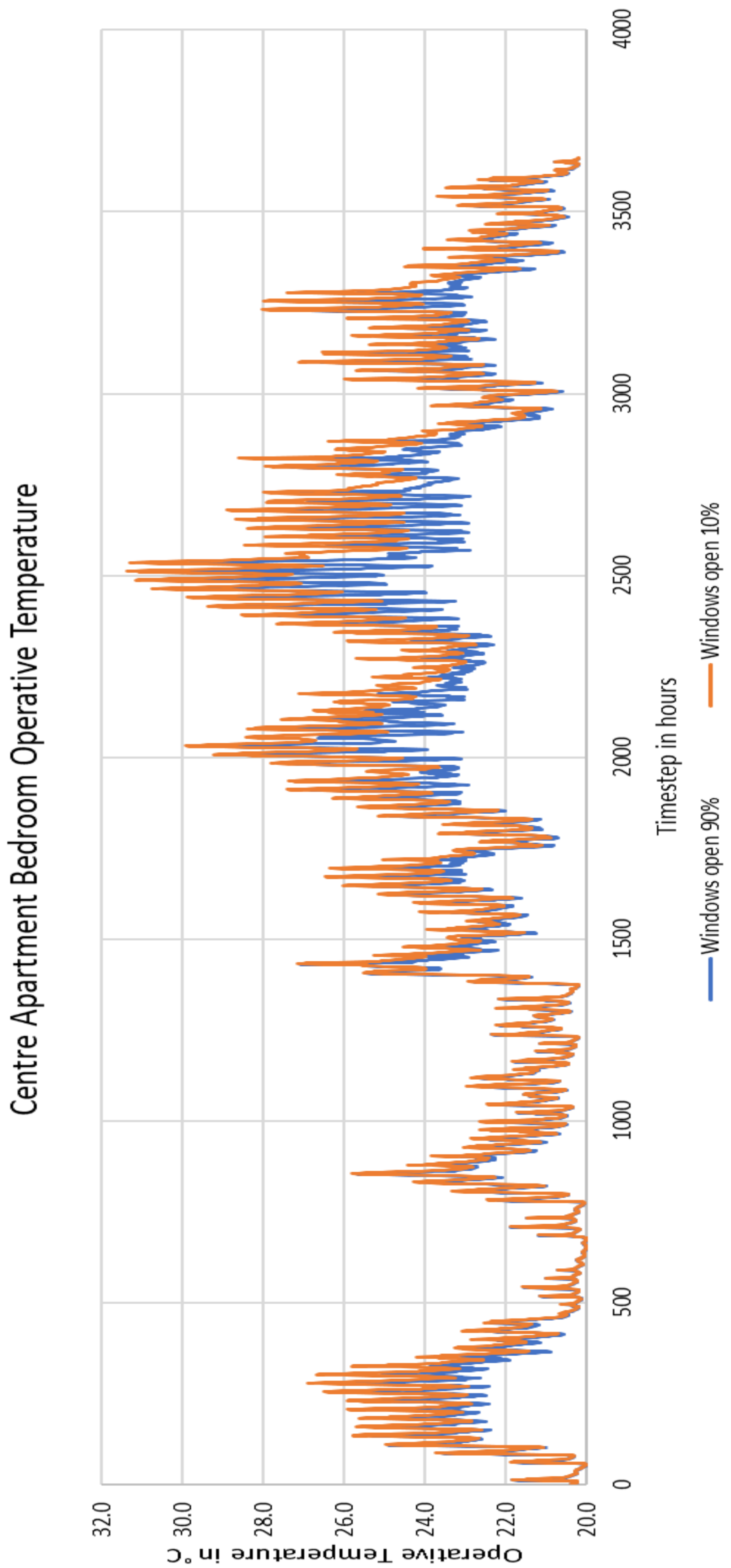

Figure E.0.2. Indoor temperature variation in bedroom in centre apartment of typology 1 building when windows are opened

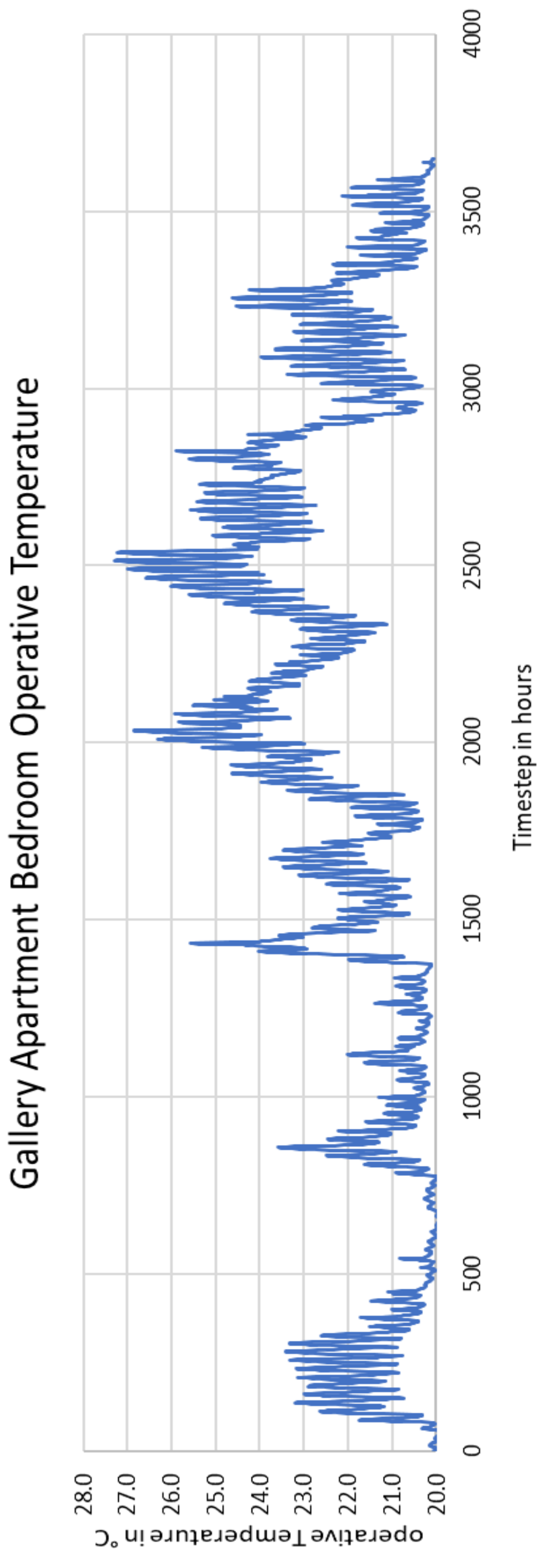

Figure E.0.3. Indoor temperature variation in bedroom in gallery apartment of typology 2 building when windows are opened

Table E.0.1. Table showing the number of hours the temperature exceeds 25°C and 28°C in the bedroom

Apartment Type	Thermal Mass	Window operable area [%]	No. Of hours exceeding Temperature above 23°C in Bedroom 1	No. Of hours exceeding Temperature above 23°C in Bedroom 2
Corner Apartment	Light	0	2171	-
		10	1739	-
		90	1026	-
	Medium	0	2154	-
		10	1723	-
		90	1020	-
	Heavy	0	2190	-
		10	1985	-
		90	991	-
Middle Apartment	Light	0	2032	-
		10	1680	-
		90	1036	-
	Medium	0	1901	-
		10	1684	-
		90	1036	-
	Heavy	0	2099	-
		10	1672	-
		90	1017	-
Gallery Apartment	Light	0	1234	1230
		75	1154	1147
	Medium	0	1059	1065
		75	1006	1002
	Heavy	0	1020	1028
		75	982	986

Table E.0.2.The cooling energy requirement for the bedrooms in the apartment simulations

Apartment Type	**Thermal Mass**	**Window operable area [%]**	**Cooling Energy bedroom room (kWh)**	**% reduction from the closed scenario**
Corner Apartment	Light	closed	405.1931	
		tilt open	399.6889	1.4
		turn open	377.3499	7.0
	Medium	closed	351.6596	
		tilt open	346.5195	1.5
		turn open	326.9458	7.0
	Heavy	closed	340.0836	
		tilt open	336.5417	1.0
		turn open	317.2311	6.7
Middle Apartment	Light	closed	416.3072	
		tilt open	405.3827	2.6
		turn open	380.2417	8.7
	Medium	closed	369.4799	
		tilt open	357.7534	3.2
		turn open	333.5716	9.7
	Heavy	closed	352.8365	
		tilt open	343.1786	2.7
		turn open	321.1405	9.0
Gallery Apartment	Light	closed	245.0088	
		open	235.8139	3.8
	Medium	closed	180.9822	
		open	177.8611	1.7
	Heavy	closed	168.966	
		open	166.424	1.5