Impact of occupant-facade interaction on thermal comfort during the cooling season

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Abstract

Our planet is currently facing significant challenges such as overpopulation, climate change, and resource depletion, leading to severe environmental degradation. The construction industry, in particular, has played a major role in aggravating these issues. The increase in carbon emissions has contributed to rising global temperatures, necessitating higher energy consumption in buildings to maintain thermal comfort during extreme heat conditions, which in turn further contributes to climate change. To break this cycle, designers and researchers have developed various passive strategies for buildings to reduce energy consumption. However, improper design and implementation of these strategies often compromise indoor comfort.

The building envelope, as the protective layer of a building, plays a critical role in maintaining indoor comfort. Therefore, it is essential to focus on facade strategies that not only reduce energy usage but also ensure user comfort. This thesis explores the development of passive facade strategies aimed at reducing energy consumption and maintaining thermal comfort during the cooling season. Through a systematic literature review, existing passive facade strategies employed to reduce cooling loads were examined, revealing a gap in considering occupant interaction.

The thesis investigates the potential of occupant-facade interaction as a passive strategy to reduce energy usage and maintain thermal comfort. Occupant behaviour models are identified and implemented to assess their impact on indoor comfort and air quality. The research seeks to provide insights into the benefits of occupant involvement and how it influences thermal comfort during the cooling season. The objective is to determine whether occupant behaviour alone can effectively maintain comfort and indoor air quality without relying on external mechanical systems.

By studying the relationship between occupant behaviour and the facade, this research aims to contribute valuable information on the role of occupants in reducing energy consumption and ensuring thermal comfort. The findings will shed light on the potential of occupant-facade interaction as an effective passive strategy in building design, with the ultimate goal of designing energy-efficient buildings that prioritize occupant comfort and well-being during the cooling season. Additionally, the findings of this research can serve as a foundation for the development of strategies that promote occupant interaction with the facade, leading to further reductions in energy consumption. By understanding the impact of occupant behaviour on thermal comfort and air quality, designers and building professionals can devise innovative approaches to optimize occupant-facade interaction, thereby minimizing the reliance on energy-intensive mechanical systems.

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01 | Introduction

1.1 Research framework

1.1.1 Problem statement

The escalating concentration of greenhouse gases in the atmosphere is widely recognized as the primary driver of climate change. This increase is closely tied to the rapid urbanization of cities, which has resulted in a significant surge in carbon emissions and greenhouse gas levels (Puppim, 2017). Consequently, the demand for energy continues to rise, while fossil fuel resources struggle to keep pace.

Global warming and climate change have led to a notable increase in surface and air temperatures, resulting in extremely high temperatures across the globe. This poses a substantial risk of indoor overheating, causing not only extreme discomfort but also severe health issues and even fatalities. Regrettably, many modern buildings in the Netherlands are ill-prepared to withstand extreme heat, as most of them are designed for colder climatic conditions, thereby adversely affecting indoor thermal comfort. Research indicates that concurrent heatwaves have become six times more frequent in the past four decades due to global warming (This Is How Concurrent Heat Waves Are Impacting the World, 2022). If this trend persists, heatwaves are projected to become even more frequent and could become the new normal.

The building envelope, which serves as a barrier between the outdoor and indoor environments, plays a pivotal role in determining indoor comfort. Its design can have a significant impact on indoor climate conditions, including adequate natural ventilation, effective mitigation of overheating on hot days, and temperature regulation during cold periods. Consequently, optimizing the design of the building envelope can offer substantial advantages in terms of thermal comfort and energy conservation.

This study aims to investigate the efficiency of passive design strategies integrated into the building envelope in maintaining indoor thermal comfort specifically during the cooling season. Considerable research has already explored the effects of various façade design strategies on occupant thermal comfort and the mitigation of indoor overheating. However, there is a notable gap in the literature regarding the role of occupant behaviour in these studies. Thermal comfort is a subjective experience, influenced by factors such as age, gender, and cultural background. Empowering users to make decisions based on their individual thermal comfort preferences can potentially enhance comfort standards. This thesis also seeks to explore how occupant behaviour can contribute to improving thermal comfort in buildings without relying heavily on energy-intensive systems.

By investigating the interplay between passive design strategies, occupant behaviour, and thermal comfort, this research endeavors to provide insights that can inform the development of occupant-centric building design strategies.

1.1.2 Research questions

Following the posed problem, the main research question can be framed as :

"What is the impact of occupant-facade interaction on thermal comfort during the cooling season"

The main question can be further divided in the following sub-questions for analysis:

1. What is the influence of facades on indoor thermal comfort?
2. What are the passive facade strategies used to decrease overheating without de pending on mechanical conditioning systems.
3. What is occupant behaviour and how is it used in building performance simulation software?
4. How can occupant behaviour influence indoor thermal comfort?
5. What are the existing occupant behaviour models for window operation?
6. What factors are found to influence window operation?
7. How can occupant behaviour models (window operation) be integrated into Design Builder software?
8. What is the key performance indicator considered for evaluating thermal comfort?
9. Can the results from this research be further developed to reduce the use of mechanical systems and still maintain thermal comfort?
10. What are the main limitations of considering occupant behaviour?

1.1.3 Objective

The objective of this thesis is to investigate the impact of occupant behaviour on facade performance, specifically in relation to thermal comfort. This research aims to gain insights into how occupants interact with the building facade to enhance their comfort conditions and evaluate the consequences of these interactions on the indoor thermal environment. To achieve this objective, simulation software Design builder will be utilized as a valuable tool for analyzing and modelling different scenarios. These simulations will consider various key performance indicators (KPIs) that are relevant to thermal comfort.

The focus of this study is on occupant behaviour, which encompasses the actions and decisions made by occupants in response to their thermal environment. These behaviours may include opening or closing windows, adjusting shading systems, or utilizing personal cooling devices. By incorporating these interactions into the simulation models, it becomes possible to evaluate the impact of occupant behaviour on indoor thermal comfort.

The scenarios created in this study will involve different façade archetypes and occupant behaviour models. This approach allows for the exploration of various occupant behaviours and their influence on thermal comfort conditions. For example, the study may examine how occupants adjust shading systems during peak solar radiation periods or how the opening and closing of windows affect indoor air temperature and ventilation. By analyzing these scenarios and their corresponding KPIs, a comprehensive understanding of the relationship between occupant behaviour and facade performance can be obtained.

This study mainly focuses on window operation models implemented for the different façade archetypes. Overall, this thesis seeks to shed light on the crucial role of occupant behaviour in shaping facade performance and its impact on indoor thermal comfort. By leveraging simulation tools and considering key performance indicators, the study aims to provide valuable insights into the design and operation of buildings to create environments that prioritize occupant comfort and energy efficiency.

In addition to its impact on indoor temperatures, window operation also influences indoor air quality. Therefore, this thesis will further analyze the effect of occupant behavior on indoor air quality, specifically focusing on CO_2 concentration levels across all the identified scenarios and archetypes. By examining the relationship between occupant behavior and CO_2 levels, valuable insights can be gained regarding the effectiveness of different occupant behavior models in maintaining acceptable indoor air quality. This analysis will contribute to a comprehensive understanding of the role of occupant-façade interaction in achieving both thermal comfort and indoor air quality in buildings.

1.1.4 Research approach

The research approach or methodology consists of 6 main phases, ranging from research to analysis to the results. These phases may overlap at certain points for re-evaluation.

Phase 1: Research framework

In this phase, the research topic is thoroughly examined and evaluated to determine its relevance and significance in the field of Building Technology and to society as a whole. The scope of the topic is assessed, and the research problem is framed based on existing knowledge. This involves critically analyzing the topic and narrowing it down to specific aspects that require attention. Supporting questions are formulated to guide the next phase, which involves gathering relevant literature to inform the final research question.

Phase 2: Background research, literature review and theoretical framework

Literature review is conducted on the relevant topics which support the main research problem. In this phase, existing literature is reviewed and analyzed to create a foundation for further phases. A theoretical framework is formed by exploring various reports, books, articles, papers, and websites. The information gathered is critically analyzed to identify the missing links or research which then forms the basis for the thesis. This phase is sub-divided into various sections, each addressing a specific topic which helps in answering the main research question and sub-questions. The first topic for the background research is thermal comfort and its models, this section defines thermal comfort and the important parameters that affect thermal comfort. It also talks about the thermal comfort models used for analysis. The next topic is about the cooling season and rising temperatures. The main literature review consists of two main sections, the first looks at façade strategies and how they affect the indoor thermal comfort. The second is about occupant behaviour. On the whole, this section forms the groundwork required for the main research of the thesis.

Phase 3: Identifying facade archetypes and occupant behaviour models for window operation.

In this phase, specific facade archetypes are identified for comparison in terms of their performance. These archetypes are developed based on key factors that have a significant impact on the research, such as window-to-wall ratios and construction typology. Additionally, from the studied occupant behaviour models, two models are selected that have different influencing factors and levels of complexity. For comparison purposes, two additional cases are created without occupant behaviour, one with windows always closed and one with windows always open. This phase focuses on establishing a range of scenarios that will be used in the simulations to generate comparative results.

Phase 4: Case build-up

The identified facade archetypes and occupant behaviour models are combined to create 36 different scenarios. These scenarios encompass various combinations of archetypes, occupant behaviour models, base cases, and cases with night ventilation. These scenarios are used in the simulations to generate comparative results. Models are created for these scenarios in design builder simulation software.

Phase 5 : Simulation in design builder

In this phase, the simulation models created in the previous phase are used to conduct thermal performance tests. The models incorporate the selected occupant behaviour models to simulate realistic occupant interactions with the building facade. The study adopts a scenario-based approach, categorizing occupant behaviour and facade solutions into predefined scenarios. Simulations are run using weather data specific to Netherlands locations, and the thermal performance of each scenario is assessed.

Phase 6 : Results, analysis and conclusions

The final phase involves analyzing and discussing the results obtained from the simulations. Statistical analysis is conducted to compare the thermal comfort and occupant behaviour across different scenarios. The findings are critically examined, and conclusions are drawn based on the analysis. The limitations of the research are discussed, and recommendations are provided for further development in the field. Opportunities for future research in the topic are identified and highlighted. This phase brings together all the findings and insights from the study to provide a comprehensive understanding of the impact of occupant behaviour on facade performance and thermal comfort.

1.1.5 Research outline

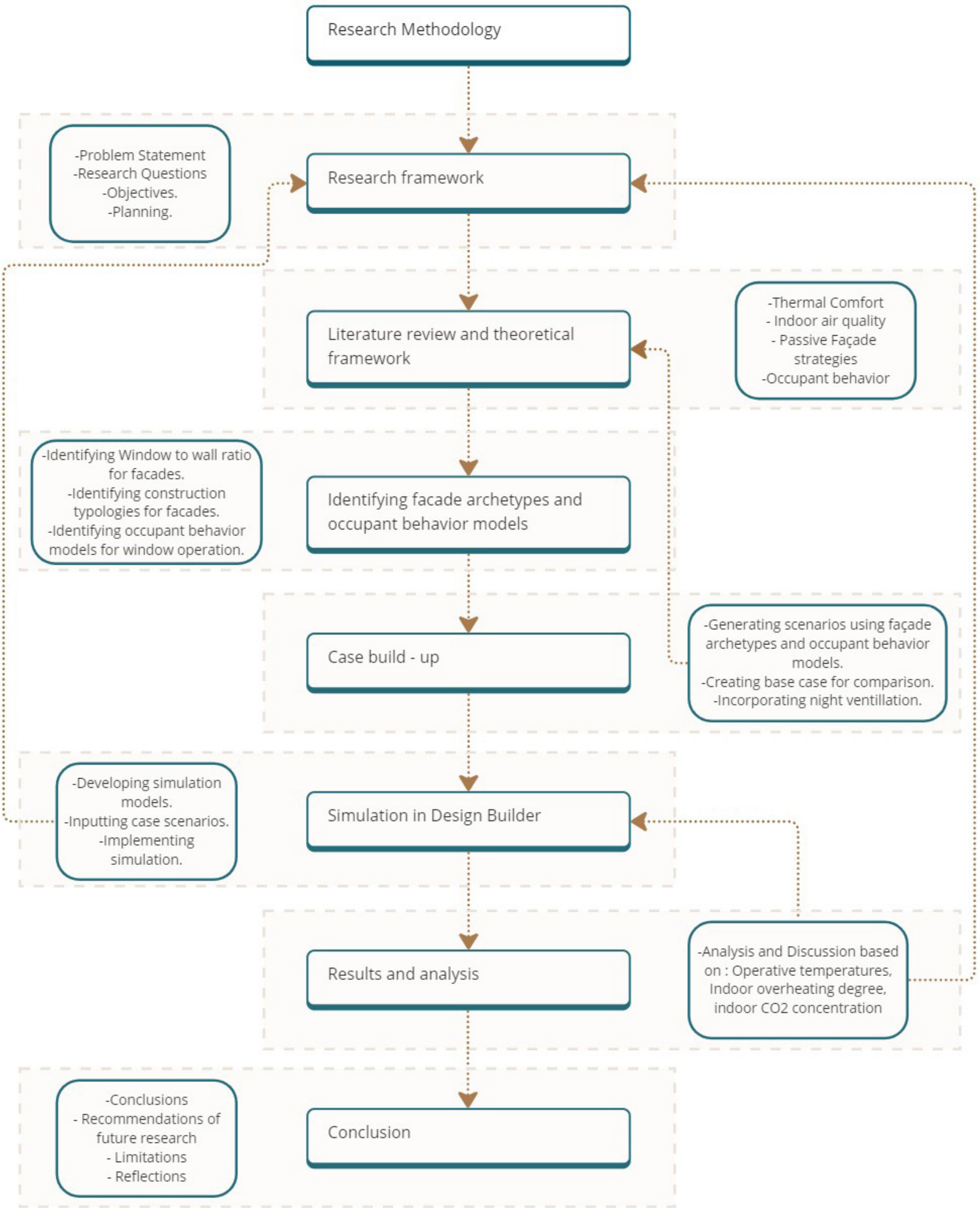


Fig.1 Flowchart of the research methodology used in this thesis

02 | Background Research

2.1 Thermal comfort

2.1.1 Definition

Thermal comfort is a fundamental aspect of indoor environmental quality that significantly affects occupants' well-being, productivity, and overall satisfaction in buildings. It refers to the subjective perception of thermal conditions in a space, where individuals experience a state of thermal satisfaction or dissatisfaction based on their physiological and psychological responses to the thermal environment (ASHRAE, 2017).

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) provides a widely recognized definition of thermal comfort as "that condition of mind that expresses satisfaction with the thermal environment" (ASHRAE Standard 55-2020). This definition emphasizes the subjective nature of thermal comfort, acknowledging that individuals may have varying preferences and responses to thermal conditions based on factors such as personal physiology, activity levels, clothing, and cultural background.

Thermal comfort is influenced by several parameters, including air temperature, radiant temperature, air velocity, humidity, and personal factors. The interactions among these parameters can lead to variations in thermal perception and preferences among occupants. Achieving thermal comfort requires creating an indoor environment that aligns with the majority of occupants' thermal expectations and preferences (Fanger, 1970). To assess and evaluate thermal comfort, various thermal comfort models have been developed. These models aim to quantify the relationship between environmental parameters and occupants' thermal perception. The most widely used model is the Predicted Mean Vote (PMV) model, proposed by Fanger (1970) and the Adaptive Thermal Comfort model (ASHRAE Standard 55-2020), which will be discussed in the further sections.

Understanding the definition of thermal comfort and its influencing factors is crucial for designing buildings that provide optimal indoor thermal conditions and promote occupants' well-being and productivity. By considering the range of factors affecting thermal comfort, architects, engineers, and building professionals can create environments that enhance occupant satisfaction and comfort.

2.1.2 Influencing factors

Since humans perceive comfort very differently, it is quite difficult to define an optimal temperature which would be comfortable to everyone. Nevertheless, according to Fanger's theory on human-body heat exchange, 6 parameters affect thermal comfort which are categorized into personal factors and environmental factors (Fanger, 1970). The personal factors relate to the occupants' characteristics and the environmental factors relate to the thermal environment. Personal factors are : metabolism and clothing resistance, environmental factors are : relative humidity, air velocity, air temperature and mean radiant temperature. Other psychological factors like individual's expectations also affect the way thermal comfort is perceived by occupants(Taleghani et al., 2013b).

Metabolism: Each individual has a unique metabolic rate that can vary based on activity level and environmental conditions. Metabolism refers to the rate at which the body converts chemical energy into heat and mechanical work. Factors such as physical activity, body size, and food and beverage consumption can influence metabolic rates and indirectly impact thermal preferences (ASHRAE Handbook, 2021). The metabolic rate is measure in met units and is defined by AHSRAE 55-2010 as:

1 met = 58.2 W/m^2 (18.4 Btu/h·ft^2)
which is equal to the energy produced per unit surface area of an average person seated at rest.
The surface area of an average person is 1.8 m^2 (19 ft^2).

The ASHRAE 55-2010 standard also gives a table of 'met' values for different activities that humans perform. For example, 0.7met for sleeping, 1.2-1.4 for light activities standing. Studies also show that consumption patterns of food and beverages may affect metabolic rates, which in turn affects thermal preferences indirectly (Szokolay, 2004). This study focuses on office spaces so the metabolism value will be considered is 1 met for office activity .

Clothing Resistance: The amount of thermal insulation provided by clothing worn by individuals significantly affects their thermal comfort. Clothing resistance impacts heat loss and thermal balance. The insulation value of clothing can be influenced by the number of layers, the type of material used, and how air flow and relative humidity interact with the fabric (ASHRAE Handbook, 2021). Clothing resistance is measured by 'clo' units and is defined by AHSRAE 55-2010 as:

1 clo is equal to 0.155 $m^2 \cdot K/W$ (0.88 $°F \cdot ft^2 \cdot h/Btu$).
This corresponds to trousers, a long-sleeved shirt, and a jacket.

For this project, the simulation is conducted during the summer months in an office space so the clo value considered will be 0,61 clo.

Relative Humidity: Relative humidity refers to the amount of water vapor present in the air, expressed as a percentage of the maximum capacity of the air to hold water vapor at a specific temperature. High relative humidity reduces the effectiveness of evaporative cooling through sweating, while extremely dry environments can also be uncomfortable. Maintaining indoor relative humidity below 60% and preferably between 30-50% is recommended for optimal comfort (ASHRAE Handbook, 2021).

Air Velocity: Air velocity is the rate of air motion and is measured in meters per second (m/s). The average speed of air surrounding an occupant determines the air velocity. Air velocity influences heat exchange between individuals and the surrounding environment (ASHRAE Handbook, 2021). In warmer conditions, increased air velocity through the use of fans can enhance heat loss and improve comfort. However, in colder climates, higher air velocity may be perceived as a draught and may not be desirable.

Air Temperature: The average temperature of the air surrounding an occupant, known as air temperature or dry-bulb temperature, directly affects thermal comfort. It is measured using a dry-bulb thermometer and is typically expressed in degrees Celsius or Fahrenheit. (ASHRAE Handbook, 2021).

Mean radiant temperature : Mean radiant temperature is the measure of heat transfer between surfaces and the human body through radiation. It depends on the temperature and emissivity of the surrounding surfaces and materials. Variations in mean radiant temperature can impact thermal comfort, as individuals may perceive different levels of warmth or coolness based on the radiant heat exchange with their surroundings (ASHRAE Handbook, 2021).

Some additional factors that are considered for thermal comfort analysis are as follows:

Air Quality: The quality of indoor air can impact thermal comfort. Poor air quality, such as high levels of pollutants, can lead to discomfort and health issues. Adequate ventilation and air filtration systems are important for maintaining good indoor air quality (ASHRAE Handbook, 2021).

Psychological Factors: Individual perceptions, expectations, and psychological factors can influence how thermal comfort is experienced. Factors such as personal preferences, adaptation to different climates, and cultural influences can impact an individual's perception of comfort (de Dear & Brager, 2002).

Solar Radiation: Solar radiation, including direct sunlight and solar heat gain through windows, can affect thermal comfort. Exposure to excessive solar radiation can lead to overheating and discomfort. Proper shading and control of solar radiation are important considerations in building design (ASHRAE Handbook, 2021).

Seasonal Variations: Thermal comfort can vary with different seasons. Seasonal changes in outdoor temperature and weather conditions can impact indoor comfort. Designing for both summer and winter conditions ensures year-round comfort (ASHRAE Handbook, 2021).

Building Design and Layout: The design and layout of a building can affect thermal comfort. Factors such as room dimensions, orientation, insulation, and thermal mass influence the distribution of heat and the ability to maintain a comfortable indoor environment (ASHRAE Handbook, 2021).

It is essential to consider these additional factors alongside the previously mentioned influencing factors to comprehensively address thermal comfort in building design and operation. This study will focus mainly on operative temperatures which is calculated based on air temperature, mean radiant temperature and air velocity.

2.1.3 Thermal comfort models

As discussed in the previous sections, it is clear that thermal comfort has a significant role in maintaining a healthy indoor environment and in energy consumption of buildings. Consequently, extensive research conducted by scientists and scholars resulted in studies to develop the best methods and models for assessing and estimating thermal comfort. Several thermal comfort models have been developed in recent decades. These models have been developed based on distinct environments and have been verified using unique experimental data sets. Thus, not all models can be used for any scenario, and so all models are not accepted in international standards (Zhao et al., 2021b).

The most commonly used thermal comfort models are, the predicted mean vote(PMV) model by Fanger and the adaptive thermal comfort model(ASHRAE 55). Studies also show that there is a new Data driven thermal comfort model, which uses data to improve the prediction accuracy. (Zhao et al., 2021b). For the purpose of this research we will focus on the most widely accepted thermal models, which are the heat-balance model and the adaptive model. The heat-balance uses data from climate chamber studies and is based on heat flows in and around the body, which gave rise to a model based on physics and physiology. The most popular Heat-balance models are the Predicted Mean Vote(PMV) model (Fanger, 1970) and the Standard effective temperature model (SET), in this study the PMV model is considered for comparison (ASHRAE Handbook, 2021).

The Predicted Mean Vote (PMV) Model

The Predicted Mean Vote (PMV) model, proposed by Fanger, is a widely recognized and extensively used thermal comfort model in the field of building design and indoor environmental quality assessment (Fanger, 1970; ASHRAE, 2017). The PMV model is based on Fanger's human-thermal balance equation, which takes into account various environmental and personal factors that influence thermal comfort perception (Fanger, 1970). The PMV model assumes that the human body seeks thermal equilibrium by balancing heat gain and heat loss with the surrounding environment (Fanger, 1970). It predicts the average thermal sensation of a group of people on a seven-point thermal sensation scale ranging from -3 (cold) to +3 (hot) (ASHRAE, 2017). The model incorporates several parameters, including air temperature, mean radiant temperature, relative humidity, air velocity, clothing insulation, and metabolic rate, to calculate the predicted thermal sensation and comfort level (ASHRAE, 2017).

To further evaluate the comfort conditions, the PMV model also considers the Predicted Percentage of Dissatisfied (PPD), which estimates the percentage of people who would feel dissatisfied with the thermal conditions outside the range of thermal neutrality (ASHRAE, 2017). The PPD takes into account the distribution of thermal sensation preferences within a population and provides a measure of the thermal acceptability for occupants (ASHRAE, 2017).

While the PMV model has been widely used and accepted, it is important to acknowledge its limitations. The model was primarily developed based on steady-state conditions in climate chambers, which restricts its applicability in non-uniform and transient environments (ASHRAE, 2017; Humphreys, 2005). The dynamic nature of outdoor conditions, variations in clothing choices, and individual adaptive behaviours to changing thermal environments may not be adequately captured by the PMV model (ASHRAE, 2017; Humphreys, 2005).

Despite these limitations, the PMV model remains a valuable tool for assessing and designing thermal comfort conditions in conditioned indoor spaces, especially in the early stages of building design and HVAC system selection (ASHRAE, 2017).

The Adaptive Model

The adaptive thermal comfort model is an alternative approach to understanding and predicting thermal comfort, which recognizes the human capacity to adapt to varying environmental conditions (ASHRAE, 2017; de Dear et al., 2013). Unlike the PMV model, which assumes a fixed comfort zone, the adaptive model acknowledges that people can adjust their thermal expectations and responses based on the prevailing conditions (ASHRAE, 2017; de Dear et al., 2013).

The adaptive model is based on field studies that observe and analyze the thermal sensation and behaviour of occupants in real-world settings (de Dear et al., 2013). This model takes into account factors such as indoor and outdoor air temperature, air velocity, humidity, clothing insulation, metabolic rate, and occupants' thermal history and adaptation strategies (ASHRAE, 2017; de Dear et al., 2013). The key concept of the adaptive model is the establishment of acceptable temperature ranges, known as the adaptive comfort zone, within which occupants can adapt and find thermal comfort (de Dear et al., 2013). The adaptive comfort zone is influenced by factors such as climate, cultural background, building design, and individual preferences (ASHRAE, 2017; de Dear et al., 2013).

Studies have shown that the adaptive model is particularly applicable in naturally ventilated buildings and spaces where occupants have greater control over their thermal environment (ASHRAE, 2017; Humphreys, 2005). It accounts for the dynamic and non-uniform nature of thermal conditions, acknowledging that individuals can adjust their clothing choices, activity levels, and thermal expectations to maintain comfort (ASHRAE, 2017; Humphreys, 2005).

It is important to note that the adaptive model may have limitations in certain controlled environments or buildings with strict temperature regulations, where occupants have limited ability to adjust the thermal conditions (ASHRAE, 2017; Humphreys, 2005). Additionally, the adaptive model requires careful consideration of local climate data and the specific context of the building and its occupants (ASHRAE, 2017).

The adaptive model provides a more flexible and context-specific approach to thermal comfort assessment, acknowledging the influence of human behaviour and adaptation on comfort perception. It is often used in the design of sustainable and energy-efficient buildings that aim to provide comfortable conditions while reducing energy consumption (ASHRAE, 2017; de Dear et al., 2013).

Various adaptive thermal comfort models have been developed to capture the dynamic nature of human comfort and the influence of personal and environmental factors. These models recognize that occupants can adapt their behaviour and expectations to achieve thermal comfort in different conditions. Some notable adaptive models include the California Adaptive Model (ASHRAE RP-884), the PMV-PPD Adaptive Model (ASHRAE Standard 55), and the Adaptive Comfort Model by de Dear and Brager. These models consider factors such as outdoor climate, metabolic rates, clothing insulation, and thermal expectations to provide a more accurate assessment of thermal comfort.

In this research, the focus will be on the CEN EN 15251 Adaptive Thermal Comfort Model, developed by the European Committee for Standardization (CEN). This standard takes into account the adaptive capacity of individuals and the influence of climate on thermal comfort. It provides guidelines and principles for assessing and predicting thermal comfort in buildings, considering both environmental and personal factors.

EN 15251 Adaptive thermal comfort model

The CEN EN 15251 Adaptive Thermal Comfort Model is a standard developed by the European Committee for Standardization (CEN) that provides guidelines for assessing and predicting thermal comfort in buildings. This model takes into account the dynamic nature of thermal comfort and acknowledges that comfort preferences can vary based on the specific climate and seasonal conditions. The CEN EN 15251 standard emphasizes the importance of considering outdoor climate data, such as temperature and solar radiation, in addition to indoor environmental parameters when assessing thermal comfort. It recognizes that occupants have the ability to adapt to different thermal conditions by adjusting their clothing, activity levels, and other factors.

In this research, the CEN EN 15251 Adaptive Thermal Comfort Model will be utilized as a framework for evaluating and analyzing thermal comfort levels. By employing this standard, the study aims to assess the effectiveness of passive strategies in achieving thermal comfort in non-mechanically conditioned spaces. The use of this recognized standard ensures a consistent and reliable approach to evaluating thermal comfort and facilitates comparisons with other research studies and industry practices. By employing the CEN EN 15251 model, the research aims to contribute to the understanding and application of adaptive thermal comfort principles in building design and operation, ultimately promoting energy-efficient and occupant-centric approaches to thermal comfort management.

In 2007, the European Committee for Standardisation (CEN) introduced the EN15251:2007 standard, as part of the SCATs project. This standard includes an equation specifically designed for naturally ventilated buildings, which is as follows (Taleghani et al., 2013) :

$$Tco = 0{,}33 \times Trm7 + 18.8\ °C$$

where, Trm7 the exponentially weighted running mean of the
daily outdoor temperature of the previous seven days based on the equation below

$$Trm7 = \frac{(T\text{-}1 + 0.8T\text{-}2 + 0.6T\text{-}3 + 0.5T\text{-}4 + 0.4T\text{-}5 + 0.3T\text{-}6 + 0.2T\text{-}7)}{3.8}$$

Within this standard, the permissible deviation of the indoor operative temperature from the comfort temperature is classified into four distinct categories as shown in table 1.

Table.1 Table depicting the CEN standard comfort temperature categories (Taleghani et al., 2013; EN 15251)

Category	Explanation	Limit of deviation (°C)	Range of acceptability (%)
I	High level of expectation for very sensitive and fragile users (hospitals, ...)	± 2	90
II	Normal expectation for new buildings	± 3	80
III	Moderate expectation (existing buildings)	± 4	65
IV	Values outside the criteria for the above categories (only in a limited period)	± > 4	< 65

Conclusion

In conclusion, thermal comfort is a complex and multifaceted concept influenced by various factors. Extensive research in the field has led to the development of different models and approaches to assess and predict thermal comfort in buildings. It has been observed that individuals respond to thermal conditions through behavioural, psychological, and physiological adaptations, which are influenced by local climate, social and cultural factors. Behavioural adaptation plays a significant role in determining thermal comfort, as individuals naturally tend to adjust their activities, clothing, and environmental conditions to avoid discomfort and maintain a comfortable state. People have the ability to adapt and modify their surroundings, such as opening windows or adjusting blinds, to create a more desirable thermal environment.

The adaptive model of thermal comfort recognizes the dynamic nature of comfort and acknowledges that comfort temperatures can vary based on external weather conditions and seasons. This model considers a wider range of comfort temperatures compared to the PMV model, making it particularly suitable for free-running buildings in hot climates. Studies have consistently demonstrated that individuals exhibit a broader range of thermal comfort acceptance when they are given the freedom to interact with their thermal environment and make behavioural or personal adjustments. This finding highlights the importance of user control and adaptive strategies in achieving optimal thermal comfort in buildings.

One study by de Dear and Brager (1998) investigated the impact of user control on thermal comfort and found that occupants in naturally ventilated buildings, where they had the ability to adjust windows and use personalized fans, reported higher comfort levels compared to occupants in mechanically conditioned buildings. The study emphasized the positive influence of user control on thermal comfort satisfaction. Another study by Humphreys and Nicol (2002) examined the thermal comfort responses of occupants in naturally ventilated buildings during the summer season. The results showed that individuals who had the opportunity to modify their thermal environment, such as adjusting windows or using shading devices, expressed a wider range of thermal comfort preferences. This study highlighted the role of personal adjustments in achieving individualized thermal comfort.

Furthermore, a research conducted by Schiavon et al. (2017) investigated the effect of occupant-controlled windows in office buildings. The study found that individuals who had control over their window positions and were able to adjust them according to their preferences exhibited a broader range of thermal comfort acceptance. The findings indicated that allowing occupants to modify their thermal environment resulted in higher comfort levels and satisfaction. These studies collectively demonstrate that providing occupants with the ability to interact with their thermal environment and make behavioural or personal adjustments leads to a wider range of thermal comfort acceptance. User control and adaptive strategies empower individuals to tailor their immediate surroundings to their comfort preferences, enhancing their overall comfort experience.

The adaptive comfort model offers a valuable approach for assessing and determining comfort levels while promoting energy conservation in buildings. It is particularly useful for analyzing passive strategies and non-mechanically conditioned spaces. By utilizing the adaptive model in this research, it will be possible to evaluate thermal comfort and explore the effectiveness of passive strategies in maintaining occupant comfort while reducing energy consumption.

Overall, understanding and achieving thermal comfort in buildings is crucial for creating healthy and sustainable indoor environments. By considering the interplay between individual adaptation, local climate, and design strategies, it is possible to enhance occupant comfort while optimizing energy efficiency. The adaptive comfort model provides a valuable tool for achieving these objectives and improving the overall thermal performance of buildings. This thesis focusses on the use of passive strategies to maintain thermal comfort, hence the adaptive model is considered in this study for evaluation.

2.2 Indoor Air quality

Indoor air quality refers to the level of pollutants present in the air within buildings, which can have a significant impact on human health and well-being (Nandan et al., 2021). Poor indoor air quality can be caused by various factors such as inadequate ventilation, the presence of pollutants from building materials, furnishings, cleaning products, and outdoor sources. Indoor air contains various toxins like VOC, HCHO, CO_2, SO_2, NO_2 and $PM_{2.5}$ (Nandan et al., 2021). One crucial aspect of indoor air quality is the concentration of carbon dioxide (CO_2). CO_2 is a natural component of air and is produced through human respiration, combustion processes, and other sources. High levels of CO_2 can indicate poor ventilation and inadequate fresh air exchange, leading to a buildup of other pollutants and a decrease in indoor air quality (Wargocki et al., 2000). Although indoor air quality consists of a number of factors, for this research CO_2 concentration is considered since it is found to be a useful way to measure air quality, ventilation levels and also leads to an increase in other pollutants (Satish et al., 2012).

Elevated CO_2 levels can have adverse effects on occupant comfort, cognitive function, and productivity. Studies have shown that high CO_2 concentrations can cause symptoms such as headaches, drowsiness, difficulty in concentrating, and reduced decision-making abilities (Satish et al., 2012). Furthermore, prolonged exposure to high CO_2 levels may contribute to health issues such as respiratory problems and increased susceptibility to respiratory infections(Seppänen et al., 1999). Hence, for this research CO_2 concentration is analysed based on the window operation models considered for the different archetypes to see if they comply with the acceptable limits as no mechanical ventilation or air supply is provided in these cases.

Similar to thermal comfort, certain standards have been put into place for CO_2 concentration levels to ensure occupant well-being. Standards like ASHRAE, ISHRAE 10001 and EN 15251 define CO_2 concentration levels that are acceptable for non residential buildings. CO_2 concentration is measured in parts per million (ppm), which is the number of particles of CO_2 present in one million particles of air. This research considers the EN 15251 standard for acceptable CO_2 concentration levels. The EN 15251 has defined categories for different levels, this is shown in table 11.

Table.2. Table depicting the categories of acceptable CO2 concentration levels in accordance to EN 15251

Category	CO_2 concentration acceptability limit in ppm
I	<= 350
II	> 350 and <= 500
III	> 500 and <= 800
IV	> 800

2.3 Cooling season

2.3.1 What and when is the cooling season

The cooling season refers to the time of the year when cooling systems are utilized to maintain comfortable indoor temperatures in response to elevated outdoor temperatures. It typically occurs in regions with warmer climates or during the hotter months of the year. In the Netherlands, the cooling season generally begins in late spring or early summer and extends through to early autumn. During this period, temperatures can rise significantly, especially in urban areas that are affected by the urban heat island effect. The urban heat island effect is characterized by higher temperatures due to the concentration of buildings, paved surfaces, and limited green spaces that absorb and radiate heat (KNMI, 2021). In the Netherlands the cooling season is generally from mid- June to September .

2.3.2 Energy impact during the cooling season

The cooling season places a considerable energy demand on buildings and electrical grids due to the increased use of cooling systems. As temperatures rise, buildings require active cooling methods to maintain occupant comfort. This often involves the use of air conditioning systems and heat pumps, which consume electricity and contribute to increased energy consumption and greenhouse gas emissions. In the Netherlands, the energy impact during the cooling season is significant, as buildings heavily rely on cooling systems to counteract the rising temperatures and ensure comfortable indoor conditions. This increased energy demand poses challenges in terms of sustainability, grid stability, and environmental impact (KNMI, 2021; IEA, 2020).

2.3.3 Implication of the increase in heat waves

The increasing frequency and intensity of heatwaves have profound implications for the cooling season. Heatwaves are characterized by prolonged periods of extreme heat, often accompanied by high humidity levels. These events can lead to adverse health effects, including heat-related illnesses and increased mortality rates, particularly among vulnerable populations. The Netherlands has experienced an upward trend in the occurrence of heatwaves, which places additional pressure on cooling systems and energy resources. To mitigate the impacts of heatwaves, strategies such as urban greening, cool roofs, and heat-resistant urban planning are being implemented. These measures aim to reduce the urban heat island effect, enhance natural cooling mechanisms, and provide more resilient and comfortable urban environments (Heusinkveld et al., 2014).

To address the challenges associated with the cooling season and heatwaves, it is important to implement energy-efficient cooling technologies and sustainable design practices. High-efficiency air conditioning systems, heat pumps, and chilled water systems can help reduce energy consumption during the cooling season. Passive cooling strategies, such as natural ventilation, shading devices, and cool roofs, can also be employed to minimize heat gain and reliance on mechanical cooling. Furthermore, promoting energy conservation awareness among the public and fostering sustainable practices can contribute to reducing the energy impact during the cooling season and mitigating the implications of heatwaves. This includes encouraging energy-efficient behaviour, such as adjusting thermostat settings, optimizing building insulation, and adopting smart control systems (CIBSE, 2021).

For this study, simulations are carried out during the cooling season to assess the effect of passive strategies on indoor thermal comfort. The cooling period considered is from 1st June to 10th September.

03 | Literature Review

3.1 Facade strategies

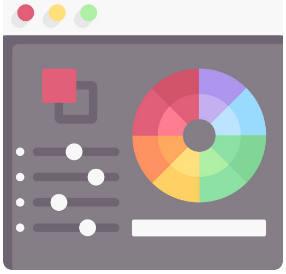
3.1.1 Influence of facades on thermal comfort

To understand the influence of building facades on thermal comfort, a number of papers were studied. The information obtained from these papers is explained in the this section. The key word strings used to look for relevant papers from sources such as scopus, science direct, research gate and google scholar is as follows:

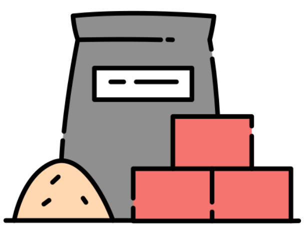
> (facade OR glazing OR (building AND envelope) AND ((thermal AND comfort) OR (energy) OR (energy AND saving))

The thermal comfort of indoor spaces and the associated energy consumption for heating and cooling are significant considerations in building design and operation. Mechanical cooling and heating systems are commonly employed to achieve and maintain indoor comfort levels, but they consume substantial amounts of energy. Building envelopes play a crucial role in shaping the thermal comfort of a space and have a direct impact on the energy required for maintaining comfort. Therefore, it is imperative to thoroughly understand the influence of facades on thermal comfort in order to optimize building performance and reduce energy consumption. This section aims to explore the relationship between facades and thermal comfort, highlighting their importance in achieving energy-efficient building design and operation.

The thermal comfort of a building can be influenced by three main factors related to the facade: design parameters, building material properties, and site parameters (Raji et al., 2016). Design parameters encompass elements such as the type of glazing, window area, and shading systems employed in the facade design. These factors directly impact the amount of solar radiation, daylight, and heat transfer entering the building (Nguyen et al., 2020). Glazing type plays a significant role in determining the amount of solar radiation that enters the building and affects thermal comfort. High-transmittance clear glass can improve daylight penetration and reduce energy consumption for lighting purposes (Sailor, 2008). Additionally, in heating-dominant climates, a high SHGC is desirable to maximize passive solar heat gains (Sunikka-Blank & Galvin, 2012). On the other hand, in hot climates, selecting glazing with a low SHGC can help limit solar heat gains and maintain thermal comfort (Santamouris et al., 2015). The WWR, which represents the proportion of window area compared to the total wall area, also impacts thermal comfort. Lower values of WWR tend to reduce heat transmission through the glazed area, leading to improved thermal comfort and energy savings (Gonçalves et al., 2017).



Design parameters



Building material properties

Site parameters

Fig. 2 Three main factors related to facades according to (Raji et al., 2016)

Building material properties play a crucial role in the thermal performance of the facade. Properties such as thermal mass, insulation, and airtightness affect the heat absorption, retention, and transmission characteristics of the building envelope. These properties influence the indoor temperature stability and energy efficiency of the building (Almomani et al., 2020). The U-value of the facade, which represents its thermal transmittance, influences heat transfer through the building envelope. Choosing materials with low U-values can minimize heat loss or gain and improve thermal comfort (Gonçalves et al., 2017). Insulated glazing units with lower U-values provide better thermal insulation and contribute to reduced energy consumption (Wang et al., 2018).

Site parameters, including building orientation and climatic features, also contribute to the performance of the facade. The orientation of the building determines the exposure to solar radiation throughout the day, affecting the amount of heat gain or loss. Climatic features, such as ambient temperature, humidity, and wind patterns, influence the external conditions that impact the facade's thermal behaviour (Yang et al., 2020). Considering these three parameters in the design and operation of facades is essential for achieving optimal thermal comfort within buildings. By carefully selecting facade design elements, utilizing suitable building materials, and considering site-specific factors, architects and engineers can create facades that enhance thermal comfort, energy efficiency, and occupants' well-being (Nguyen et al., 2020).

The research conducted by **Khadraoui and Sriti (2018)** presents the key findings derived from a comprehensive study that combined empirical measurements conducted in existing buildings and parametric analysis through simulation. The primary objective of this investigation was to assess the impact of both material and conceptual aspects of the facade on the thermal comfort of office spaces located in a hot and arid climate. The initial phase of the study involved on-site measurements, which confirmed the significance of carefully considering the physical properties of the building materials used in the facade. Specifically, the study emphasized the importance of thermal inertia in mitigating thermal discomfort in hot and arid climates. The choice of building materials emerged as a crucial factor influencing the thermal performance of the facade. The subsequent phase of the study employed "EnergyPlus" software with the "Open Studio" platform to conduct a parametric analysis. The focus of this analysis was on a prominent thermal aspect of the facade, namely, thermal inertia. The results demonstrated that an increase in the thermal inertia of facade materials exerted a positive influence on the thermal behaviour of the building, ultimately enhancing the comfort of the occupants. (Khadraoui & Sriti, 2018)

Raji et al. (2016) looked at the influence of two important facade elements - Glazing type and window to wall ratio, on thermal comfort and energy saving potential. The authors considered an educational high rise building for their analyses. The study investigated the effect of window size on building energy consumption, specifically focusing on the window-to-wall ratio (WWR). Different values of WWR were simulated, ranging from 100% (fully glazed) to 30% (uninsulated opaque facade). The results showed that lower values of WWR led to higher energy savings for cooling and heating, but slightly increased energy use for electric lighting compared to a fully glazed facade. The replacement of glazed areas with uninsulated opaque elements had limited energy benefits, particularly in climates where heating is the dominant energy consumption. The study found that a WWR of around 50% achieved the highest energy savings when the external wall was well-insulated. Furthermore, the type of glazing also influenced energy performance, with double-glazed clear glass performing better than single-glazed tinted windows. in this case, the results of this study were focussed on reducing heating demand (Raji et al., 2016).

The performance of a facade relies on the characteristics of glass panes, such as their ability to reflect, absorb, or transmit solar radiation. Clear glass with high transmittance is beneficial for daylight penetration and reducing energy consumption for lighting, especially in heating-dominant climates. In hot climates, glazing with a low solar heat gain coefficient (SHGC) is necessary to limit solar heat gains. Additionally, choosing glass with a low U-value reduces thermal transmission. In terms of energy retrofitting, double-glazed clear panes showed more energy savings for heating compared to triple-glazed windows. For cooling, a facade design with a tinted glass pane performed best. It's important to consider heating and cooling needs when selecting the most energy-efficient window strategy. Overall, this study highlights the importance of WWR and glazing type in determining facade performance in terms of thermal comfort and energy use (Raji et al., 2016).

In conclusion, the design of facades plays a crucial role in ensuring thermal comfort within buildings. Factors such as glazing type, window-to-wall ratio (WWR), solar heat gain coefficient (SHGC), U-value, and orientation significantly impact thermal comfort. The selection of glazing types with high transmittance and appropriate SHGC values can optimize daylight penetration and reduce energy consumption for lighting. In heating-dominant climates, higher SHGC values are desirable to maximize passive solar heat gains, while in hot climates, lower SHGC values help limit solar heat gains. Lower WWR values contribute to reduced heat transmission but must be balanced with potential reductions in daylight and solar heat gains. Opting for materials with low U-values enhances thermal insulation and reduces heat transfer through the facade. Proper orientation of the facade with respect to the sun's path and the inclusion of shading devices contribute to better thermal comfort. Considering these factors during facade design can enhance energy efficiency and occupant well-being.

3.1.2 Review of passive façade strategies used during the cooling season

The previous section highlights how the building envelope plays a crucial part in maintaining thermal comfort in buildings and hence it is important for designers and engineers to carefully examine the effects of a façade they plan to execute. A number of studies have been conducted to observe which façade strategy would perform best without the use of mechanical systems, in terms of indoor comfort especially due to the rapid increase in temperatures across the world. In this literature review, a number of these studies will be discussed.

The keyword strings used to look for relevant papers are given below, the sources were obtained from scopus, research gate, and science direct.

(I) (facade OR glazing OR (building AND envelope) AND (extreme AND heat) OR (heat AND wave) OR (overheating) AND (thermal AND comfort) AND (passive AND design) OR (passive AND strategy))

(II) ((facade OR envelope) AND indoor AND ((extreme AND heat) OR (heat AND wave) OR (overheating)) AND (thermal AND comfort))

In this section, a comprehensive review of the existing literature on passive facade strategies used during the cooling season is presented. The aim is to explore various approaches and techniques employed to enhance thermal comfort and reduce energy consumption in buildings during warm periods. The selection process involved a systematic search that initially identified around 160 relevant papers. Through a rigorous evaluation, based on relevance, applicability, and type of facade strategy, 40 papers were shortlisted. From these 40 papers, the ones which were focussed on office and institutional buildings were shortlisted. Further, these papers were divided based on the type of facade strategy analysed, and the papers that focussed on policy based impact and only having minor facade enhancements were eliminated. Finally, 20 papers were chosen to be included in this review. The selected studies cover a range of passive facade strategies, across various regions to showcase variability and provide valuable insights into their effectiveness and potential applications. By examining the findings and methodologies of these studies, this review aims to provide a deeper understanding of the passive facade strategies employed for cooling purposes and their impact on building performance. Moreover, the review also seeks to identify any research gaps in the existing literature, which will serve as the foundation for further development in this thesis. By addressing these research gaps, this study aims to contribute to the existing knowledge and provide valuable recommendations for the design and implementation of passive facade strategies during the cooling season.

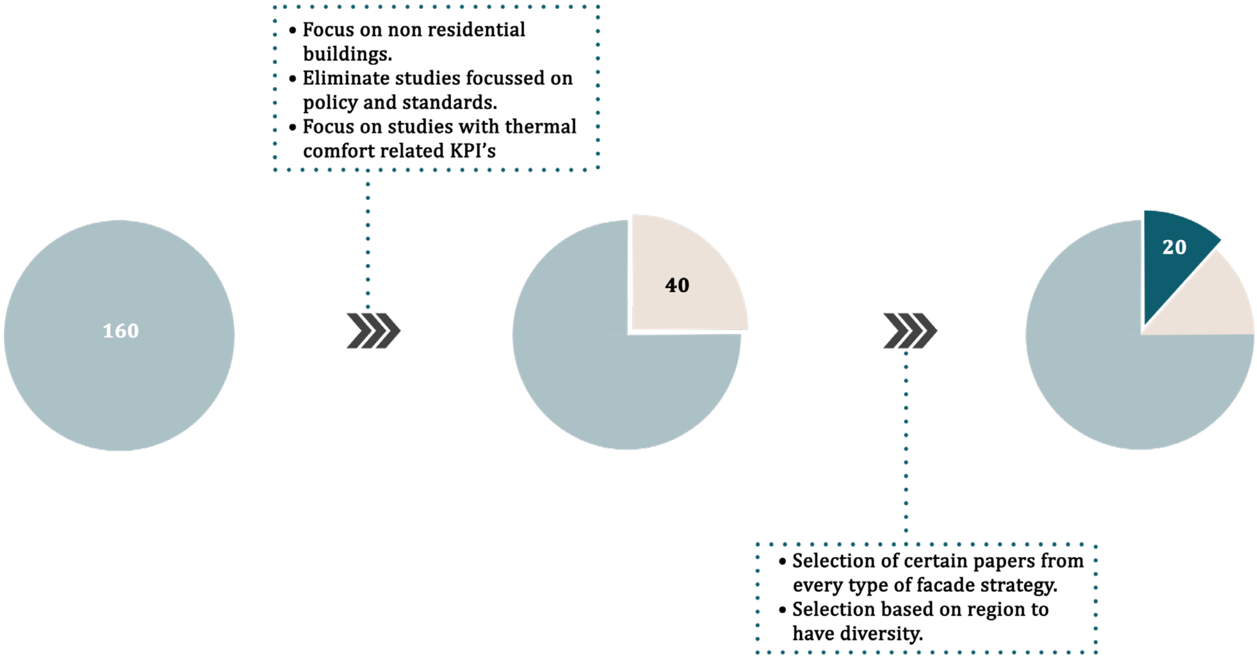


Fig. 3 Diagrammatic representation of the selection process for literature review (number of papers)

The 20 papers selected were published between the years 2002 to 2022, as show in in figure 4. The research from these papers were conducted in various climatic zones as defined by ASHRAE standard 169, this is shown in figure 5. The variation in the climatic zones was an important factor in selecting the papers, as the climate of a region has a large influence on the impact of these facade strategies on comfort, along with this, the papers selected are all within the past decade to maintain the advancement of technologies and concepts in this field.

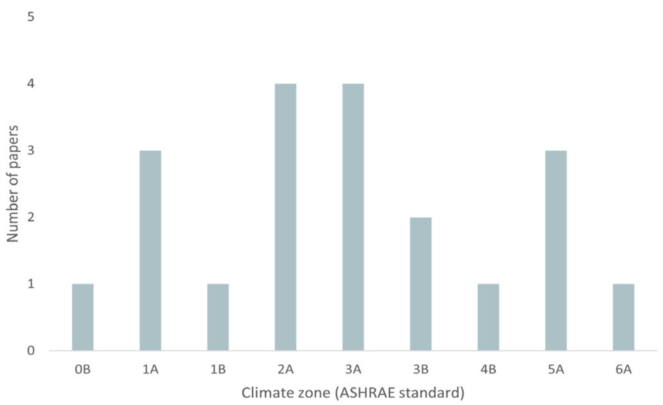


Fig. 4. Graphical representation of the different climatic zones considered by the 20 papers as defined by ASHRAE 169

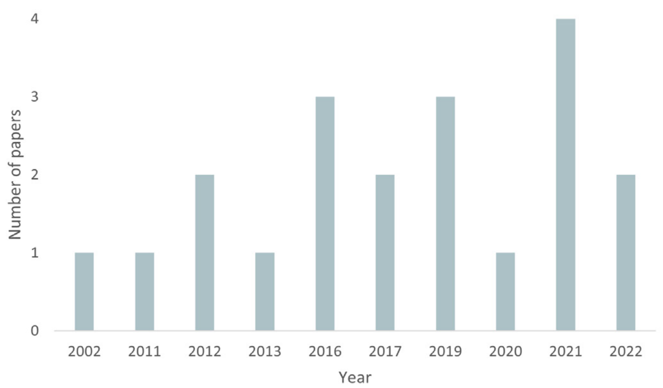


Fig. 5. Graphical representation of the years of publication of the 20 papers

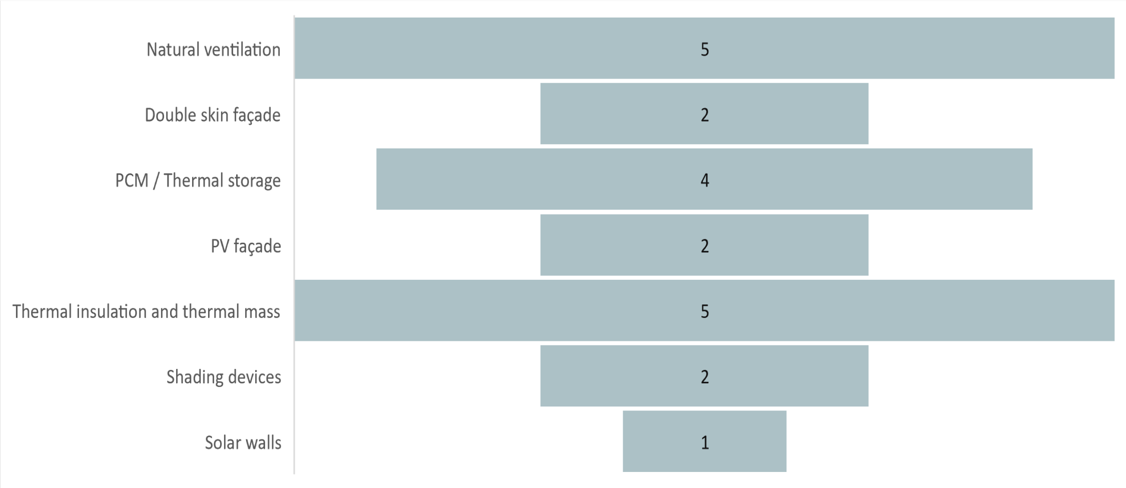


Fig. 6. Graphical representation of the different facade strategies considered for the studies

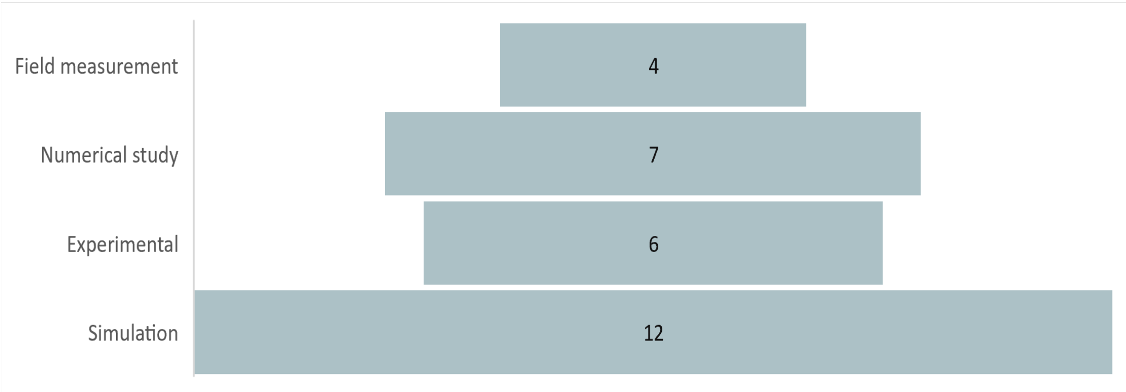


Fig. 7. Graphical representation of the method of study used in the different papers

From the 20 papers, 7 main groups of facade strategies considered are identified, the distribution is shown in figure 6. These strategies are the most commonly used and tested strategies in the built environment. In every paper, the method of analysis or study is different, 4 main methods are identified and the distribution is shown in figure 7.

Various facade strategies are currently under development and undergoing testing to achieve optimal performance. These strategies encompass a range of approaches, including both traditional and innovative methods. Traditional strategies include utilizing natural ventilation, cross ventilation, shading, and strategic building orientation. On the other hand, researchers are also exploring innovative systems such as incorporating phase change materials (PCM) in facades, implementing Trombe and solar wall systems, integrating photovoltaic (PV) systems, and developing novel natural ventilation systems. These diverse strategies demonstrate the ongoing efforts to improve facade performance and enhance the overall energy efficiency and comfort of buildings.

Table 2 provides a comprehensive overview of the 20 papers that were reviewed for this thesis. The table presents key information about each paper, including the objective of the study, the type of study conducted, the building function that was analyzed, the climate zone in which the study took place, the key performance indicators (KPIs) used to evaluate the performance of passive strategies, the specific passive strategy that was tested or analyzed, any user interaction considered in the study, and the results and conclusions drawn from each paper.

The purpose of this table is to present a concise and simplified summary of each paper, allowing for a clear understanding of the studies conducted. By examining the table, one can easily identify the passive strategies that were used or tested in each study, as well as the impacts of these strategies on the building's performance. Furthermore, the table helps to identify any common research gaps that exist across all the papers, providing insights into areas where further research is needed. Also, by examining the KPIs used in the various papers, it becomes possible to gain insights into the specific metrics and indicators that were commonly employed to assess the performance of passive strategies. The selection and use of KPIs provide a standardized framework for evaluating the effectiveness of different strategies across multiple studies.

In essence, this table serves as a valuable tool for comprehending the range of passive strategies explored in the reviewed papers, understanding their effects, and identifying overarching research gaps that require additional investigation. It aids in gaining an overview of the studies and facilitates the identification of trends and patterns in passive building design and performance evaluation.

Due to the amount of information the table is presenting in landscape orientation in the following pages.

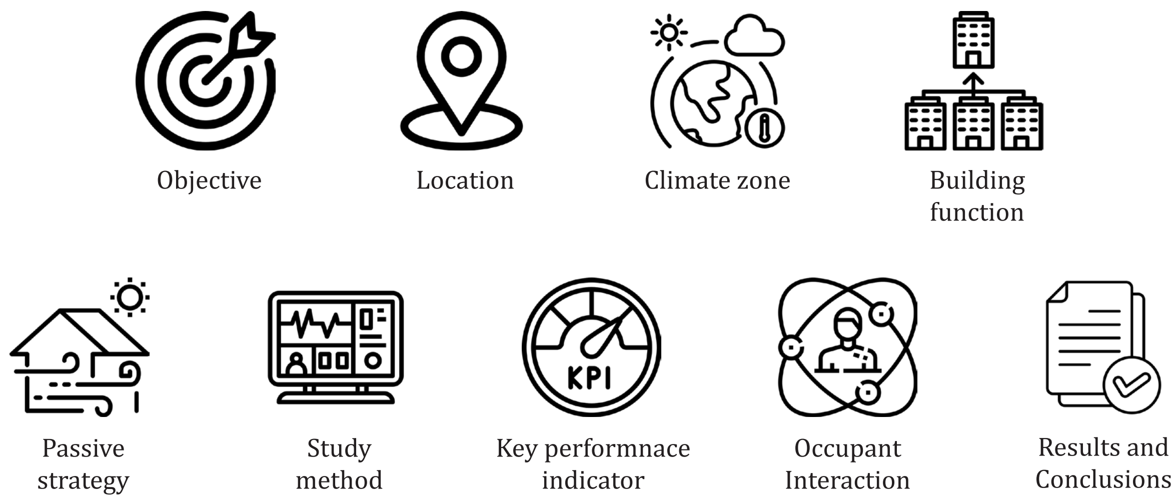


Fig. 8. The different aspects considered for tabulating the papers selected for literature review

Table 3. Tabular representation of the papers studied as part of the literature review

Sl.No	Article/Paper	Objective	Type of study	Location	Building Function	Climatic Zone (ASHRAE)	KPIs	Passive strategy tested	User Interaction	Results and Conclusions
1	Nasrollahi, N., & Ghobadi, P. (2022)	To use passive strategies in high-rise office buildings in hot and dry climates. Tries to help reduce energy consumption and provide thermal comfort in indoor spaces by improving the performance of natural ventilation systems and achieving the optimal position of the openings	Field measurement and numerical investigation	Tehran	Smart-high rise ofice building	3B	Indoor Temperature Air velocity	natural-ventilated buildings based on wind-driven and buoyancy-driven forces (cross-ventilation) Double Skin Façade	Not considered	The position of the building openings and the combination of their different positions can have a positive effect on the performance of the cross-ventilation system of tall buildings. The use of natural ventilation is recommended as a complementary strategy in high-rise buildings. The DSF system also helps to improve the thermal control of indoor spaces by creating the stack effect, air circulation, and vertical ventilation.
2	Zahiri, S., & Altan, H. (2016).	To improve the thermal performance of school buildings in the city of Tehran in Iran during warm season. - this study aims to provide environmental design guidelines for female secondary school buildings in a hot and dry climate of Tehran in the warm season with regard to passive design strategies and the students' thermal comfort.	Field studies and simulation analysis	Tehran	Female secondary school	3B	Heat gains Solar radiation Indoor air temperatures Shading device dimensions and geometry. Air movement rate Heat flows Thermal conductivity U-values Average internal temp Mean indoor air Temp	1. Orientation 2. Shading devices 3. Ventilation 4. Thermal insulation (walls and roof) 5. Thermal mass in walls	Not considered	The simulation results indicate that the building fabric and the thermal properties, as well as all-day natural ventilation, had significant influences on reducing the indoor air temperatures in the classrooms and keeping it in acceptable conditions.
3	Gupta, M. K., Rathore, P. K. S., & Singh, A. K. (2022).	the thermal performance of clay bricks integrated with sensible heat storage material, latent heat storage material, and hybrid (sensible + latent) was investigated	Experimental	experimental research is performed on the rooftop of the center for advanced studies, AKTU, Lucknow which is situated in the geographical location 26.94 North and 80.94 East, in India.	NA	1A	Time Lag Peak temperature reduction Thermal amplitude Decrement factor Max temp Min Temp	1. Sensible heat storage brick 2. Latent heat storage brick 3. Hybrid heat storage brick	Not considered	The study found that the SSB, LSB, and HSB bricks resulted in average peak temperature reductions of 1.01°C, 1.81°C, and 1.67°C respectively, compared to the conventional brick (CB). Additionally, the SSB, LSB, and HSB bricks exhibited inside thermal amplitudes of 12.14%, 13.74%, and 13.40% respectively, in comparison to the CB. Among these developed bricks, the LSB brick performed the best, demonstrating both significant peak temperature reduction and a time lag performance of 180 min. These findings indicate the superior thermal performance of the LSB brick compared to the other bricks in terms of temperature reduction and time lag.
4	Mahdaoui, M., Hamdaoui, S., Ait Msaad, A., Kousksou, T., El Rhafiki, T., Jamil, A., & Ahachad, M. (2021).	In this study, the integration of phase change material (PCM) in building hollow bricks) is proposed to improve the thermal performance of external walls. The objective of the present work is the enhancement of the storage capacity and insulation resistance of this latter through its integration by a phase change material.	The present study deals with physical modeling and numerical simulation of heat transfer through a building brick incorporate phase change material (PCM)	Morocco	NA	3A	Inner surface temperature variation Time Lag decrement factor Indoor dry bulb temp humidity indoor air velocity	Behavior of clay hollow brick impregnated with a PCM.	Not considered	The incorporation of phase change material (PCM) into the hollow brick enhances its capacity to store and insulate heat. This is evident through a notable decrease in temperature fluctuations and a noticeable delay in the transfer of thermal energy across the brick-wall containing PCM. This integration provides a compelling passive method for regulating indoor temperatures, thereby enhancing occupants' comfort and contributing to reduced energy usage in air conditioning systems within buildings.
5	Hwang, R. L., & Shu, S. Y. (2011).	Demonstrate the importance of Taiwan's envelope regulation upon energy usage and indoor thermal comfort.	Simulation	Taiwan	Tourist service centre	2A	Air temperature Mean radiant temp Relative humidity Air velocity Direct and diffuse solar radiation	Building envelope regulations	Not considered	Factors such as long-wave radiation from isothermal surfaces and solar radiation falling on the human body were taken into account. The study investigated different types of glazing, window areas, and shading devices to assess their impact on thermal comfort in a hot and humid climate region. The results showed that careful design of building envelope components can achieve both thermal comfort and energy conservation. The study also evaluated the energy-saving potential of comfort control systems based on the Predicted Mean Vote (PMV) index and found that it decreases with higher building envelope loads.
6	Han, J., Lu, L., Peng, J., & Yang, H. (2013).	Understanding and assessment of the airflow and heat transfer within the ventilated air cavity would enable architects to improve the thermal design of building external envelopes during building design stage. This study, therefore, focuses mainly on the investigation of the airflow characteristics of the air cavity	Experimental and numerical analysis.	Hong kong polytechnic university - E114°10 , N22°18 and at an altitude above sea level of 32.0 m.	NA	2A	Inlet velocity of air channel Indoor air temperature	Ventilated double sided PV façade system.	Not considered	The indoor air temperature within the Photovoltaic Façade (PVF) is significantly lower compared to the conventional shading devices in the conventional façade (CF). Furthermore, the temperature inside the PVF is less influenced by variations in outdoor weather conditions when compared to the CF. This innovative glazing system has the potential to not only generate electricity but also contribute to energy savings by reducing the cooling load of air conditioning systems, particularly in subtropical climates. Additionally, it ensures visual comfort in the indoor environment.

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7	Elsharkawy, H., & Zahiri, S. (2020).	The study investigates the impact of retrofitting on occupants' thermal comfort and building energy performance in the current and future climate scenarios (2030, 2050 and 2080)	Quantitative methodology which incorporated a questionnaire-based survey, indoor monitoring, and dynamic thermal modelling.	East London	Council housing tower	5A	Operative Temperature Relative humidity	Thermal performance of external walls - U values Thermal insulation of envelope	Not considered	Improved building performance may lead to over-insulated and airtight envelopes, increasing the risk of overheating during warmer seasons. Enhancing the U-value of external walls reduces winter heating energy use. However, thermal comfort varies among different demographic groups, necessitating consideration of real occupancy patterns. Overheating risk is insufficiently addressed in Building Regulations Approved Documents. It is also important to consider occupany patterns while evaluating overheating risk.
8	Stazi, F., Mastrucci, A., & di Perna, C. (2012).	This research investigates the thermal behavior of Trombe walls and their impact on heating and cooling energy needs and indoor thermal comfort. It also analyzes and optimizes the behavior of a solar wall system in different accommodation scenarios with varying envelope insulation levels. The focus is on using the Trombe wall as a non-ventilated solar wall in winter and as a Trombe wall with cross ventilation, shaded by roller shutters	Monitoring, Dynamic simulations, and parametrci analysis	Ancona	Housing accomodation	3A	Average outdoor temp Internal surface temp room temp heat flux Heat gains wall thermal resistance	Solar walls - Trombe walls .	Not considered	Solar walls are effective in intermediate seasons but increase cooling energy needs in summer. They exhibit favorable thermal behavior and indoor comfort. Simulations show that solar walls outperform conventional walls in heating seasons, especially with exterior double glazing. However, using solar walls without screening in summer can lead to excessive heat gains. Additional strategies like cross ventilation improve their summer performance.
9	Zhang, T., & Yang, H. (2019).	This study focus on the closed working mode of the air layers in building envelopes. This work aims to find these two dividing points in the air layer thickness, and to establish a simplified method for the judgment of the heat transfer pattern in insulation air layers.	numerical, simulation based	Harbin, Beijing, Wuhan and Hong kong	not given	2A	Covective and radiative heat transfer characteristics(Layer height, thickness and inclination angle. Temperature difference) Surface Emmisivity	Reserving intermediate air layers	Not considered	The incorporation of insulation air layers in building envelopes proves to be an effective measure in reducing monthly heat gain and heat loss. A specific case study demonstrates that by utilizing air layers as insulation in walls, roofs, and windows, the total annual heat transfer through the building envelopes can be reduced by 10.54-39.23%, varying according to the climate conditions.
10	Hengstberger, F., Zauner, C., Resch, K., Holper, S., & Grobbauer, M. (2016).	We carried out dynamic simulations of a facade integrated collector in stagnation to determine the optimum melting temperature of a thin layer of PCM at various positions between the absorber and the interior wall.	Simulation based	-	-	-	Temperature heat flux	Façade integrated solar thermal collectors	Not considered	Numerical simulations demonstrate that a thin layer of high temperature PCM positioned near the absorber in a facade integrated solar thermal collector ensures thermal comfort in the room behind the collector, even during prolonged periods of stagnation. The PCM quickly recharges at night due to the large temperature difference and proximity to the absorber. The regeneration process is reliable, with minimal impact from room or ambient conditions.
11	Cakyova, K., Figueiredo, A., Oliveira, R., Rebelo, F., Vicente, R., & Fokaides, P. (2021).	This study is focused on the analysis of different passive ventilation strategies towards indoor CO2 concen tration reduction preventing overheating risk, thus assuring high levels of indoor environmental quality	numerical, simulation based	Cyprus	Passive house	2A	CO2 concentration Overheating risk	Influence of turning of ventilation system. Natural ventilation	Not considered	The study aimed to balance energy demand, indoor comfort, and CO2 concentration. Scenarios were evaluated, and findings showed that Scenario 1 had good CO2 levels but high summer overheating. Scenario 2 had similar overheating risks and unacceptable CO2 concentrations. In Scenario 3-A, window openings for night ventilation achieved excellent CO2 levels and reduced overheating. Scenario 3-B had comparable overheating to 3-A and minimal periods of high CO2 concentrations. The study highlights the importance of passive ventilation strategies, especially night ventilation, for optimal indoor environmental quality with low CO2 and reduced overheating.
12	Zhu, N., Hu, N., Hu, P., Lei, F., & Li, S. (2019).	Study of the thermal performance of room integrated with double layers SSPCM wallboard were studied experimentally.	Experimental and numerical analysis.	Wuhan, China	Experimental space	1A	Indoor air temperature Interface temperature heat flow of wall surface	Double layers shape-stabilized phase change material (SSPCM) wallboard	Not considered	The study found that using a double-layer PCM wallboard effectively reduced indoor temperature fluctuations and improved thermal comfort. The PCM wallboard demonstrated strong heat storage capacity and enhanced the building's thermal inertia. The air gap between the two layers further improved thermal performance by reducing conduction heat transfer. Overall, integrating double layers of shape-stabilized PCM wallboard in buildings can effectively regulate indoor temperatures and enhance energy efficiency.

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13	Sun, Y., Wu, Y., Wilson, R., & Sun, S. (2016).	The work presented in this paper details the optical and thermal analysis of Parallel Slat TIM (PS TIM) structures that were sandwiched in be tween the two glazing panes of a double glazing unit.	Simulation and experimental	Nottingham, UK	NA	5A	Thermal conductance Temperature slat conductivity, thickness and emissivity	Double skin façade system	Not considered	The study found that incorporating a parallel slat transparent insulation material (PS-TIM) in a double glazing façade system significantly improved thermal insulation capabilities. The PS-TIM effectively reduced heat transfer through conduction, convection, and radiation, resulting in lower thermal conductivity and enhanced overall thermal resistance. This integration showed promising potential for enhancing thermal insulation and energy efficiency in buildings. The findings are valuable for professionals in the field of building envelope design and contribute to the development of energy-efficient building technologies.
14	Hamidi, Y., Malha, M., & Bah, A. (2021b).	Investigates the thermal performance of hollow brick walls filled with phase change material (PCM) and examines the impact of the PCM's location within the wall on its thermal behavior.	Simulation based	Er-rachidia (Morocco)	NA	3A	Heat Flux density Energy saving potential Thermal energy storage capacity Thermal comfort	PCM in brick walls	Not considered	The study's findings suggest that the placement of phase change material (PCM) within the hollow brick wall has a significant impact on its thermal performance. When the PCM is positioned in the outer layer of the wall, it efficiently absorbs and stores thermal energy during the day, resulting in reduced heat transfer into the building's interior. By strategically positioning PCM, heat transfer can be effectively controlled, energy consumption can be reduced, and the overall thermal performance of buildings can be enhanced.
15	Gourlis, G., & Kovacic, I. (2017).	This paper presents retrofit alternatives for a case study in Austria. Optimization measures and natural ventilation patterns were tested under currentproduction levels and hypothetical future scenarios for their adequacy to minimize overheating without the installation of an active cooling system.	Numerical and experimental	Austria	Industrial	6A	Indoor temperature Cooling energy savings Indoor air quality building envelope performance	Phase change materials	Not considered	Combinations of natural ventilation patterns and retrofit measures effectively reduce overheating without mechanical cooling. The findings highlight the divergence between adaptive and fixed temperature approaches to thermal comfort assessment, suggesting a need for further research. Cool coatings and exterior shading improve the thermal environment for low internal heat gains. For higher heat gains, a combination of coatings and shading proves effective. Complete thermal refurbishment may not be necessary.
16	Carrilho da Graça, G., Martins, N. R., & Horta, C. S. (2012).	Presents the results of the thermal and airflow simulation of an existing naturally ventilated shopping mall located near Lisbon, Portugal.	Simulation based	Lisbon	Commercial	3A	Thermal comfort Indoor air quality Energy efficiency airflow Occupant satisfaction Thermal stratification	Natural ventilation	Not considered	The study found that implementing natural ventilation systems in shopping malls can be challenging due to limited design time, local knowledge, and commercial pressures. In mild climates like Lisbon, natural ventilation resulted in over 30% reduction in HVAC energy consumption compared to closed malls. However, in colder climates like Paris, natural ventilation increased heating demand, making closed malls with mechanical ventilation and heat recovery a better option. These findings highlight the need to consider indoor comfort criteria, use thermal simulation during design, and tailor ventilation strategies to specific climatic conditions.
17	Hamidi, Y., Malha, M., & Bah, A. (2021).	To assess the thermal performance and energy efficiency of passive façade configurations and determine their effectiveness in providing natural ventilation for indoor spaces.	Simulation and experimental	Morocco	NA	3A	Air velocity Volume flow rate	Natural ventilation	Not considered	The simulation results showed that the Case 4 configuration was the most suitable for the heating seasons, while the Case 2 configuration was most effective for the cooling seasons. Combining the Passive Second Skin Façade with other passive technologies such as geothermal exchange, air radiative sky cooling systems, and effective sunshades during summer can further enhance thermal comfort. The findings of this study contribute to the development of Passive Façade designs and
18	Sabapathy, K. A., & Gedupudi, S. (2022).	The aim is to assess the impact of the straw insulation retrofitted envelope on the thermal behavior of the room and its suitability for different climatic conditions in India.	Simulation	India	NA	Multiple zones(1A,0B,5A,1B,4B)	indoor air temperature, decrement factor, and time lag. Need for occupant adaptation	Envelope insulation	Slightly considered	With the inlet vent open, indoor temperatures varied in relation to outdoor temperatures, but the presence of straw insulation reduced the temperature variations.Heat transport through vent openings had a significant impact on indoor temperatures, with the inlet vent contributing to heat addition and insulation inhibiting heat removal.Increasing straw insulation thickness had minimal effect on indoor temperatures.Closing the inlet vent temporarily or throughout the day improved indoor thermal
19	Calama-González, C. M., Ascione, F., León-Rodríguez, Á. L., & Ferrari, S. (2019).	Examines the impact of using an egg-crate shading device on the indoor environmental quality of classrooms in a hot climate.	in-situ monitoring	Spain	School classroom	3A	Incident solar radiation Indoor operative temperature illuminance level	Shading device	Not considered	The egg-crate shading device significantly reduced incident solar radiation, particularly during summer and mid-season. During an unoccupied period, the classroom with the shading device had lower indoor temperatures and higher indoor natural illuminance compared to the classroom without the device. When the classroom was occupied, the influence of the shading device on indoor temperatures was limited due to user control and high thermal loads.
20	Rosso, F., Cabeza, L. F., Castaldo, V. L., Cantarini, L., Cotana, F., Ferrero, M., & Jin, W. (2017b).	Aims to assess the optical, energy, and thermal properties of cool concrete in dynamic conditions, providing insights into its effectiveness in mitigating heat transfer and reducing energy consumption.	Experimental -lab testing and on site testing	-	NA	-	solar reflectance and thermal emittance	Material properties	Not considered	This research investigated cool-colored concrete prototypes with IR pigments. The prototypes had varying thermal-optical properties based on pigment content. Natural-White concrete had the highest reflectance and lowest surface temperatures with IR pigments. Black, blue, and red samples showed improved NIR reflectance and cooler surfaces with IR pigments. These materials have potential for thermal-energy retrofits and urban paving systems.

Nasrollahi and Ghobadi (2022) studied the impact of natural ventilation and the double-skin facade (DSF) system on enhancing thermal comfort in high-rise buildings situated in hot and dry climates through field studies and numerical analysis. The field study demonstrated that high-rise office buildings equipped with a building management system (BMS) effectively provided thermal comfort but consumed more energy than the standards. Incorporating controllable openings and natural ventilation significantly reduced cooling energy consumption. Numerical modelling using CFD simulation investigated the height and position of openings, as well as the cross-ventilation and stack effect of the DSF system by using a hypothetical six-storey high-rise office building as the subject of research. The investigation focused on exploring the influence of different configurations of inlet and outlet positions, which are depicted in figure 9, on the effectiveness of cross-ventilation.

The findings revealed that high-rise buildings with a BMS(building management system) efficiently delivered thermal comfort to occupants. Environmental factors, such as the position of floors and windows, correlated with thermal sensation and comfort. As the building height increased, the upper floors experienced improved volumetric flow rate and thermal comfort index compared to the lower floors. The position and combination of building openings had a positive impact on the performance of cross-ventilation systems. Among the nine configurations studied, configurations with the inlet at the top (A) had a more favourable effect on internal flow rate. The configurations with the inlet in the middle of the wall (B) resulted in the highest average internal temperature due to low-pressure zones and reduced volumetric flow. The DSF system contributed to thermal control through the stack effect, air circulation, and vertical ventilation. The study concluded that natural ventilation alone was insufficient to provide thermal comfort in hot and dry areas, resulting in a "slightly warm" sensation. The position of inlet openings played a significant role in achieving comfort conditions, while the impact of outlet openings was less pronounced. Inlet openings positioned at the top section of the facade created more favourable conditions in terms of average PMV values by increasing airflow velocity. The analysis showed that while the last floor experienced improved thermal comfort with increased building height, the middle floors mostly remained outside the comfort zone (Nasrollahi & Ghobadi, 2022).

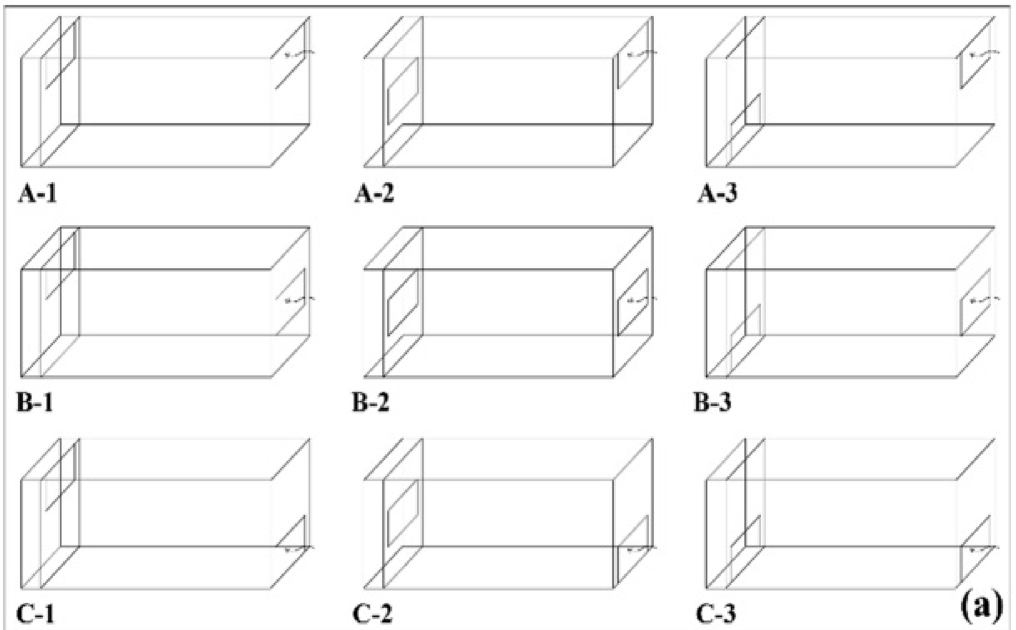


Fig. 9. Nine configurations of inlet and outlet positions studied by (Nasrollahi & Ghobadi, 2022)

This paper presented by **Zahiri and Altan (2016)** aimed at improving the thermal performance of school buildings in Tehran, Iran, during the warm season. The research involved field studies, on-site measurements, and a questionnaire-based survey in a typical female secondary school. On-site monitoring assessed indoor air temperatures and humidity levels in six classrooms, while occupants provided feedback on their thermal sensations and preferences. Additionally, thermal simulation analysis was performed to evaluate and enhance the thermal performance of the classrooms based on passive design strategies and students' thermal requirements. The study investigates the effectiveness of passive design strategies such as orientation, thermal insulation, shading devices, ventilation, and thermal mass materials. These strategies significantly impacted indoor air temperatures, maintaining an acceptable thermal condition. However, despite the implementation of passive design techniques, the study revealed that many occupants still found the thermal environment uncomfortable.

The questionnaire survey conducted was based on the ASHRAE 7-point scale and the 3-point McIntyre scale. The results showed that the students were not satisfied with their thermal environment and a large percentage of students preferred a cooler environment. DesignBuilder software was utilized to conduct thermal simulation analysis in two classrooms(one facing south and the other facing north) for a period of one week, aiming to evaluate and enhance their indoor thermal performance based on passive design strategies and students' satisfaction with thermal comfort. In an attempt to optimize passive design strategies and improve indoor thermal conditions, a series of simulations were performed. The suggested optimum design solution involved implementing various passive strategies, including south and south-east orientation, thermal insulation (10 cm in wall and 5 cm in the inner side of the roof), the use of solar shading devices such as 30 cm side fins and overhangs, all-day natural ventilation, and incorporating thermal mass materials with a thickness of 25-30 cm. These strategies were found to have a significant impact on reducing indoor air temperatures during the warm season in Tehran, resulting in an acceptable thermal condition. The field study experiments conducted in May showed that after applying the optimal solution, the maximum indoor air temperature decreased by approximately 5K in the south-facing classroom and 4K in the north-facing classroom. These findings highlight the effectiveness of passive design strategies in improving indoor thermal comfort and their potential to create a more favourable indoor environment (Zahiri & Altan, 2016).

A study by **Zhang and Yang (2019)** numerically investigates the flow and heat transfer characteristics of insulation air layers with different geometrical sizes and temperature boundary conditions. By analyzing the variation tendencies of the streamlines, isotherms, and temperature profiles, a simplified Rayleigh number (Ra) based judgment basis is summarized for the heat transfer pattern of the insulation air layers. Simultaneously, the critical thicknesses of the heat transfer pattern are determined under different temperature boundary conditions. Furthermore, the coupled convective and radiative heat transfer characteristics and the influencing factors of the heat transfer through the air layer are examined.

The findings reveal several important insights. Critical thicknesses are determined for different temperature boundary conditions. The study demonstrates that radiation plays a dominant role in heat transfer, contributing more than 60% of the total heat transfer rate. It is found that the height of the air layer inversely affects the natural convection intensity, and increasing the thickness effectively weakens the heat transfer rate up to a certain point. However, further increments in thickness beyond that point do not significantly improve performance. Based on the results, a recommended air layer thickness of 20-30 mm is suggested for exterior building envelopes, depending on the temperature difference condition. Specifically, a thickness of 20 mm is optimal for large temperature differences, while a thickness of 30 mm is optimal for small temperature differences. The study also highlights the potential for improving thermal performance by reducing the surface emissivity of the air layer. Decreasing emissivity from 0.95 to 0.2 can improve the thermal resistance of the air layer by 87.15-172.73% (Zhang & Yang, 2019).

They also considered a case study to demonstrate the benefits of using air layers as insulation in walls, roofs, and windows. It reveals that such insulation can lead to a reduction in the total annual heat transfer through building envelopes by 10.54-39.23%, depending on the climate conditions. Overall, these results provide valuable insights into the behaviour and optimization of insulation air layers (Zhang & Yang, 2019).

Elsharkawy and Zahiri (2020) conducted a study to assess the impact of improving the thermal insulation of a building envelope based on U-values and the retrofitting of the envelope on thermal comfort. The study was carried out in two phases. Firstly, the researchers evaluated the performance of a tower block, a prevalent social housing prototype in London. They examined the effect of over-cladding and improved external wall insulation (EWI) on energy use and overheating risk using simulation models in current and future climate scenarios. Different U-values were applied to investigate the impact of EWI thermal properties on indoor comfort and heating energy consumption.

The results demonstrated that improving the U-value of external walls reduced heating energy use in winter but led to gradual increases in indoor temperature during climate change scenarios. The second phase focused on the thermal comfort of a south-facing living room and bedroom with an improved building envelope. Two dominant occupancy and energy-use profiles were considered, and the results highlighted the need to incorporate these profiles for accurate energy performance and realistic predictions of post-retrofit overheating risks. The study also emphasized the significant influence of occupancy profiles on overheating risk, with households characterized by high occupancy and energy-use profiles facing a higher risk compared to those with low occupancy profiles. Integrating real occupancy profiles and considering building characteristics can enhance the prediction of building performance and optimize energy efficiency strategies. It is important to tailor evaluations of overheating risk to specific household types and building typologies, taking into account factors such as occupancy patterns, construction materials, and building age. By considering diverse occupancy scenarios and adaptive strategies, the study suggests that the risk of overheating can be reduced while improving thermal comfort and energy efficiency in buildings (Elsharkawy & Zahiri, 2020).

The study by **Cakyova et al. (2021)** aimed to analyze different passive ventilation strategies to reduce indoor CO_2 concentration and prevent overheating risks, ensuring high indoor environmental quality. The research methodology involved collecting data through interviews with Passive House residents to identify their expectations, complaints, and concerns about indoor environmental quality. The Tseri Passive House in Cyprus was used as a case study for whole building dynamic simulations using EnergyPlus software.

Three ventilation scenarios were evaluated: the original settings (scenario 1), mechanical ventilation active during the day and turned off at night (scenario 2), and natural night ventilation (scenario 3). The objective was to find a balance between energy demand, indoor comfort, and CO_2 concentration. Scenario 1 showed good CO_2 levels but high overheating during summer. Scenario 2 exhibited similar overheating risks as scenario 1 and unacceptable CO_2 concentrations. Scenario 3-A, with window openings for night ventilation, achieved excellent CO_2 levels below the normative limit and reduced overheating. Scenario 3-B, with limitations based on outdoor temperature and wind speed, had similar overheating to 3-A and negligible periods of high CO_2 concentrations. Analyzing the cooling demand based on the ventilation strategies, it was found that night ventilation through window openings resulted in approximately 28% reduction in cooling demand during the simulation period. The study demonstrated the effectiveness of night ventilation in reducing CO_2 concentrations and mitigating overheating, particularly in Southern European climates during the summer season. Further research is needed to evaluate improvements in mechanical ventilation systems, as scenario 1 showed periods of moderate indoor air quality during the night with two people in the same room (Cakyova et al., 2021).

The above studies looked at the conventional passive methods of improving thermal conditions, such as natural ventilation, thermal mass, use of shading and orientation of buildings. With the development of research new techniques are being invented and implemented as passive strategies to maintain comfort, one such technique is the use of thermal energy storage systems within the facade. One particular thermal energy storage system is becoming increasingly popular in the research communities which is the use of phase change materials in building envelopes.

In a study conducted by **Gupta et al. (2022)** in India, the thermal performance of clay bricks integrated with three types of thermal storage materials was investigated. The experiment aimed to assess the effectiveness of sensible heat storage (SSB), latent heat storage (LSB), and a hybrid storage material (HSB) in reducing peak temperatures and improving thermal characteristics. Paraffin and coconut oil were used as phase change materials for latent heat storage, while dry river sand served as the sensible heat storage material. Additionally, a regular clay brick was included for comparison.

The study analyzed various parameters including peak temperature reduction, time lag, thermal amplitude, and decrement factor. The results revealed significant improvements in thermal performance with the integration of thermal storage materials. The average peak temperature reductions achieved were 1.01°C for SSB, 1.81°C for LSB, and 1.67°C for HSB. Furthermore, the integration of SSB, LSB, and HSB led to inside thermal amplitude reductions of 12.14%, 13.74%, and 13.40%, respectively, compared to the regular clay brick. Among the developed bricks, LSB demonstrated superior performance. It not only exhibited the highest peak temperature reduction but also showed a time lag of 180 minutes, indicating delayed heat transfer compared to the regular clay brick (0 minutes) and the other integrated bricks (110 minutes for SSB and 120 minutes for HSB). These findings emphasize the potential of integrating thermal storage materials, particularly latent heat storage, into clay bricks to enhance their thermal characteristics and mitigate peak temperatures (Gupta et al., 2022).

Another study by **Mahdaoui et al. (2021)** conducted in Morocco also incorporated phase change material (PCM) in a hollow brick to evaluate the thermal response. The objective was to enhance the storage capacity and insulation resistance of the brick in hot areas commonly found in Mediterranean regions. A parametric study was conducted to assess the impact of PCM thermophysical properties, indoor and outdoor conditions on the thermal behaviour of the hollow brick. Numerical simulations using Ansys Fluent software, based on the finite volume method, were performed to analyze the thermal response. The enthalpy porosity-based method was employed to model the phase change process, and the numerical results were validated against experimental data from the literature.

The findings revealed that the latent heat and melting temperature are crucial properties to consider when selecting a PCM. Higher latent heat indicates better performance, while the melting temperature should be close to the average external thermal wave within the comfort range. Increasing the amount of PCM integrated into the brick significantly improved its thermal performance. However, the quantity of PCM should be optimized considering economic and mechanical strength aspects. The external convective heat transfer coefficient had a minor effect on the variation of the inner surface temperature of the brick, whereas the internal coefficient had a relatively significant influence. The integration of PCM in the hollow brick improved its storage ability and insulation power, resulting in a significant reduction in thermal wave amplitude and phase shift across the brick wall. This approach allows for optimized design and thickness of building materials, while also providing passive regulation of indoor temperature, enhancing internal comfort, and reducing energy consumption of air conditioning systems. The study demonstrated the favourable thermal behaviour of the brick with PCM, highlighting its potential for improving building performance (Mahdaoui et al., 2021).

To address the issue of overheating during periods of stagnation, **Hengstberger et al. (2016)** came up with a solution involving a layer of phase change material (PCM) embedded in the absorber insulation was explored. Dynamic simulations of a facade-integrated collector were conducted to determine the optimal melting temperature of the PCM layer at different positions between the absorber and the interior wall. The results showed that a high-temperature PCM with a melting temperature of up to 85°C, placed close to the absorber, effectively ensured thermal comfort in the room behind the collector even during extended periods of stagnation.

The simulations demonstrated that the proximity to the solar absorber and the high melting point of the PCM offered technical advantages. The regeneration process during the night, where the PCM solidifies and prepares for the next day, was found to be highly efficient due to the significant temperature gradients involved. The study also compared simulations using PCMs with different melting temperatures and positions. It was observed that PCMs with a wide range of melting temperatures could be used if positioned correctly. The research highlighted the importance of effective regeneration of the PCM for long-term thermal protection. Low-temperature PCMs positioned farther from the absorber showed limitations in their ability to fully recharge and buffer excess heat during extended stagnation. In contrast, higher temperature PCMs positioned closer to the absorber exhibited faster regeneration and maintained optimum thermal comfort throughout the stagnation period. The findings indicated that high-temperature PCMs, placed in proximity to the absorber, offer a promising solution for maintaining thermal comfort in buildings with facade-integrated solar thermal collectors (Hengstberger et al., 2016).

The study conducted by **Zhu et al. (2019)** focuses on investigating the thermal performance of a building integrated with double layers of shape-stabilized phase change material (PCM) wallboard. The study aimed to evaluate the thermal regulation capabilities of the PCM wallboard and its potential for improving the energy efficiency of buildings. The researchers conducted experiments to measure the heat transfer characteristics and thermal performance of the double-layer PCM wallboard under different external conditions.

The experimental setup involved constructing a test room equipped with the PCM wallboard and monitoring various parameters such as room temperature, heat flux, and energy consumption. The researchers investigated the effects of different factors, including PCM thickness, air gap between the two layers, and external temperature variations, on the thermal performance of the PCM wallboard. The results of the study showed that the double-layer PCM wallboard effectively reduced the indoor temperature fluctuations and enhanced the thermal comfort of the test room. The PCM wallboard demonstrated a significant heat storage capacity and improved the thermal inertia of the building. The presence of the air gap between the two layers further enhanced the thermal performance by reducing the heat transfer through conduction. The study concluded that integrating double layers of shape-stabilized PCM wallboard in buildings can effectively regulate indoor temperatures and improve energy efficiency. The research findings provide valuable insights for the application of PCM materials in building design and contribute to the development of sustainable and energy-efficient buildings (Zhu et al., 2019).

The study by **Hamidi et al. (2021)** investigates the thermal performance of hollow brick walls filled with phase change material (PCM) and examines the impact of the PCM's location within the wall on its thermal behaviour. The study focuses on the use of PCM to enhance the thermal properties of building walls and improve energy efficiency. The researchers conducted numerical simulations using a validated computational model to analyze the heat transfer characteristics of hollow brick walls filled with PCM. The simulations considered various scenarios with different PCM locations, including the outer layer, the inner layer, and the middle layer of the wall. The researchers evaluated parameters such as the temperature distribution, heat transfer rate, and thermal energy storage capacity to assess the impact of PCM location on the thermal behaviour of the walls.

The results of the study indicate that the location of the PCM within the hollow brick wall significantly affects its thermal performance. When the PCM is placed in the outer layer of the wall, it effectively absorbs and stores thermal energy during the day, leading to reduced heat transfer into the building's interior. This configuration helps to regulate indoor temperatures and improve thermal comfort. In contrast, when the PCM is positioned in the inner layer of the wall, it acts as a thermal buffer, absorbing excess heat from the interior and releasing it back during cooler periods, thereby reducing energy consumption for heating. Furthermore, the study found that placing the PCM in the middle layer of the hollow brick wall offers a balanced thermal behaviour, providing both heat storage capacity and heat transfer regulation. This configuration ensures a more uniform temperature distribution across the wall and helps maintain a stable indoor environment. The analysis highlights the importance of optimizing the location of PCM within the wall to maximize its thermal benefits. Proper PCM placement can effectively regulate heat transfer, reduce energy consumption, and enhance the thermal performance of buildings (Hamidi et al., 2021).

Extensive research has been conducted on strategies such as PV facades, solar walls, and ventilated cavities to assess their performance when used in building envelopes. One particular study by **Han et al. (2013)** focused on analyzing the airflow and heat transfer within a ventilated cavity installed behind a PV panel. The study employed an experimental approach, comparing the performance of a PV facade with a conventional glass facade.Two identical experimental setups were created, one for the PV facade and another for the conventional facade. The primary objective of the study was to analyze the airflow properties of the air cavity. The inlet condition and velocity of the outside air drawn into the cavity were carefully examined to ensure accurate results. The findings revealed that the indoor air temperature of the PV facade was significantly lower compared to the conventional facade with an internal shading curtain. The conventional facade exhibited larger temperature variations. The maximum air temperature inside the PV facade test module was measured at 29°C, while it reached 34°C inside the conventional facade module. This indicated a clear advantage of incorporating a ventilated air channel behind a PV facade. The study highlights the potential benefits of using a ventilated cavity behind a PV facade in terms of reducing indoor air temperatures and improving thermal performance (Han et al., 2013).

The study conducted by **Stazi et al. (2012)** focuses on investigating the performance of solar walls in residential buildings with varying insulation levels. The study incorporates both experimental and numerical analysis. The authors conducted experiments to evaluate the thermal behaviour of solar walls in different residential building prototypes. They examined the impact of solar wall design parameters, such as the air gap thickness, absorber plate type, and insulation levels, on the thermal performance of the building. Measurements are taken to assess variables such as air temperature, surface temperature, and heat transfer rates. The authors also developed a numerical model to simulate the thermal behaviour of the solar walls. The model considered various factors, including solar radiation, airflow, and heat transfer mechanisms.

The findings of the study revealed that the solar walls had a significant impact on reducing heat losses and improving the thermal performance of the residential buildings. The experimental results demonstrated that the insulation level of the building envelope influenced the effectiveness of the solar walls. Higher insulation levels led to greater heat preservation and energy savings. The numerical simulations provided further insights into the thermal behaviour of the solar walls and validated the experimental results. The simulations showed that the design parameters of the solar walls, such as the air gap thickness and absorber plate type, played a crucial role in determining their performance. Overall, the study highlights the potential of solar walls as a passive solar strategy for enhancing the energy efficiency of residential buildings. The combination of experimental and numerical analysis provides valuable insights into the behaviour of solar walls under different insulation levels, contributing to the understanding and optimization of this sustainable building technology (Stazi et al., 2012).

Sun et al. (2016) looked at the thermal performance assessment of a double glazing façade system that incorporates a parallel slat transparent insulation material (PS-TIM). The study aimed to investigate the effectiveness of the PS-TIM in improving the thermal insulation properties of the double glazing façade system. The researchers conducted thermal evaluations using numerical simulations and experimental measurements to assess the heat transfer characteristics and thermal performance of the system. The numerical simulations involved creating a computational model of the double glazing façade system with the integrated PS-TIM and analyzing its thermal behaviour under different external conditions. The experimental measurements included conducting thermal tests on a full-scale prototype of the façade system to validate the simulation results and evaluate its real-world performance.

The results of the study demonstrated that the integration of the PS-TIM in the double glazing façade system significantly improved its thermal insulation capabilities. The PS-TIM effectively reduced heat transfer through conduction, convection, and radiation, resulting in lower thermal conductivity and improved overall thermal resistance. The numerical simulations and experimental measurements both confirmed that the double glazing façade system with the integrated PS-TIM achieved lower U-values and reduced heat losses compared to a conventional double glazing system without the PS-TIM. The system demonstrated enhanced thermal performance, leading to improved energy efficiency and reduced heating and cooling loads for buildings. The study concluded that the integration of a parallel slat transparent insulation material (PS-TIM) in a double glazing façade system offers promising potential for enhancing thermal insulation and energy efficiency in buildings (Sun et al., 2016).

The paper by **Gourlis and Kovacic (2017)** explores passive strategies to mitigate summer overheating in industrial buildings, taking into account the fluctuating heat loads associated with manufacturing processes. The study focuses on the challenge of maintaining comfortable indoor temperatures and preventing overheating in industrial buildings, where high heat gains from manufacturing activities can lead to uncomfortable working conditions and increased energy consumption for cooling. The researchers investigate the effectiveness of passive measures in reducing overheating risks while considering the variability of manufacturing process loads. Through the use of dynamic thermal simulations, the researchers analyze different passive strategies, including natural ventilation, solar shading devices, thermal mass utilization, and night cooling techniques. They evaluate the performance of these measures in terms of indoor temperature levels, cooling demand, and thermal comfort for building occupants.

The results of the study demonstrate that a combination of passive measures can effectively mitigate summer overheating in industrial buildings. Natural ventilation strategies, such as the use of operable windows and roof vents, prove to be effective in facilitating airflow and heat dissipation, particularly during night time when outdoor temperatures are lower. The implementation of solar shading devices, such as external blinds or louvers, helps to reduce solar heat gains and prevent excessive solar radiation from entering the building. This reduces the cooling demand and helps maintain comfortable indoor conditions. Furthermore, the utilization of thermal mass in the building's structure, such as concrete or masonry walls, allows for heat absorption during the day and release of stored heat during cooler periods, contributing to temperature stabilization and thermal comfort improvement. Night cooling techniques, such as night time ventilation or pre-cooling the building using cool outdoor air during off-peak hours, also prove to be effective in reducing indoor temperatures and minimizing overheating risks (Gourlis & Kovacic, 2017).

The paper by **Hamidi et al. (2021)**, focuses on the investigation of four passive second skin façade configurations as a natural ventilation system in both winter and summer seasons. The objective of the study is to assess the thermal performance and energy efficiency of these passive façade configurations and determine their effectiveness in providing natural ventilation for indoor spaces. The researchers aim to contribute to the design of sustainable buildings with improved indoor comfort and reduced energy consumption. This research considered two methods for evaluation : simulations and experimental numerical study.

The researchers present a study that utilized validated computational fluid dynamics (CFD) simulations to evaluate the effectiveness of different configurations of the passive second skin façade as a passive ventilation system in various climate zones of Morocco during both cooling and heating seasons. The simulation results identified the Case 4 configuration as the most suitable for heating seasons and the Case 2 configuration as the most effective for cooling seasons. These configurations achieved an average volume flow rate between 200 m3/h and 400 m3/h, with specific dimensions for the second-skin façade area and air vent area. The study also highlights the importance of combining the Passive Second Skin Façade with other passive technologies for enhanced thermal comfort, such as geothermal exchangers, air radiative sky cooling systems, and appropriate sunshades during the summer months. This paper reinforces the positive effects of using natural ventilation and double skin facades to maintain thermal comfort within buildings.

The study conducted by **Sabapathy and Gedupudi (2022)** explores the thermal performance of a naturally ventilated room with a straw insulation retrofitted envelope in various climatic zones of India. The aim is to assess the impact of the straw insulation retrofitted envelope on the thermal behaviour of the room and its suitability for different climatic conditions in India. The authors conducted field experiments in different cities representing distinct climate zones: Chennai (hot and humid), Jaipur(composite),Shimla(cold), Ahmedabad (hot and dry), and Bengaluru (temperate/ moderate).

The experimental setup involved retrofitting the room's external walls with straw insulation panels. Temperature and humidity sensors were placed inside and outside the room to monitor the thermal conditions. The study examined the indoor air temperature, relative humidity, and thermal comfort indices, such as Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD).

The findings of the study indicate that the straw insulation retrofitted envelope significantly improves the thermal performance of the room in all three climatic zones. In the hot and humid climate of Chennai, the retrofitted room exhibited reduced indoor temperature and improved thermal comfort. In the hot and dry climate of New Delhi, the straw insulation helped in maintaining lower indoor temperatures and reducing the cooling load. In the cold climate of Shimla, the retrofitted room demonstrated enhanced insulation and reduced heat loss, resulting in improved indoor thermal comfort. The findings suggest that straw insulation can effectively regulate indoor temperatures and

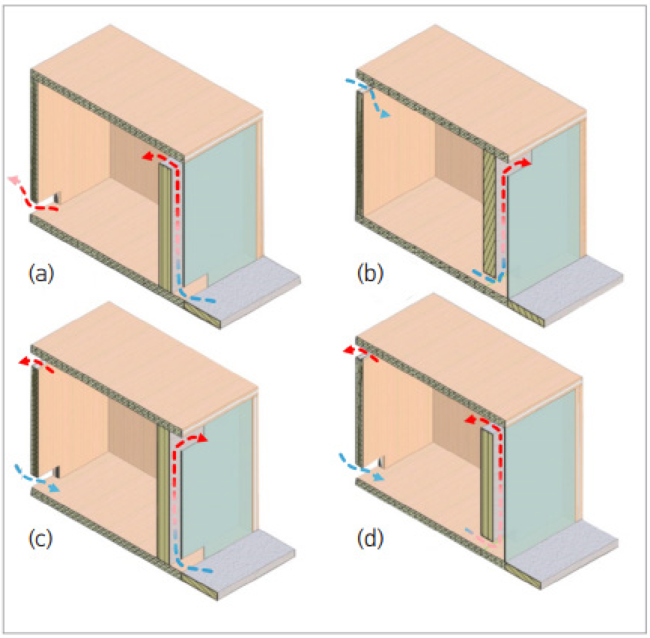


Fig.10. Cross-section of the studied configurations: Case 1 (a), Case 2 (b), Case 3 (c), and Case 4 (d) (Hamidi et al., 2021)

enhance thermal comfort. The authors also attempt to consider occupant adaptation in terms of the vent state and concluded that this could have a significant influence on thermal comfort.
The paper by **Calama-González et al. (2019)** examines the impact of using an egg-crate shading device on the indoor environmental quality of classrooms in a hot climate. The study assesses parameters such as thermal comfort, daylighting, and energy consumption to evaluate the effectiveness of the shading device in improving the overall indoor environment. The research findings indicate that the egg-crate shading device successfully reduces the solar heat gain in the classrooms, leading to improved thermal comfort for occupants. The device also contributes to reducing glare and enhancing daylighting conditions, creating a more comfortable and visually pleasing learning environment. Additionally, the shading device helps in reducing energy consumption by minimizing the need for artificial lighting and cooling systems.

The paper provides valuable insights into the potential benefits of using an egg-crate shading device for retrofitting classrooms in hot climates. The study demonstrates the positive impact of the shading device on various aspects of indoor environmental quality, highlighting its potential to create more sustainable and comfortable learning spaces. The research methodology employed in assessing parameters such as thermal comfort and daylighting adds credibility to the findings. However, it is important to note that the study focuses specifically on classrooms in a hot climate, which limits the generalizability of the findings to other types of buildings or climates. Additionally, the study does not extensively explore the potential drawbacks or limitations of using an egg-crate shading device, such as potential maintenance issues or the impact on exterior aesthetics.

The paper by **Rosso et al. (2017)** investigates the performance of cool concrete as a sustainable solution for building envelopes and urban paving. The study aims to assess the optical, energy, and thermal properties of cool concrete in dynamic conditions, providing insights into its effectiveness in mitigating heat transfer and reducing energy consumption. The research focuses on the optical properties of cool concrete, particularly its solar reflectance and thermal emittance. The study employs advanced laboratory techniques to measure these properties and compares them with conventional concrete materials. The results demonstrate that cool concrete exhibits significantly higher solar reflectance and thermal emittance, leading to lower surface temperatures and reduced heat absorption. This characteristic plays a crucial role in mitigating the urban heat island effect, where cities experience elevated temperatures due to the abundance of concrete and asphalt surfaces.

The authors also investigate the energy-saving potential of cool concrete. The researchers analyze its impact on cooling loads and the overall energy consumption of buildings. By employing numerical simulations and energy modelling, they quantify the potential energy savings achieved by incorporating cool concrete into building envelopes and urban paving systems. The findings reveal that cool concrete can effectively reduce cooling loads, resulting in substantial energy savings and improved energy efficiency in buildings. The research provides in-depth insights into the optical and thermal properties of cool concrete in dynamic conditions, enhancing the understanding of its performance under real-world scenarios. The comprehensive approach taken by the researchers, combining laboratory experiments and numerical simulations, adds credibility to the findings and increases the applicability of the results.

However, it is important to acknowledge certain limitations of the study. The research primarily focuses on the optical and thermal properties of cool concrete, without delving into other aspects such as structural integrity, long-term durability, or the economic feasibility of its implementation. Additionally, the study's scope seems to be centered on the assessment of the material's properties, with less emphasis on the practical considerations and potential challenges associated with its widespread adoption.

Conclusions

The literature review highlights several passive strategies for improving building performance and reducing energy consumption. These strategies include passive ventilation, integration of phase change materials (PCMs), transparent insulation materials, and specific measures for industrial buildings. Passive ventilation strategies, such as natural night ventilation, have shown great potential in reducing CO_2 concentration and preventing overheating in buildings. They provide effective airflow and ventilation, improving indoor environmental quality and reducing the reliance on mechanical cooling systems. Natural ventilation not only enhances occupant comfort but also contributes to energy efficiency and a healthier indoor environment.

The integration of shape-stabilized PCM wallboard into building envelopes has been found to positively impact thermal performance. PCM wallboard acts as a thermal energy storage medium, absorbing excess heat during the day and releasing it during cooler periods. This technology helps regulate indoor temperature, reduce temperature fluctuations, and improve thermal comfort. The use of PCMs has the potential to enhance building performance and reduce energy consumption. The utilization of parallel slat transparent insulation material (PS-TIM) in double glazing façade systems has demonstrated promising results in improving thermal insulation and energy efficiency. PS-TIM helps minimize heat gains, reduce cooling loads, and enhance the overall thermal performance of the building envelope. This passive measure effectively mitigates thermal bridging and contributes to energy savings.

Overall, the literature review reveals that passive strategies play a crucial role in improving building performance and reducing energy consumption. Passive ventilation, integration of PCMs, utilization of transparent insulation materials, and industrial-specific measures offer valuable solutions for achieving sustainable buildings. These strategies contribute to better indoor environmental quality, energy efficiency, and occupant comfort. However, it is important to consider the specific context, climate, and building characteristics when implementing passive strategies. Further research and validation are needed to assess the long-term performance, economic feasibility, and scalability of these strategies across different building types and operational conditions. Additionally, a comprehensive and integrated approach to building design, combining multiple passive strategies, is crucial to optimize energy efficiency and indoor environmental quality.

In conclusion, passive strategies offer significant potential for improving building performance and reducing energy consumption. The findings from the literature review emphasize the importance of considering passive measures during the design and operation of buildings to achieve sustainable and energy-efficient built environments.

3.1.3 Research gap

The literature review revealed that an important aspect seems to be missing from the reviewed papers which is the consideration of occupant behaviour and their interaction with the building environment. Occupants play a significant role in shaping the thermal conditions within a building by making adjustments and adapting to their surroundings to achieve a comfortable state. This interaction with the indoor environment can be seen as a passive strategy in itself. The adaptive behaviours can include activities such as opening or closing windows, adjusting blinds, using personal fans, or wearing appropriate clothing. By neglecting the study of occupant behaviour and their interaction with the building facade, the reviewed papers have missed an important passive strategy that directly impacts the thermal performance and energy consumption of buildings. The behaviour of occupants can have a substantial influence on the indoor environment, and understanding their actions and preferences is essential for optimizing building design, operation, and energy efficiency.

Investigating occupant behaviour as a passive strategy for maintaining thermal comfort is crucial for several reasons. First, it allows for a more realistic assessment of the building's performance in real-world scenarios. Building simulations and models often assume static occupant behaviours, which may not accurately reflect actual human behaviour and its impact on the indoor environment.
Secondly, understanding occupant behaviour provides insights into the potential energy-saving opportunities associated with passive strategies. By recognizing how occupants naturally interact with their environment, it becomes possible to design buildings that can better accommodate and leverage these behaviours to enhance thermal comfort while minimizing energy consumption.

Lastly, considering occupant behaviour fills a significant research gap in the field. While passive design strategies focus on architectural and engineering aspects, the human factor is equally important. Exploring occupant behaviour and its interaction with the building facade can shed light on the interplay between occupants and their environment, leading to more informed design decisions and improved building performance.

Therefore, the objective of this thesis is to specifically investigate occupant behaviour as a passive strategy for maintaining thermal comfort. By studying how occupants interact with their environment and the potential impact on energy consumption and thermal performance, this research aims to bridge the existing research gap and contribute to a more comprehensive understanding of passive strategies in building design and operation.

3.2 Occupant behaviour

3.2.1 Introduction

The International Energy Agency - Energy in the Buildings and Communities Program (IEA-EBC) Annex 53 states that there are six factors that affect energy consumption in buildings: (1) weather conditions, (2) building structure, (3) energy and services systems within the building, (4) requirements for indoor design, (5) how the building is operated and maintained, and (6) the behaviour of the occupants. (Yoshino et al., 2017b). The majority of studies concentrate on operational energy, which relates to energy and service systems, building and upkeep. Nonetheless, there is a growing recognition that modifying the energy consumption behaviours of occupants is a cost-effective option for reducing building energy consumption, surpassing the technical solutions proposed by such studies (Uddin et al., 2021). As a result, occupant behaviour modelling is gaining popularity in numerous research studies related to energy-efficient construction and occupants' thermal satisfaction.

Occupant behaviour (OB) in the built environment refers to how people interact with the physical space provided to them in buildings. It includes their activities, preferences, and habits that can affect the indoor environment, energy consumption, and overall building performance. Understanding occupant behaviour is essential for designing sustainable and healthy buildings, as well as improving their operational efficiency. Upon reviewing literature on occupant behaviour, it is found that OB is described in a number of ways.

Balvedi et al. (2018) refers to OB as a manner of people interacting with buildings in terms of energy use, including controlling devices such as windows, blinds, lighting systems, and heating, ventilation, and air conditioning systems. Gaetani (2019) writes that the presence and behaviour of individuals that influence a building's energy use are referred to as occupant behaviour, she also goes on to mention that OB may be the main reason why simulation predictions and actual building performance deviate. Occupant behaviour encompasses both the actual presence of individuals within a building and their activities that impact the building's energy consumption and thermophysical behaviour, such as utilizing electric appliances, Operating windows and shading mechanisms, and adjusting temperature control settings. (Gaetani, 2019).

Variables that affect occupancy and device usage in a building can be grouped into three main categories: environmentally related, time-related, and random. Environmental variables are related to physical aspects such as the building's location, solar orientation, layout, and local climate. Time-related variables are related to the routines of the occupants. Psychological variables have been largely ignored in studies of occupant behaviour due to the challenges involved in quantifying and monitoring them. (Balvedi et al., 2018).

Occupants respond to their environment in various ways beyond just observing it. These responses include physiological adaptations, such as sweating or shivering, personal adaptations, such as adjusting clothing or activity level, and environmental adaptations, such as changing the thermostat or opening/closing windows and blinds. These adjustments, made to restore comfort, are referred to as adaptive behaviours. Those behaviours related to energy that enable a particular activity are referred to as non-adaptive behaviours. (de Dear and Brager 1998). The three broadly classified behaviours: Presence, adaptive and non-adaptive are discussed in the following sections.

3.2.2 Occupant behaviour classifications

Occupant Presence

In the context of the built environment, "occupant presence" refers to the presence of people in a building or space. Occupants are a significant source of heat, moisture, and pollutants that can impact indoor air quality and building energy consumption. Understanding the impact of occupant presence is crucial for optimizing building performance and occupant comfort. This includes considering the number of occupants, their activity level, and their behaviour patterns. For example, the number of occupants in a space can affect ventilation requirements, while the behaviour of occupants can impact lighting and HVAC use.

Occupant presence in a building affects its energy efficiency and level of comfort in two ways. First, by emitting heat, humidity, CO_2 , and pollutants. Second, indirectly by being the trigger for both adaptive and non-adaptive energy-related behaviours (Gaetani, 2019).

The presence of occupants has a direct effect on the heat balance of a building, which happens when the human body produces heat through oxidation, known as the metabolic rate. This heat is then released from the body through a combination of evaporation, convection, and radiation. To calculate the internal heat gains from people, the number of occupants in a specific zone is multiplied by their metabolic rate (Gaetani, 2019).

Adaptive behaviour

Adaptive behaviour in the built environment refers to the ability of occupants to adjust their surrounding environments to maintain or restore their thermal comfort expectations and preferences in response to changes in the indoor environment (de Dear and Brager 1998). This adaptive behaviour is influenced by several factors, including individual characteristics such as age, gender, and activity level, as well as contextual factors such as building design, climate, and cultural background. (Nicol et al., 2012)The perception of comfort is individual and influenced by various social and psychological aspects. It is uncommon for two people to experience the same level of comfort or discomfort under identical conditions, though there may be broad trends. People can be categorized based on their inclination towards adaptation, with passive occupants requiring less frequent adjustment of their surroundings compared to active occupants (Gaetani, 2019).

One of the main benefits of adaptive behaviour is that it can lead to reduced energy consumption in buildings by allowing occupants to tolerate a wider range of indoor temperatures. This is particularly important in the context of climate change and the need to reduce carbon emissions from buildings. To support adaptive behaviour, buildings can be designed with features such as operable windows, shading devices, and thermal mass to provide occupants with more control over their indoor environment.

Shading devices play a significant role in the performance of window systems by affecting the transmittance of short-wave and thermal radiation. They have a direct impact on the energy performance of buildings by reducing solar gains and potentially minimizing heat losses through the use of movable insulation. Additionally, shading devices can indirectly influence building energy performance by affecting the amount of electrical lighting required. They also contribute to visual comfort by controlling the availability of daylight, the amount of transmitted light, and the views to the outside. The effectiveness of shading devices depends on factors such as their location (interior, exterior, or between-glass), transmittance, absorption of radiation, inter-reflection between the shading device and the glazing, and the position of the shade (partially open or closed) (Gaetani, 2019).

Windows and doors in buildings can be opened to allow outdoor air to enter, impacting the indoor conditions and air quality. The flow rate of ventilation air depends on factors such as opening area, temperature difference, wind speed, and direction. Building performance simulation tools use coefficients to model this airflow. External factors like neighbouring buildings and urban heat islands can affect wind conditions and outdoor temperature. Window and door opening models in simulations focus on predicting the open or closed state of the openings.

Non-Adaptive Behaviour

Non-adaptive behaviour in the built environment refers to actions that do not adjust the indoor environment but still impact energy use. Unlike adaptive behaviours, non-adaptive behaviours are not carried out with the intention of restoring comfort, but rather to facilitate a specific activity. (Gaetani, 2019). Examples include leaving lights on when leaving a room, using electronic devices unnecessarily, or failing to close doors properly. Non-adaptive behaviour can result in unnecessary energy consumption and should be addressed through education and building management strategies.

The prediction of non-adaptive behaviours does not rely on environmental factors, but rather on the occupants' presence and their time-based requirements for performing different activities. (Gaetani, 2019).

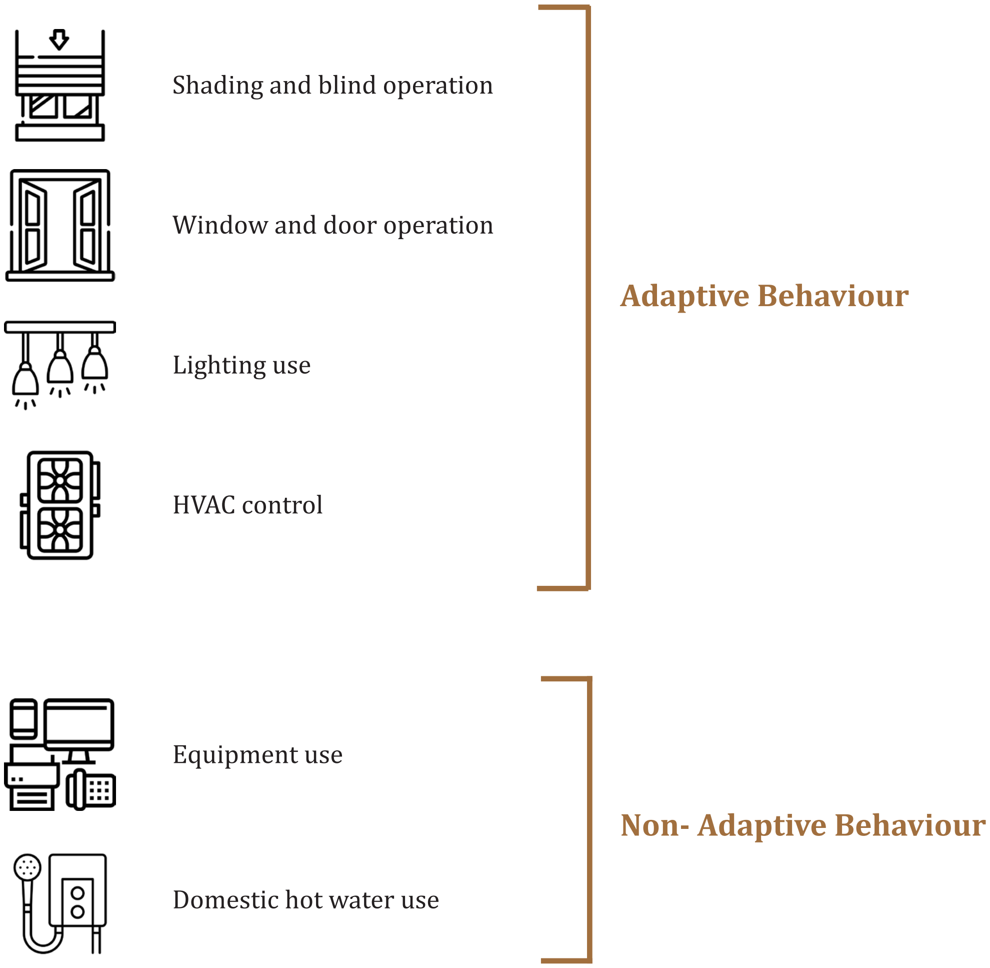


Fig. 11. Graphical representation of adaptive and non-adaptive behaviours

3.2.3 Occupant behaviour modelling in building performance simulation

Literature strongly indicates that occupant behaviour plays a critical role in both energy conservation and thermal comfort within buildings. Therefore, the integration of occupant modelling within building performance simulation is gaining popularity among designers and engineers. Building performance simulation (BPS) is a valuable tool for evaluating the energy and comfort performance of buildings.

BPS is characterized by the use of mathematical and computational models to represent the physical attributes and control tactics of a building design or an actual building (or multiple buildings) and its associated systems (Hong, Langevin, and Sun 2018). Building performance simulation (BPS) models are generally considered deterministic, which means they do not incorporate any random variables or degree of uncertainty. These models rely on well-defined inputs and produce a single, distinct set of outputs (Gaetani, 2019).

There are a number of widely used occupant behaviour modelling approaches. The most commonly used approaches are described below. The order follows increasing complexity from schedules to the more recently used approach, agent-based modelling.

Schedules, and deterministic models

Schedules represent time-based factors ranging from 0 to 1 that function as multipliers of maximum quantities to determine the actual internal gains due to various factors such as occupant presence, lighting, and equipment use. These schedules can be based on established standards or statistically aggregated data collected through observation. (Gaetani, 2019). Schedules are usually used to model occupant presence and non-adaptive behaviour. Typically, various 24-hour schedules are used for weekdays, weekends, and other important daily variations. These schedules are usually developed based on monitored data or a combination of engineering methods and data monitoring (Happle et al., 2018).

The approach that is often used to simulate adaptive behaviours, such as the use of shading devices and windows or doors, for which a schedule based solely on time may not be appropriate, are known as deterministic models, which average out individual differences, space or location, and time. Therefore, they are best suited for modelling environments where the behaviour being modelled is predictable and averaged (Gaetani, 2019). Deterministic rulesets operate under the assumption that there are clear cause-and-effect relationships between specific drivers and resulting actions. These are frequently incorporated into building energy models implicitly. These models yield consistent and predictable behaviours with no variability (Happle et al., 2018).

Non-probabilistic modelling

Data-based models are dependent on the dataset used to train them, and they usually incorporate information about environmental stimuli. Even though they are deterministic and generate predictable outputs based on known inputs, they are referred to as non-probabilistic models in contrast to deterministic models. The primary disadvantage of non-probabilistic models is their reliance on the specific dataset used (Mahdavi and Tahmasebi 2015).

Statistical Modelling

Statistical modelling in building performance simulation involves establishing a mathematical relationship between occupant behaviour, indoor/outdoor conditions, energy consumption, and time. The results of statistical modelling are linked to the occupancy state or the likelihood of observing a specific behaviour at a particular time (Diao et al., 2017).

Statistical modelling is a conventional technique widely used in modelling occupant behaviour. It involves analyzing the relationship between building occupants' behaviour and various dynamic environmental conditions, such as indoor temperature, CO_2 levels, and humidity. However, this approach has limitations, as it is typically focused on one or two fixed categories of behaviour, such as light switch status or window opening. To improve statistical modelling, it is necessary to consider a broader range of behaviours and analyze them from different perspectives (Uddin et al., 2021).

Probabilistic and Stochastic Modelling

D.R.G. Hunt published a study in 1979 titled "The use of artificial lighting in relation to daylight levels and occupant presence," which proposed that the relationship between a predictor variable or variables and occupants' (Hunt 1979), actions was probabilistic rather than deterministic. The study was published in the Building and Environment journal. (Gaetani, 2019).

Stochastic or probabilistic models are designed to account for the diversity of human behaviour. They assume that actions are driven by a probability function that depends on one or more predictor variables. Unlike deterministic models, stochastic models cannot produce consistent results with a small number of runs and require a large number of simulations to obtain reliable outcomes. Additionally, these models cannot account for consistency. (Gaetani, 2019).

Stochastic models for occupant behaviour involve using statistical distributions to estimate the probability of particular actions or situations. These models consider the relationship between observed behaviour and environmental factors, as well as specific events like an occupant entering the room or the time of day. Stochastic models for occupant presence typically use first-order Markov chains (Happle et al., 2018).

Models that predict human actions for environmental controls, such as opening windows, turning on lights, or adjusting thermostats, use stochastic methods and rely on sensor or observation data. These models aim to capture more variations in behaviour by predicting probabilities of actions and can include behaviour that cannot be explained by external, objective variables, such as indoor air temperature or daylight illuminance (Happle et al., 2018).

Agent-Based Modelling

Agent-based models (ABMs) provide a more intricate simulation framework as they move from predicting behaviour at a group level to predicting behaviour at an individual level. These models predict the impact of occupants by simulating individuals, their interactions with each other, and their interactions with the building (Gaetani, 2019). ABM is a framework used for simulation that involves one or more independent actors, known as agents, that act based on a set of behaviour rules and interact with each other and the surrounding environment. These behaviour rules are critical to energy simulation because they determine how and when agents interact with each other based on the conditions present in the environment (Uddin et al., 2021).

Agent-based models introduce a significant increase in model size due to the need to model each individual separately. This approach still relies on stochastic modelling for resolution, resulting in a very high level of complexity (Gaetani, 2019). In ABM, each aspect of an agent can be modelled to make them behave and think like humans. However, there are still limitations in applying ABM to study building occupant behaviour as it is still in the early stages of development (Uddin et al., 2021).

3.2.4 Window operation and influencing factors

In this thesis, the focus is on the occupant's adaptive behaviour, specifically their window operation habits. When considering passive cooling strategies, the most common and conventional method is natural ventilation through windows and doors (Liu et al., 2022). The papers studied as part of the literature review confirms the effectiveness of natural ventilation as a reliable cooling strategy. Operable windows hold a significant advantage in terms of occupant-friendliness and ease of operation. They provide individuals with direct control over the indoor environment, allowing them to adjust window openings according to their comfort preferences and the prevailing outdoor conditions. This level of control empowers occupants to actively participate in regulating indoor temperatures and promoting thermal comfort. Furthermore, operable windows offer additional benefits such as improved air quality, daylighting, and a sense of connection to the outdoor environment.

Occupants tend to open of close windows due to a trigger, this trigger may be due to indoor conditions, or psychological or physiological factors. Factors such as temperature, occupancy, daylight levels, and personal preferences have been found to significantly influence occupant-window interaction. These factors are mainly divided into 5 groups : physical environmental factors , contextual factors, psychological factors, physiological factors and social factors (Fabi et al., 2012).

Physical Factors
Temperature and thermal comfort play a significant role in determining window operation. Occupants tend to open windows to regulate indoor temperature, seeking a balance between personal comfort and the outdoor environment (Humphreys, 2005). Other physical factors include humidity levels, air quality, and ventilation requirements (Nguyen et al., 2019).

Contextual Factors
Contextual factors encompass external conditions such as outdoor climate, weather patterns, and diurnal variations. The availability of natural ventilation options, such as cross-ventilation or prevailing winds, can also influence window operation (D'Oca et al., 2014). Additionally, building location, orientation, rainfall, occupancy and the presence of shading devices affect occupants' decision to open or close windows (Fabi et al., 2012).

Psychological Factors
Individual preferences, attitudes, and perceptions play a crucial role in window operation behaviour. Personal comfort preferences, cultural influences, and past experiences with window use shape occupants' decisions (D'Oca et al., 2014). Visual and auditory stimuli from the surrounding environment, such as noise or views, can also impact window operation choices (Fabi et al., 2012).

Physiological Factors

Occupants' physiological factors, such as age, gender, health conditions, and activity levels, can influence their window operation behaviour. For instance, individual metabolic rates, thermal sensitivity, and personal thermal insulation needs vary, leading to different preferences for window opening or closing (Humphreys, 2005).

Social Factors
Social driving forces in window operation behaviour involve interactions among occupants and are influenced by factors such as household composition. This includes determining who has control over thermostat settings and window opening/closing decisions within a residential building.

Understanding the interplay between these influencing factors enables the development of occupant-centric window control strategies that enhance comfort, energy efficiency, and indoor environmental quality. By considering the physical, contextual, psychological, and physiological dimensions, designers and researchers can create more effective guidelines and interventions for optimizing window operation behaviour. Many studies in the field of window operation patterns have neglected the inclusion of psychological and physiological factors due to their inherent complexity in quantification Fabi et al., 2012). In the following section, a comprehensive review is conducted to examine window operation patterns identified by researchers, this review also highlights the influencing factors considered by the researchers.

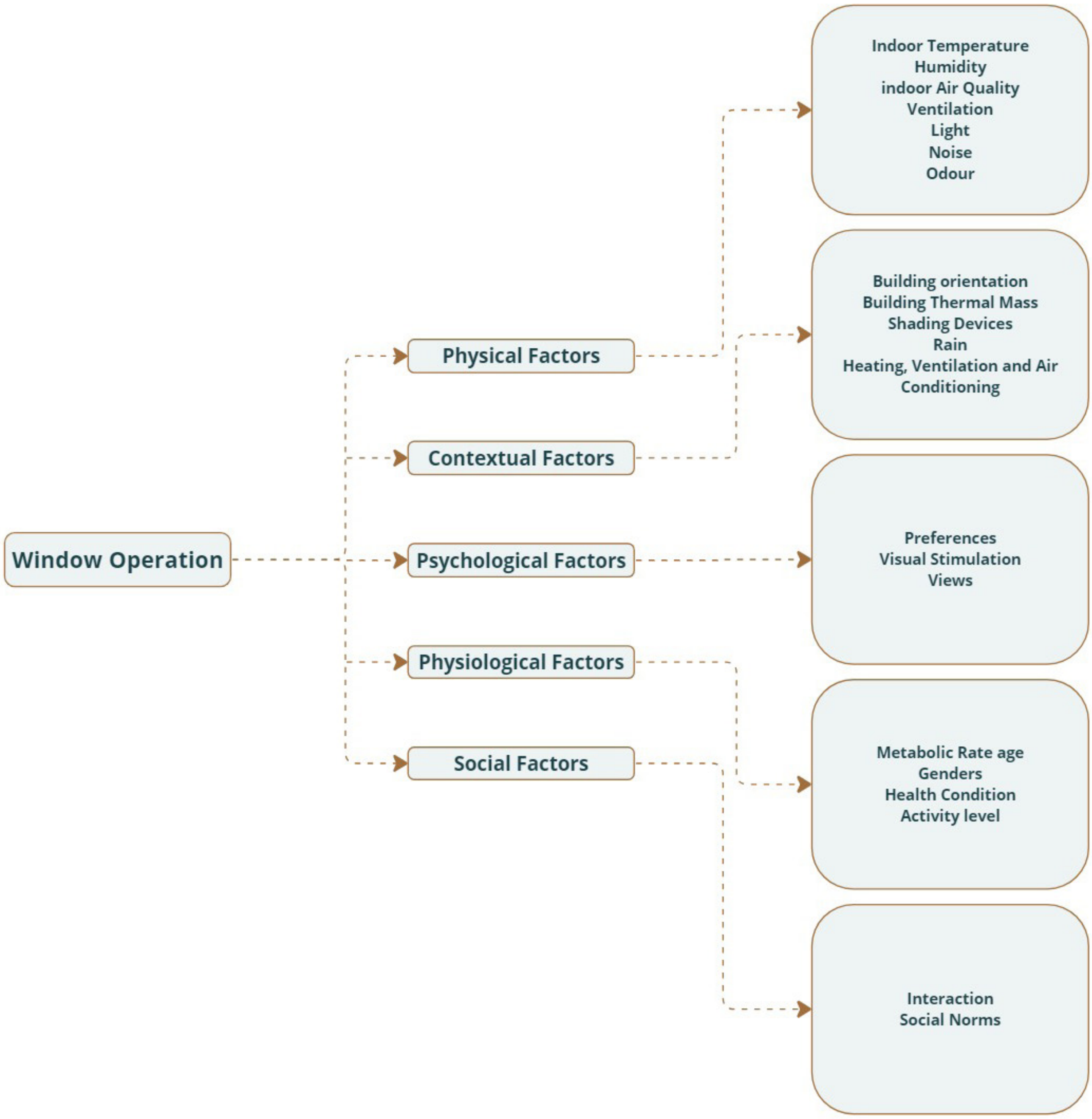


Fig. 11a. Graphical representation of the factors influencing window operation

3.2.5 Review of window operation occupant behaviour models.

Understanding and incorporating occupant behaviour in building performance analysis is essential for accurately predicting energy consumption and thermal performance. In this study, the focus is on adaptive occupant behaviour, which refers to the ability of occupants to adapt and modify their behaviour in response to changes in their environment, particularly their interaction with windows. To predict occupant behaviour, researchers have conducted numerous studies using various methods, including on-site observations and occupant questionnaires. These studies aim to identify and understand the factors that influence occupant behaviour and to develop models that can predict adaptive behaviour patterns.

Additionally, several papers have been published specifically addressing occupant-window operation modelling. These papers propose different modelling approaches to predict how occupants use and control windows in different building types and climates. The models consider factors such as occupant preferences, window characteristics, and environmental conditions. However, it is worth noting that in this study, the focus is on manually controlled windows, where occupants have control over opening and closing them.

For this study eight papers are reviewed, the selected papers on window operation modelling mainly employ conventional modelling methods rather than agent-based methods. Conventional modelling approaches rely on statistical analysis and mathematical models to represent and simulate occupant-window interaction. These models consider factors such as indoor and outdoor environmental conditions, occupant behaviour patterns, and building characteristics. The aim is to capture the typical window operation behaviour observed in real buildings. By reviewing and understanding these papers, valuable insights will be gained into the various modelling approaches used to analyze occupant-window interaction. This understanding will inform the development of simulation models for this study, allowing for the integration of occupant behaviour in the analysis of building performance. By incorporating occupant-window interaction into the simulation software, it will be possible to assess the impact of different occupant behaviour patterns on thermal comfort.

The papers studied are presented in table.3 for a comprehensive overview. This table is shown in the next page. Each of these papers are then briefly explained highlighting the important aspects that would contribute to this project.

Table 4. Tabular representation of the papers studied on window operation patterns

	Author(s) year (ref)	Model (M) or Simulation framework (S)	Type of Behavior	Building Function	Location	Influencing Factors Analysed	Key Influencing factor(s) found	Models used for Derivation	Season	Software used for simulation
1	(Haldi & Robinson, 2009)	M	Window Operation	Offices	Switzerland	Indoor Temperature Occupancy Patterns Outdoor Temperature Active/Passive users	Indoor temperature Outdoor Temperature Occupancy Pattern Rain	Logistic Models and discrete time Markov processes	All seasons	
2	(Yun & Steemers, 2008)	M	Window Operation	Offices	UK	Indoor Temperature Outdoor Temperature Occupance	Indoor Temperatures Previous window state Time of day effects	Probabilistic Models	Summer	
3	(Rijal et al., 2007)	S	Window Operation	Offices	UK	Clothing and activity Temperature Season and time of day Active/Passive subjects	Indoor and Outdoor temperatures	Logistic Models	All seasons	ESP-r and EnergyPlus
4	(Zhou et al., 2018b)	M	Window Operation	Offices	China	Indoor and Outdoor Temperature, Humidity PM2.5 concentration Co2 concentration Occupancy, Noise Wind speed	Outdoor Temperature	Pearson correlation analysis	Summer	
5	(Li et al., 2015)	M & S	Window Operation	Offices	China	indoor air temperature indoor air relative humidity, indoor CO2 concentration, outdoor air temperature, outdoor air relative humidity, and wind speed.	Outdoor Temperature	Logistic Models and Monte-Carlo simulation model	Transition season	
6	(Herkel et al., 2008)	M	Window Operation	Offices	Germany	Season Outdoor temperature Indoor temperature Time of day Presence	Outdoor Temperature User Occupancy	Logistic Models	All seasons	
7	(Andersen et al., 2013)	M	Window Operation	Dwellings	Denmark	Indoor: dry bulb temperature, Relative Humidity (RH), Illuminance Outdoor: Air tempeature, relative humidity, wind speed, global solar radiation, sunshine hours	Co2 concentration, Indoor temperature, Solar radiation, Outdoor temperature	Logistic Models	Winter, Spring and summer	
8	(Fritsch et al., 1990)	M	Window Operation	Offices	Switzerland	Wind speed, South vertical solar radiation, Ambient Temperature, Indoor room temperature	Ambient Temperature	Discrete Markov chain model	Winter	

The following pages dive into a comprehensive review of the studied papers, describing the method of study, and the resulting occupant behaviour patterns observed.

Yun and Steemers (2008f) conducted a study in Cambridge, UK to understand the window-opening behaviour of occupants in private and two-person offices during the summer season. A field study was carried out for three months between 13th June to 15th September 2006. The authors point out that most of the previous research focused on outdoor conditions as a stimulant to window opening behaviour, while very few have delved into considering indoor conditions. This paper attempts to analyze the relationship between window opening behaviour and indoor stimulus and develop a stochastic model for thermal simulations while factoring in the effects of time of day and previous window state as well.

For the field study, 2 naturally ventilated buildings were monitored. In one building(A), a centrally pivoted window was used for ventilation and in the second building(B), the windows were designed to open in two ways – tilt or fully open. The second building also employed night ventilation as a cooling strategy. Five offices from building A and one office from building B was selected for indoor temperature and window state measurements. During the monitoring phase it was observed that as soon as there was a change in the window state, the indoor temperature either increased or decreased, this proved to the authors that considering the indoor stimulus for analysis was logical. From the analysis, the office in building B showed a positive effect due to night ventilation in terms of indoor temperature. Occupant behaviour patterns were observed and analyzed separately for offices with night ventilation and without night ventilation. It was discerned that time of the day is an important aspect to consider while looking at occupant interaction with the window. Results showed that window state changes mostly occurred during arrival and departure time and were not as frequent during intermittent times (during working hours). This was also true for the offices with night ventilation, except that if the window was slightly open during arrival it mostly remained the same or changed to wide open. The percentage of the windows being closed in this case was very low. Since occupant behaviour was found to be time dependent, the day was divided into three parts for developing the model. Using probit and linear analysis, probability models were derived for the offices with and without night ventilation for the monitored data. Models were derived for window opening probability for different parts of the day (arrival, intermittent and departure). In these models the dependent variable is the window state which is either open or close, and the independent variable is indoor temperature. In general, most researches take outdoor temperature as the variable for developing window operation models as it is usually easier to obtain and is considered the independent variable as opposed to indoor temperature which is not very easy to obtain as it is a dependent variable.

Zhou et al. (2018c) monitored an open plan office located in Nanjing, China. The aim of this research was to identify the main factors that influence window operation in open plan offices, and to deduce the window operating patterns. For the analysis, occupants were asked to fill out questionnaires and field measurements were taken from August 20th to September 30th. Changes in temperature, humidity, PM2.5 concentration were recorded along with window and air conditioning operation and the occupancy schedule. The office had three groups of push-pull windows on the north and south walls which were double glazed and had sunshades. To identify the influencing factors, temperature, humidity, air quality, noise, distance, and wind speed were considered. Through the questionnaires occupants were asked to evaluate these factors, and filed measurements were taken for analysis. The feedback from occupants resulted in the air quality being the main driving factor for window operation, where as measurements and correlation analysis ensued that temperature was the main driving factor, of which outdoor temperature weighted the most. Hence, it was concluded that outdoor temperature was the most influential in window operation and this was used in developing the model. Three modes are considered, mode A: ventilation at night, windows are closed the following morning, mode B : ventilation in the morning, windows operation occurs after staff arrive in the morning, mode C : the window is open all day. The results depict that windows were mostly opened when the outdoor temperature was below 30°C and most frequently between 15 – 17 °C. The windows typically remained closed when the outdoor temperature exceeded 30°C. A Pearson correlation analysis was conducted and resulted in a fitting equation for the probability of a window being open. The fitting curve was described as a polynomial equation, where the dependent variable was the probability of window open-state, and the independent variable was outdoor temperature. It is also observed that occupancy plays a significant role in window operation, window open actions usually occurred in the mornings at the time of arrival.

Li et al. (2015d) studied an office building of 5 floors, in Chongqing, China from September 11th to October 31st (transition season). The office was monitored between 9:00 – 18:00 on weekdays. Six factors were identified which may affect window opening in the building, - indoor air temperature, indoor air relative humidity, indoor CO_2 concentration, outdoor air temperature, outdoor air relative humidity and wind speed. The statistical test results showed that only outdoor temperature was significantly influencing window opening behaviour in the office. Logistic regression analysis was conducted to derive a mathematical expression for the relationship between the probability of window opening and outdoor temperature. To verify this model equation, a correlation analysis was carried out between the measured and predicted window opening action for one experimental room. The results showed that the two values have significant linear correlation, and thus the fit well confirming the reliability of model. This analysis also proved that outdoor temperature influences window operation. Later the Monte-Carlo method was also used to generate random phenomena by using random numbers to analyze and forecast the probability of window opening. This method allows the researchers to solve the randomness of window operation as it is a very subjective action and depends on the occupant's psychological and physiological sensations.

Herkel et al. (2008c) developed a window operation model by conducting field studies in 21 south–facing individual offices in Freiburg, Germany for a span of 1 year (July 2002 – July 2003). The offices used a passive cooling technique to maintain thermal conditions, through internal and external heat gain reduction, thermal inertia, and night ventilation. No mechanical systems were being used, and all windows were manually operated, a slit valve was also provided to ensure minimum infiltration even when the windows were kept closed. The façade had an interesting window design as it contained two sets of windows, large windows at the sill level and smaller windows above them closer to the ceiling. The smaller windows could only be tilted open, while the large windows could be tilted as well as fully opened. Indoor temperature, outdoor temperature, occupancy, and window state were recorded for the analysis. A correlation analysis is conducted with reference to previous findings and literature. The analysis was conducted between window opening and the different probable influencing factors such as indoor temperature, outdoor temperature, seasonal effects, time of day and occupancy. The most obvious and envisioned relationship was with seasonal effects. It is observed that windows were opened mainly during the summer season and gradually decreased as the outdoor weather conditions began to become cold. With respect to outdoor temperature it was seen that the percentage of open windows not only changed with outdoor temperature but also according to the time of year. Outdoor temperature was further analyzed and compared with the logit function proposed by Nicole for the probability of windows being open. It was concluded that although the temperature is the same in different seasons people respond differently, they respond to the season rather than the temperature outside. People also preferred keeping the small windows open at higher temperatures rather than the larger windows. This could be due to the fact that the small windows allow for air circulation thus expelling the hot air from inside during warmer conditions.

Indoor temperature depends on outdoor temperature, solar radiation, and internal loads, so it can be deduced that when the outdoor temperature increases the indoor temperature also increases. Open windows can also cause overheating during a warm day if the outdoor temperature is higher than the indoor temperature. It was also found that window operation correlated with time of the day and occupancy. Occupant's presence and time of the day together give various frequencies of window opening, most windows were seen to be opened at arrival and second highest was during the intermittent time. This again changes according to the window type. Since the correlation study revealed that outdoor temperature was not the only driving factor for window opening, but occupancy depending on time of day also played a major role, these variables were considered in developing a user model. The model is divided into two stochastic processes, one to determine the probability of arrival or departure of the occupant which becomes the input for the second process. The second process is to predict the window opening probability, for which the occupancy as well as outdoor temperature is used as input, this is described in the flowchart in figure.12. A probability function is derived in terms of outdoor temperature which is then compared with a random number along with the occupancy. In conclusion, this model takes into account, the outdoor temperature as well as time of the day and occupant presence, which adds an extra layer of complexity to predicting window operation.

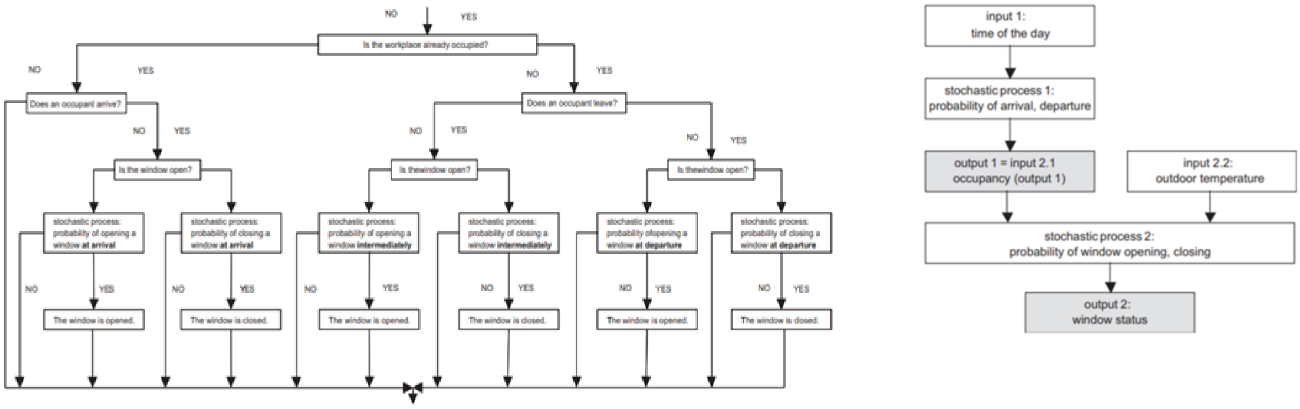


Fig. 12. Flow charts of occupant behaviour model developed by (Herkel et al. 2008c)

Rijal et al. (2007) conducted research to understand window opening behaviour and to develop an adaptive algorithm to predict the behaviour which can be used in simulation software. The authors use data from a previously conducted field study of 15 office buildings in UK from March 1996 to September 1997. Out of the 15 buildings, ten were naturally ventilated and five were air conditioned. The survey was divided into different processes, two sets of questionnaires were collected, one included responses about thermal satisfaction, clothing, use of controls and activity, the other was mainly personal information of the subjects. The researchers also took physical measurements on site and placed data loggers in the work environment for employees to input information about their clothing, activity, and use of controls. For the main part of the research, air-conditioned buildings were excluded as it is not usually common to have openable windows in airconditioned spaces. Analysis was caried out to check if window operation was related to temperature, season, and time of day, and active or passive subjects. Evidently, the frequency of opening windows was potently related to temperature, specifically when both indoor and outdoor temperatures were high. Similar to the previous study by Herkel et al. (2008c), season and time of the day played an important role, window opening frequency decreased from summer to winter, with summer being the highest season for open windows. Window opening also increased with the time of day, reaching maximum during the afternoon. The authors also investigate active and passive subjects, who have an influence on window opening as well, a passive user is one who doesn’t operate the windows as all while an active user operated them quite often.

To develop the model to predict window opening behaviour, the authors used logistic regression analysis to generate a logit equation as a function of temperature. Through the analysis it is found that both indoor and outdoor temperatures influence window opening behaviour, thus the authors included both these variables into the probability equation. Two equations were derived, one for each type of field study. To analyze the reliability of these equations, the results of one equation were compared with the results from the other filed study and vice versa. After the analysis the authors deduced that one out of the two equations will be used due to the larger data set size. To implement this into simulation software, an algorithm was generated, which was named the Humphreys adaptive algorithm and was implemented in the ESP-r software. The algorithm included the probability equation, indoor thermal state (hot or cold), and previous window state to predict the current window state. The window state has a binary value, either closed (0) or open (1). The authors continue their research by implementing this adaptive algorithm in an office model to check the effect it has on comfort and window operation. They also check the impact that window opening has on energy use in a building as compared to average ventilation rates. The research concludes by proving that the use of occupant behaviour models is beneficial and gives designers a more realistic understanding of building performance and provides a window operation algorithm which can be implemented in further research.

Andersen et al. (2013) used logistic regression to derive probability equations for window opening. Fifteen dwellings in Denmark are used to study occupant-window interaction from January to August 2008. Ten rented apartments and five privately owned houses were considered for the measurements. Eight of them were naturally ventilated while seven were equipped with exhaust ventilation. Several factors were measured within these houses to evaluate the influence they had on window operation. Indoor factors such as dry bulb temperature, relative humidity, illuminance, and CO_2 concentration; Outdoor factors such as air temperature, relative humidity, wind speed global solar radiation and sunshine hours were considered. Along with the environmental factors the window position (open or closed) was also measured. The data was divided in 4 groups according to ownership and ventilation type, for example owner occupied and naturally ventilated was group 1, rented and mechanically ventilated was group 4. To conduct a statistical analysis for the different variables these four groups were further divided into 2 sub-groups, windows closed and windows open. Coefficients required for the probability equation and magnitudes of the opening and closing models were generated per group. These coefficients could then be used according to the room type and season to obtain a probability equation of window opening for that situation. The results showed that different factors influenced window operation based on the groups. For example, in group 1, CO_2 concentration, indoor temperature and solar radiation were the main influencing factors, whereas for group 2, indoor and outdoor temperature were the key influencing factors for window opening. The authors mention that these models can be used to get a better estimation of window operation when compared to reality, although it may not be valid to generalize it as occupant behaviour is very subjective.

Haldi and Robinson (2009) conduct an extensive research based on developing and testing several occupant behaviour modelling approaches. They study and analyze various models developed from previous research and attempt to conduct statistical investigation and cross-validate the different approaches for window operation modelling. Data was taken from 14 south facing cellular offices that were previously monitored in Lausanne, Switzerland for a period of almost seven years (December 2001 – November 2008). Indoor temperature, occupancy and window opening and closing were continuously measured during this time. Outdoor temperature, wind speed, relative humidity and rainfall were measured by a nearby weather station and a sensor on the building. From the literature review, the authors selected three mathematical methods for modelling occupant interaction with windows, which are logistic regression, discrete-time Markov processes and continuous-time random processes. After discussing the three methods, the results are presented for the considered data. Similar to other research, observations showed that occupants tend to operate windows more at the time of arrival and departure. They also concluded that occupancy patterns are an integral part of window operation and must be integrated into the model. Indoor and outdoor temperatures seem to be the primary influencing factors for window actions.

The authors conducted logistic regressions using different variables and their transformations. The model with outdoor temperature showed the highest statistical significance and best fit. Thus, it was concluded that outdoor temperature will be integrated into the final model with other significant variables. Polynomial logits and deviations from comfort temperature were explored but had lower fit. The best multivariate model included outdoor temperature and indoor temperature and adding a third variable (external relative humidity) had minimal improvement. Including the factor of season did not significantly affect the model. Next the authors propose a dynamic modelling approach based on discrete-time Markov process to capture occupants' window actions. They divide the modelling into sub-models for actions on arrival, during occupancy, and at departure. The main factors influencing actions on arrival are indoor temperature and prior absence duration. Actions during occupancy are rare, with indoor temperature driving openings and outdoor temperature influencing closings.

Actions at departure are influenced by subsequent absence duration and outdoor temperature. The models' predictive power varies, with the highest for actions on arrival. The authors also analyze the duration of window openings and closings using survival curves. Opening durations are influenced by indoor and outdoor temperature, with longer openings associated with higher outdoor temperature. Closing durations are mainly influenced by indoor temperature, particularly upon arrival. The Weibull distribution is used to model the durations, indicating that window actions are not memoryless and cannot be fully captured by a Markov process. The results highlight the importance of both indoor and outdoor stimuli in determining window behaviour.

The authors go on to conduct a cross-validation test to determine the best performing model for window operation. They define some criteria on which the models will be validated: Discrimination, overall prediction, dynamics and aggregated results. Twenty simulations are run and each of the criteria are cross-validated with the data measured for the 14 apartments. Finally, the authors propose an algorithm that is a combination of a discrete-time Markov model for prediction of openings and a Weibull distribution model for the duration. This hybrid model is shown in a scheme in figure 13. A step-by-step process for the implementation of this algorithm is also given for future applications in BPS.

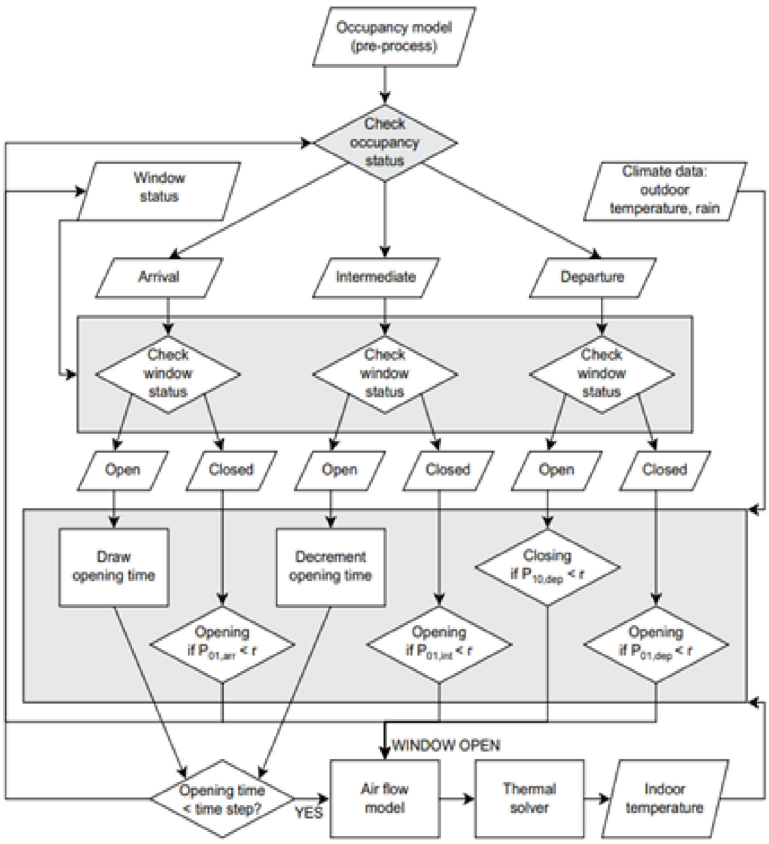


Fig. 13. Flow chart of occupant behaviour model developed by (Haldi and Robinson 2009)

Fritsch et al. (1990) used measured data from four offices in the LESO experimental building of Ecole Polytechnique, Lausanne, Switzerland. The authors begin by deducing that they can use discrete-Markov chains for developing the model as they found that a window position is dependent mainly on the previous state. They continue to check if window opening angle is a dependent variable and what are its driving factors, external, internal and human parameters are considered. The researchers found that ambient temperature had a significant impact on window opening angle. The model that they developed was specifically for the winter season.

The winter model for window opening angles is based on Markov chains with six states corresponding to different angles. During office hours, four different Markov chains are used based on different temperature ranges. The probabilities of transitioning between angles given the temperature are represented by matrices. Synthetic data of window angles is generated using the inverse function method, which ensures that the distribution function of the generated series matches the desired distribution. The model is validated by comparing autocorrelations, intercorrelations, average angles, and probabilities with real data. The validation shows good agreement between the synthetic and real time series. The model can be adapted to other offices by using measurements specific to each room and occupants. However, challenges arise from differences in office hours and the presence of air conditioning or mechanical ventilation. Future studies aim to address these challenges and improve the model.

3.2.6 Key findings and conclusions

Occupant behaviour, particularly regarding window operation, is a complex and subjective aspect that poses challenges in accurately predicting and modelling. The reviewed literature highlights the difficulty of generalizing window operation behaviour due to its dependence on various factors such as location, building type, facade design, climate, and cultural differences. However, researchers have made efforts to create models that can provide insights into window operation patterns to aid designers in understanding building performance.

The studies reviewed in the literature focus on developing models that consider different influencing factors and prediction methods. These factors include outdoor temperature, indoor conditions, building function, and location. The models aim to capture the probability of window opening, with independent variables derived from field analysis and observations. The complexity of the models varies, with some incorporating single variables and others incorporating multiple factors.Outdoor temperature is commonly identified as a significant influencing variable in window operation models. As research progresses, there is an increasing emphasis on incorporating occupancy and window state as independent variables to enhance prediction accuracy. This highlights the importance of considering not only the physical environment but also the occupants' presence and the current state of the window.

It is important to note that occupant behaviour modelling in building performance simulation is a developing field, and new insights and approaches continue to emerge. The reviewed literature indicates that occupant behaviour models for window operation are still evolving, and there is no single comprehensive model that can accurately predict all scenarios. The complexity and subjectivity of occupant behaviour make it challenging to create universally applicable models.

In conclusion, the reviewed literature emphasizes the complexity and variability of occupant behaviour, particularly regarding window operation. Researchers are actively exploring various influencing factors and prediction methods to develop models that can provide insights into window opening patterns. While progress has been made, there is still a need for further research and refinement to improve the accuracy and generalizability of occupant behaviour models. As the field advances, incorporating more comprehensive and diverse factors, such as cultural influences and individual preferences, will be crucial in enhancing the realism of occupant behaviour modelling in building performance simulation.

04 | Simulations in Design Builder

4.1 Setting up the workflow

This chapter details the internal workflow and methodology employed to examine the impact of window operation on indoor thermal comfort in office buildings. Emphasis is placed on the identification and development of scenarios, as well as the steps taken to conduct simulations. The research design and data collection process are explained, including the selection and validation of simulation tools and models. The chapter concludes with an overview of the evaluation of indoor thermal comfort, providing a foundation for the subsequent results and discussions presented in the following chapter.

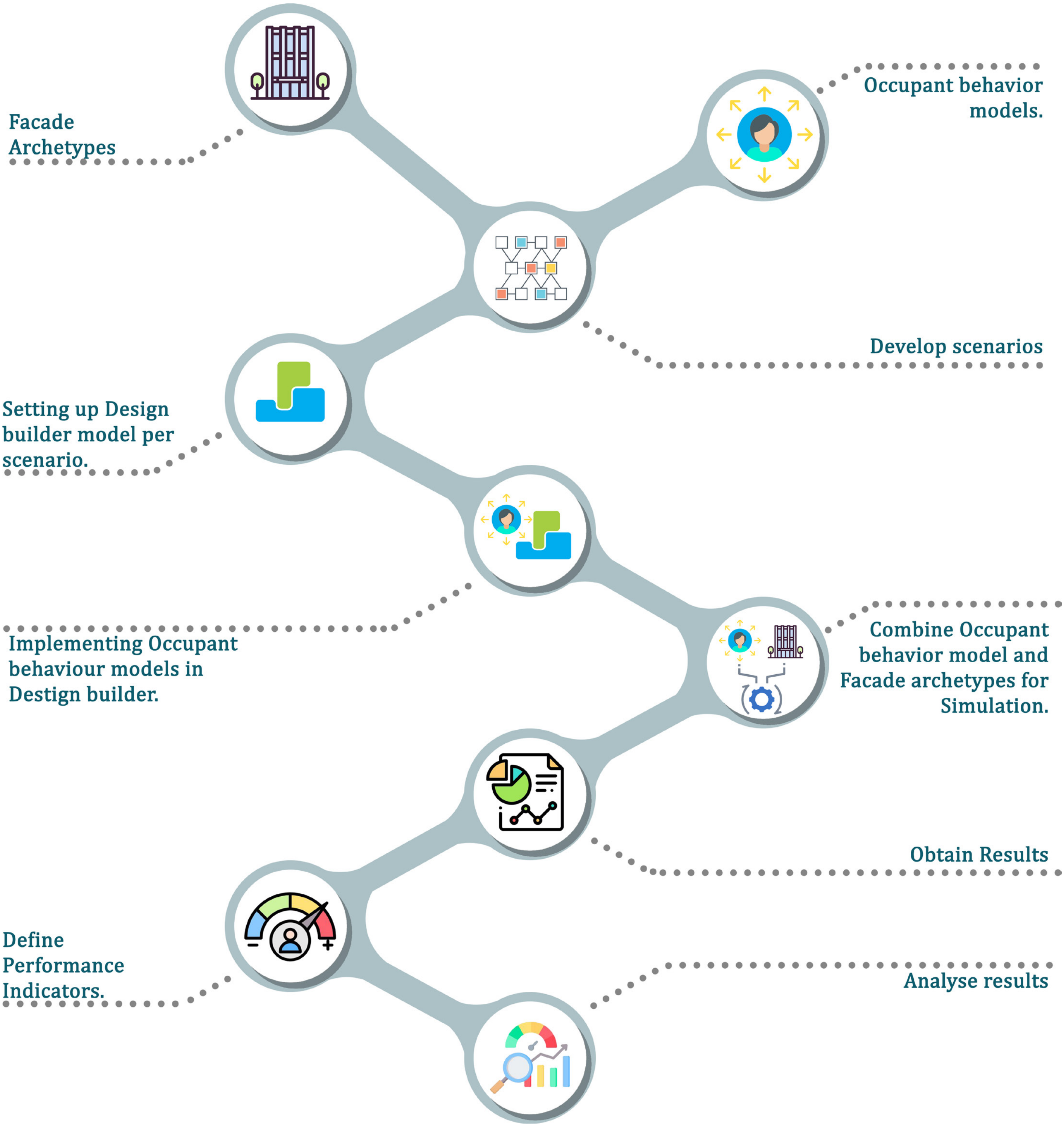


Fig. 14. Workflow diagram of the methodology used to implements occupant behaviour models in the simulation software

4.2 Scenario development

4.2.1 Office model description

For this project, the analysis and simulations are focused on a representative office space model. Specifically, a portion of an office floor is considered, with the dimensions of this space taken from the ASHRAE 140 BESTest models commonly used for building energy simulations. Since this thesis aims to assess the impact of window operation on thermal comfort as a passive strategy to reduce cooling load in the summer. To achieve this, the office space considered in the study is designed to be fully naturally ventilated, without the presence of mechanical ventilation systems or heating and cooling equipment in order to isolate the effect of window operation on thermal comfort. By removing the influence of other factors such as mechanical ventilation, the research can specifically evaluate the impact of window opening and closing on the indoor environment. This approach allows for a more focused analysis of the passive cooling potential of window operation during the summer months. By relying solely on natural ventilation, the study aims to explore how occupants' interaction with windows can effectively regulate indoor temperature and create a comfortable environment without the need for mechanical cooling systems. This aligns with the goal of reducing cooling load and energy consumption, as well as promoting sustainable building design.

The study also takes into account the adaptive nature of human behaviour in response to discomfort. By providing operable windows in an unconditioned space, the research aims to encourage occupants to actively engage with the building envelope to consciously improve the indoor thermal conditions. When faced with uncomfortable indoor temperatures, occupants may naturally seek ways to adjust their environment to create a more pleasant and suitable setting. The presence of operable windows allows individuals to exercise control over their immediate surroundings, giving them the opportunity to open or close windows based on their comfort preferences.This participatory approach not only empowers individuals to create a comfortable indoor environment but also highlights the significance of occupant behaviour in achieving optimal thermal conditions.

Considering the adaptive behaviour of occupants and providing operable windows in the research design enables a comprehensive exploration of the role of window operation in occupant satisfaction and thermal comfort. It emphasizes the importance of occupant engagement and recognizes the potential for occupants to be active contributors to their thermal comfort experience.

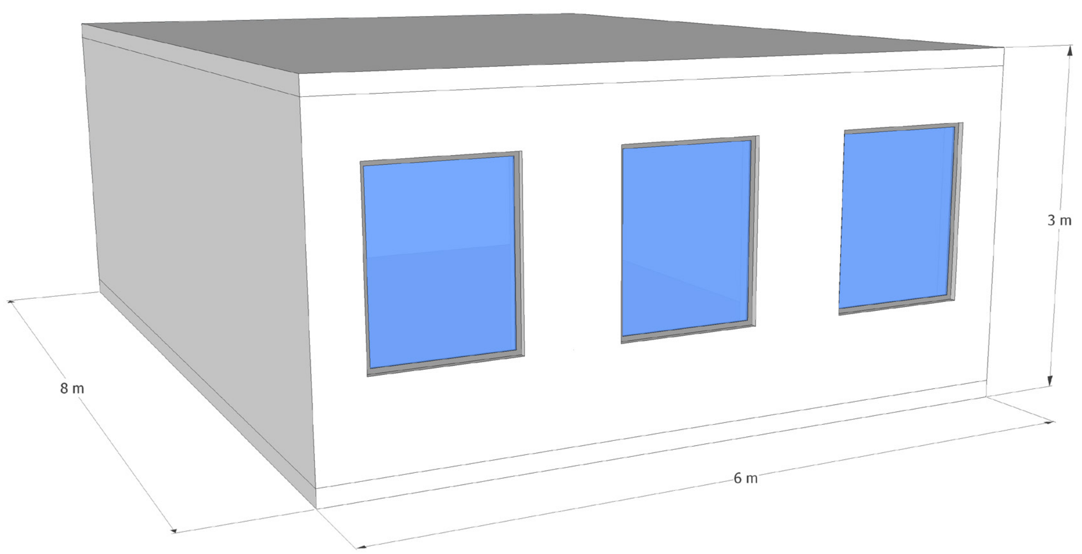


Fig. 15. 3D Model used for simulations in this research (dimensions from ASHRAE 140 BESTest case)

Figure 15 illustrates the proposed model for simulation. The dimensions of the representative office space are 6m (length) x 8m (depth) x 3m (height). The orientation of the office space is in the North-South direction, with the selected facade facing South. This particular orientation is chosen to capture the maximum solar heat gain, as the South-facing facade receives the highest solar radiation.The chosen facade for simulation will feature three operable windows, as depicted in the figure. These windows play a crucial role in allowing for occupant interaction and control over the indoor thermal conditions. The specifics of the window dimensions will be elaborated on in the subsequent sections of the research.

It is important to note that for the purpose of simulation and analysis, the remaining three walls, roof, and floor of the office space are considered adiabatic. For this project these surfaces are set to the standard construction template within design builder. The walls are made of brickwork and concrete block with EPS insulation material in between. The roof slab is plaster board on the inside and asphalt on the outside with insulation, and the floors are cast concrete. This means that heat transfer through these surfaces will not be taken into account, focusing the study primarily on the thermal performance and interaction with the selected facade. By setting up the model in this manner, with a representative office space oriented in a specific direction and featuring operable windows, the research aims to accurately evaluate the impact of window operation on thermal comfort and energy performance within the simulated environment.

4.2.2 Identifying Facade Archetypes

To comprehensively analyze the influence of window operation on indoor thermal comfort, a crucial step in the research involved identifying different façade archetypes. These archetypes were derived by examining studies conducted on existing buildings in the Netherlands, taking into account their varying characteristics and design elements. The primary objective of this research is to gain insights into how window operation affects indoor thermal comfort. Given the substantial impact of facades on thermal comfort, it is crucial to select unique typologies. The subsequent factors outline the fundamental characteristics of facades that have an influence on thermal comfort.

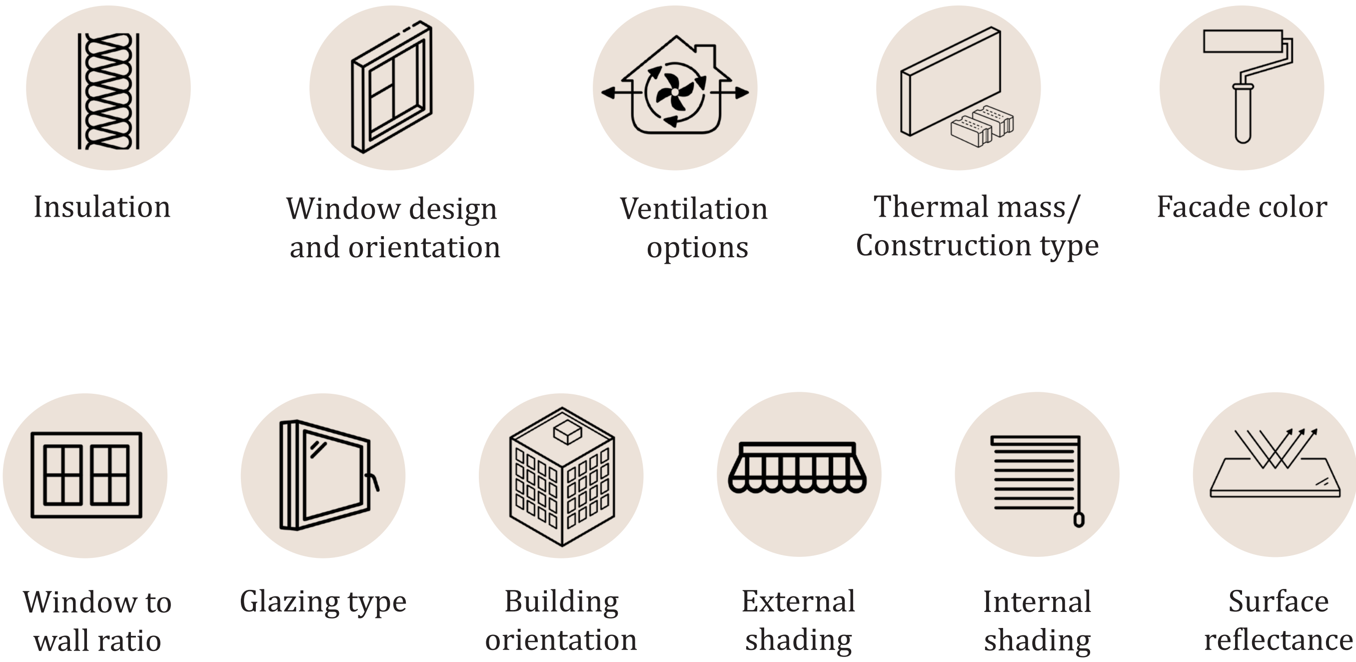
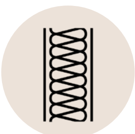


Fig.16. Graphical representation of the different facade characteristics that have an influence on thermal comfort

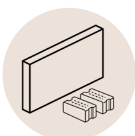
Among the above characteristics only those that are most significant in relation to facade performance in terms of occupant interaction is considered.



Insulation : For all the simulated models, the insulation material used is rockwool. However, the thickness of the rockwool insulation varies based on the specific construction typology (details are shown in table 5).

Window design and orientation : The window design is a simple aluminium framed window, which is operable. The windows all face south direction, as this orientation has highest solar gains.

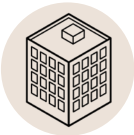
Ventilation Options : The office space is naturally ventilated with openable windows. No mechanical ventilation systems are used.



Thermal mass/Construction typology : Two construction types have been selected for this study, heavy weight construction and light weight construction. These construction types differ in terms of their thermal mass and structural composition (details are shown in table 5).

Window to wall ratio :Three different window-to-wall ratios (WWR) have been considered for the study: 40%, 60%, and 80%. These ratios represent the proportion of window area relative to the total wall area in each simulated model (details are shown in table 6).

Glazing type : The selected glazing type for the study is a commonly used option in Dutch buildings. The windows are double glazed, consisting of two glass panes with an air-filled cavity in between, the U-value of this system is 2.6 W/m^2-K . This glazing configuration is representative of the typical practice in the Netherlands.



Building orientation : The specific part of the building chosen for the study is oriented in the North-South direction, with the main focus facade facing south. This orientation allows for a more targeted analysis of the thermal performance and the influence of solar exposure on the indoor environment.

Among the characteristics mentioned above, the two key factors that vary in the study are the window-to-wall ratio and the façade construction type. These metrics were specifically chosen because they have a substantial impact on the thermal comfort experienced within buildings.

The window-to-wall ratio plays a pivotal role in determining the amount of natural light and solar heat gain entering the indoor spaces. Higher ratios result in increased solar heat gain and natural lighting, which can impact thermal comfort conditions (Shaeri et al., 2019). On the other hand, façade construction type encompasses aspects such as insulation levels, material properties, and thermal performance, which directly affect the energy transfer between the indoor and outdoor environments (Khadraoui & Sriti, 2018).

By considering these two fundamental factors, the identified archetypes provide a comprehensive representation of the range of façade configurations encountered in real-world office buildings. It is important to note that all the archetypes include operable windows, as the research specifically aims to investigate the impact of window operation on thermal comfort. By examining different combinations of window-to-wall ratios and façade construction types, it becomes possible to assess how various design choices and window operation models influence indoor thermal comfort.

In the study conducted by Ebbert (2013), a spot check was carried out in the Netherlands to analyze the Dutch office market. The spot check encompassed 115 buildings constructed between 1950 and 1990, providing insights into various construction typologies. The findings revealed that the most prevalent typologies in the Netherlands are skeleton structures and prefabricated suspended structures. The office building stock in the Netherlands comprises approximately 55 million square meters. Within this stock, around 25% of the buildings were constructed before 1977, while approximately 80% were built prior to the year 2000. Notably, a small number of these buildings had a façade with an Rc value greater than 2.5 K/Wm^2 (Papachristou et al., 2021). The focus of the study was on energy flexibility in Dutch office buildings. To analyze this, the authors examined window-to-wall ratios of 40%, 70%, and 100%, along with two façade construction typologies: heavy weight and light weight. In this case, both the heavy weight and light weight facades were made of the same material but varied in thickness and insulation position (Papachristou et al., 2021).

Building upon this information, to address the research objectives, two construction typologies have been selected for this study: a heavy weight façade and a lightweight façade. The aim is to compare these two façade constructions in terms of their thermal mass and the materials used. The specific details of these construction typologies can be found in table.5 and figure 17.

Table.5. Table presenting the construction typologies and their details used in this research

Construction Typology	Materials	Thickness(m)	U-value (W/m²-K)	R-value (m²-K/W
Heavy weight construction	Concrete block	0,1		
	Rockwool insulation	0,05	0,73	1,35
	Concrete block	0,1		
Light weight construction	Aluminium	0,01		
	Rockwool insulation	0,08	0,53	1,87
	Aluminium	0,01		

Regarding the window to wall ratio, three values have been chosen after a comprehensive review of the existing literature: 40%, 60%, and 80%. It is worth noting that although a window to wall ratio of 100% was considered in the previously mentioned study, it is deemed unrealistic and highly improbable in practice. Therefore, the chosen values aim to provide a more realistic approach to window operation and its impact on indoor thermal comfort as well as distinct typologies. Table 6 provides an overview of the different WWR and the window dimentions accordingly to fit the selected facade.

Table. 6. Table presenting the window to wall ratios used in this research

Window to Wall ratio	Window dimension (m)	Total Glazing Area (m^2)	Glazing type	Glazing detail
40%	1,6 x 1,5	2,15	Double glazed with air cavity between panes	6mm glass panes w 13mm air gap in between
60%	1,8 x 2,0	3,3		
80%	1,9 x 2,5	4,4		

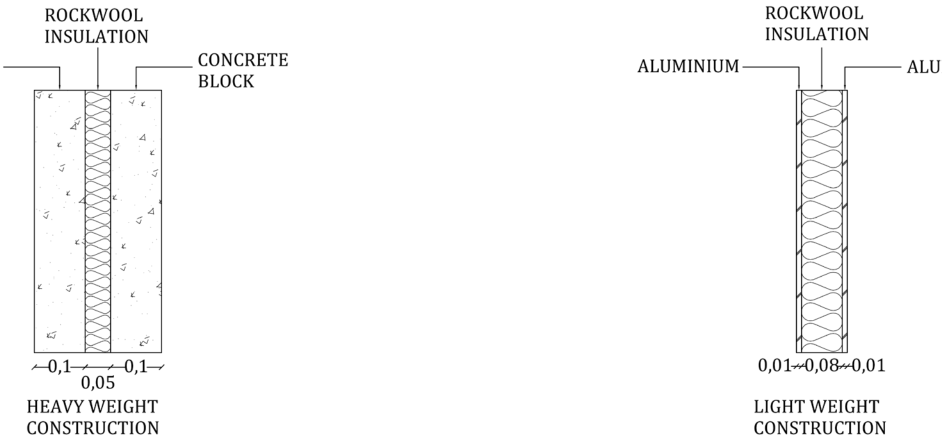


Fig. 17 . sectional representation of the construction typlogies (dimensions in meters)

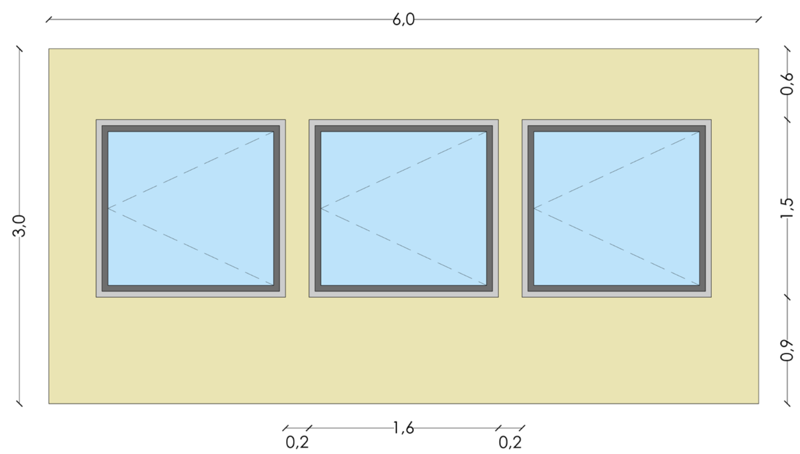


Fig. 18. Graphical depiction of facade with 40% windor to wall ratio (dimensions in meters)

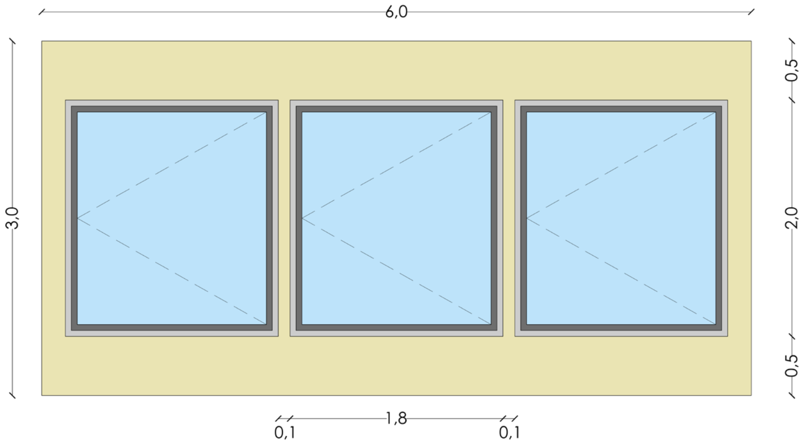


Fig.19. Graphical depiction of facade with 60% windor to wall ratio (dimensions in meters)

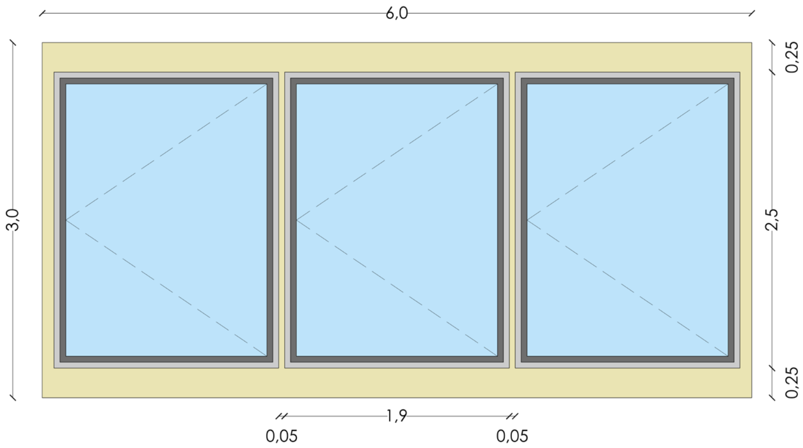


Fig. 20. Graphical depiction of facade with 80% windor to wall ratio (dimensions in meters)

Table.7. Table showing the different facade archetypes considered for this study

Scenario	Window to wall ratio	Construction Typology
A	40%	Light Weight
B	40%	Heavy Weight
C	60%	Light Weight
D	60%	Heavy Weight
E	80%	Light Weight
F	80%	Heavy Weight

Table 7 presents the six derived facade archetypes (A-F) based on the combination of two construction typologies (heavyweight and lightweight) and three window-to-wall ratios. These archetypes represent different configurations of the facades in terms of construction type and the proportion of window area to wall area.

4.2.3 Selecting occupant behaviour models

The next step in the research process is to choose occupant behaviour models that simulate window operation. Since window operation is a subjective and dynamic action influenced by occupants, it is crucial to select behaviour models that have been studied and tested by researchers. These models capture the diverse range of window opening and closing behaviours exhibited by occupants in different scenarios. In this project, specific occupant behaviour models, which have been developed by researchers, will be integrated into the design builder software. These models, based on empirical data and validated through previous studies, allow for a more realistic simulation of window operation scenarios. By incorporating these occupant behaviour models into the design builder software, the study aims to accurately capture and analyze the impact of different window operation patterns on indoor thermal comfort in a more comprehensive manner.

In order to capture the diverse range of occupant behaviour related to window operation, two specific occupant models have been selected from those described in Chapter 3. The intention behind this selection is to choose models that vary in terms of complexity, accuracy, and the influencing variables they consider. One of the selected models is characterized by a higher level of complexity and accuracy. It takes into account a wide range of influencing variables such as outdoor temperature, indoor air temperature, occupant presence, and occupant comfort preferences. This model aims to provide a detailed representation of how occupants interact with windows based on various factors affecting their thermal comfort, including the presence or absence of occupants.

The other selected model, while still capturing the essential aspects of occupant behaviour, is relatively simpler in terms of its structure and the number of variables considered. It focuses primarily on outdoor temperature as a factor influencing window operation behaviour. This model provides a more generalized representation of occupant behaviour by considering the impact of outdoor temperature alone on the decision to open or close windows.By incorporating these two distinct occupant models, the study aims to gain insights into the influence of different levels of model complexity on the simulation results. It allows for a comparative analysis of how the accuracy and level of detail in modelling occupant behaviour, including factors such as occupant presence and outdoor temperature, can affect the predictions of indoor thermal comfort in response to window operation.

Due to the complex and evolving nature of occupant behaviour modelling in Building Performance Simulation (BPS), particularly within DesignBuilder, the scope of this project limits the selection to two occupant behaviour models. This decision is based on the understanding that occupant behaviour modelling is still a developing field, and incorporating a large number of models may introduce additional complexities and challenges.By selecting two representative models, the project aims to provide a focused analysis of occupant behaviour and its influence on window operation. These models have been chosen to capture a range of behaviours and considerations while maintaining a manageable level of complexity.
The selected models have undergone rigorous research and testing by experts in the field.

A description of the two models selected is given below.

Model 1

Developed by Zhou et al. (2018c) , is a window operation model that focuses on the relationship between outdoor temperature and the state of the window. This model was developed based on field studies and monitoring of window operation in an office building. In this model, the window state is considered as the dependent variable, while outdoor temperature serves as the sole independent variable. The model proposes an equation that predicts the probability of a window being open based on the given outdoor temperature, this is given below (Zhou et al., 2018b)

$$P = 0{,}0002T^{3} - 0{,}019T^{2} + 0{,}51T - 3.08$$

Where T is the Outdoor temperature and P is the probability of a window open.

This model offers a simplified representation of occupant behaviour related to window operation, focusing solely on the influence of outdoor temperature. Its simplicity allows for easier implementation and analysis, making it suitable for certain scenarios and research investigations.

It is worth mentioning that the study conducted by Zhou et al. (2018c) was conducted in China, which has different climatic conditions compared to the Netherlands. Additionally, cultural differences associated with the region may also influence occupant behaviour regarding window operation. However, for the purpose of this study, the window operation model developed by Zhou et al. (2018c) is primarily used to predict occupant interaction with the facade. While there may be variations in the results due to the differences in climatic and cultural contexts, the model can still provide valuable insights and serve as a useful tool in understanding and analyzing occupant behaviour in relation to window operation.

Model 2

The second model selected for this study is developed by Rijal et al. (2007). Unlike the previous model, this model takes into account multiple factors for window operation prediction. It considers outdoor and indoor temperature as independent variables, along with occupant presence, previous window state, and the thermal state of the indoor environment, which is calculated using the comfort temperature defined by CEN 15251.

As window operation is a stochastic process, random numbers are generated to compare with the probability values. The model first determines the thermal state based on the temperature conditions, and then, considering the thermal state and previous window state, it compares the probability value from the logit equation with a randomly generated number to determine the window state. In this model, the window state values are binary, represented as either 0 (closed) or 1 (open).By considering multiple variables and incorporating stochastic elements, the model developed by Rijal et al. (2007) provides a more comprehensive representation of occupant behaviour in relation to window operation. This model allows for a more detailed analysis of the factors influencing window state and can contribute to a better understanding of the impact of occupant behaviour on indoor thermal comfort.

The second model, developed by Rijal et al. (2007), is based on studies conducted in the UK. Although there may be some differences in climate and occupant behaviour between the UK and the Netherlands, they share similarities that make the model relevant for this study. The results obtained from this model are expected to closely align with what would be obtained from studies conducted specifically in the Netherlands. Therefore, despite slight variations, the model remains a valuable tool for predicting occupant behaviour and window operation in the context of indoor thermal comfort.

The logit equation used in this model is as follows

$$Logit(P_w) = 0.171T_{op} + 0.166T_{out} - 6.4$$

Where, Pw is the probability of window opening , T_{op} is the indoor operative temperature and T_{out} is the outdoor temperature.

4.2.4 Creating scenarios and combinations

Overall, this research incorporates two occupant behaviour models and six facade archetypes. In addition to the selected occupant behaviour models, two additional cases will be simulated as base cases for comparison: one with windows always closed and the other with windows always open. From the literature review, it is clear that night ventilation can be a useful cooling strategy in naturally ventilated buildings during the summer, hence both window operation models will also be simulated with and without night ventilation. This results in a total of 36 combinations, comprising each scenario with each occupant behaviour model and the base cases. By exploring these various combinations, a comprehensive analysis of the influence of window operation on indoor thermal comfort can be conducted. An illustration for these combinations is given below in the form of a rubric in figure 21.

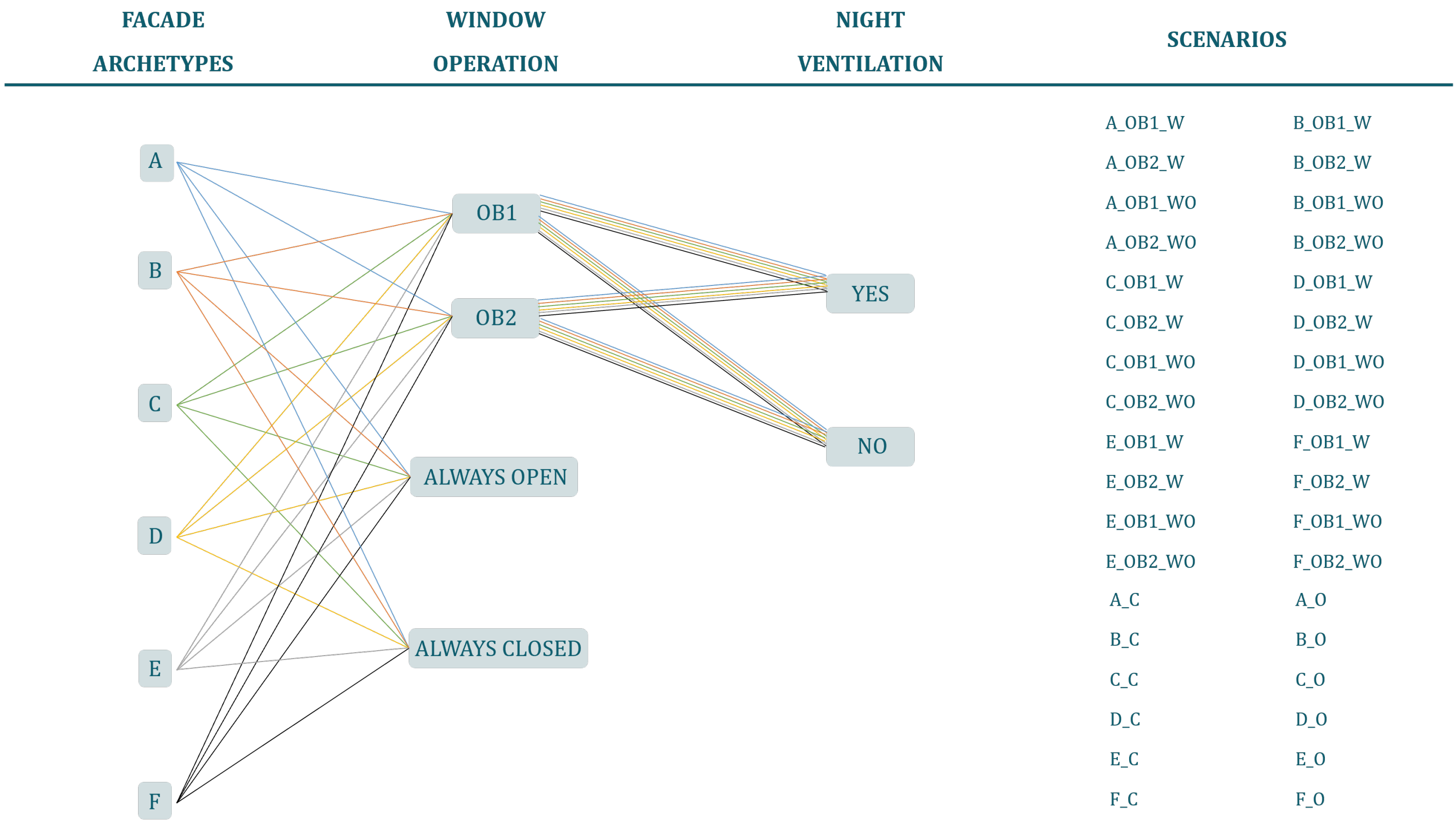


Fig. 21. Graphical representation of the scenario development rubric

Where,

OB1	-	Occupant behaviour model 1
OB2	-	Occupant behaviour model 2
W	-	With night ventilation
WO	-	Without night ventilation
O	-	Windows always open
C	-	Windows always closed

4.3 Implementing Occupant behaviour models in Design Builder

4.3.1 Design builder set up

DesignBuilder(DB) is a comprehensive building performance simulation software that enables detailed analysis and evaluation of energy efficiency, thermal comfort, and environmental performance of buildings. It provides a user-friendly interface that allows users to create, modify, and simulate building models with ease. DesignBuilder is built on the EnergyPlus simulation engine, which is a widely recognized and trusted energy analysis program. By utilizing the EnergyPlus engine, DesignBuilder ensures accurate and reliable simulation results, allowing users to gain valuable insights into the energy performance of their building designs. Unlike the Energy Plus software interface, design builder interface is more graphic and allows users to visualize their building or space for analysing with the 3D modelling feature.

DesignBuilder software provides users with a range of tabs and settings to configure before conducting simulations. These tabs include Layout, Activity, Construction, Openings, Lighting, HVAC, and CFD. Each tab corresponds to a specific aspect of the building model and simulation setup.The Layout tab serves as the starting point, allowing users to create a 3D model of the building. By adding building blocks and defining their dimensions, users can customize the geometry of the building. This tab offers flexibility in creating various forms and constructions, including curved buildings and domes. Additionally, users can incorporate openings such as doors and windows and include external shading devices using the model construction tools available.

Moving on to the other tabs, the Activity tab enables users to define occupancy schedules, activity patterns, and thermal loads within the building. The Construction tab allows for the specification of wall, roof, and floor constructions, including insulation materials and thicknesses. The Openings tab is used to configure window properties, such as glazing type, frame material, and dimensions.The Lighting tab allows users to input lighting fixtures and their characteristics, including power consumption and schedules. The HVAC tab is used to define the heating, ventilation, and air conditioning systems within the building, specifying equipment, setpoints, and control strategies. Finally, the CFD (Computational Fluid Dynamics) tab allows for more advanced airflow simulations, analyzing factors such as air movement and distribution within the building.

By utilizing these tabs and settings in DesignBuilder, users can input the necessary information and customize their building model to accurately represent the desired simulation scenario. Below, you will find a comprehensive description of the steps and settings implemented for the simulation models utilized in this research.

Steps taken to set up the design builder base model

1. After creating a new file in Design Builder, the first step is to set the model options. Since we are simulating a naturally ventilated and continuously varying office space, the calculated ventilation option must be selected under the natural ventilation and infiltration settings. By default, this is typically set to scheduled ventilation. The rest of the options can be left as default.

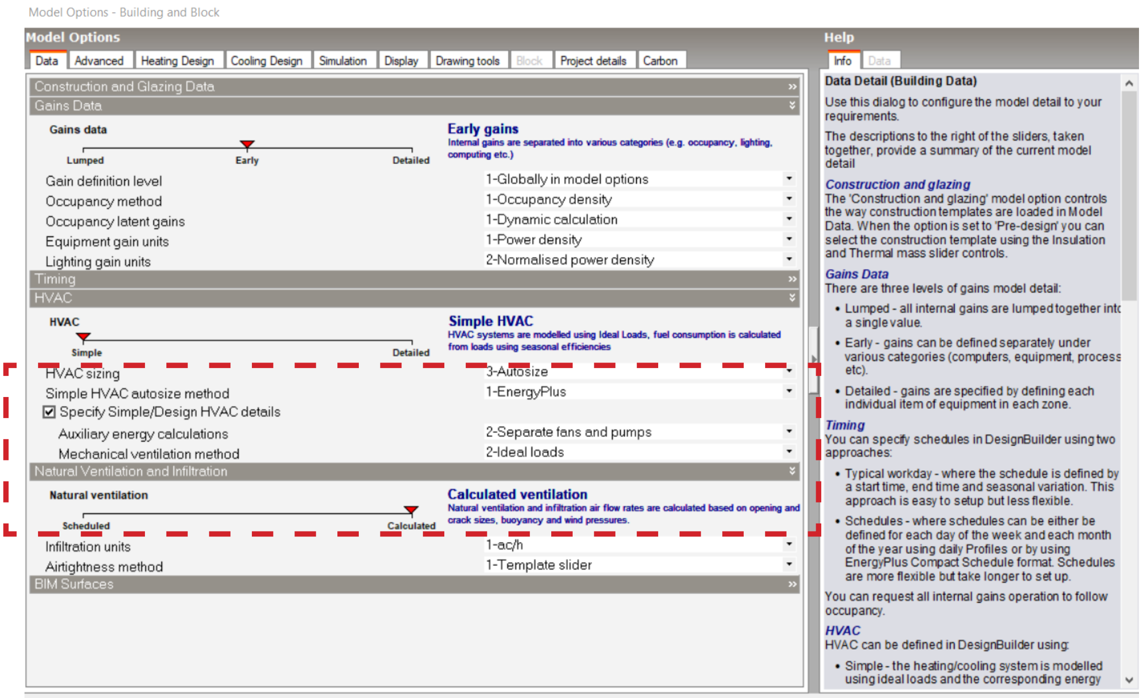


Fig.22. Design builder window for setting model options

2. After setting the model options, the next step is to create the 3D model of the space based on the desired dimensions and layout. This is achieved by adding a new building and using the new block tool to create the block within the building. By default, the block comes with pre-defined windows, which need to be removed by deselecting the default openings option. Then, the south-facing wall is selected, and windows are drawn according to the specified dimensions. This process completes the creation of the 3D model.

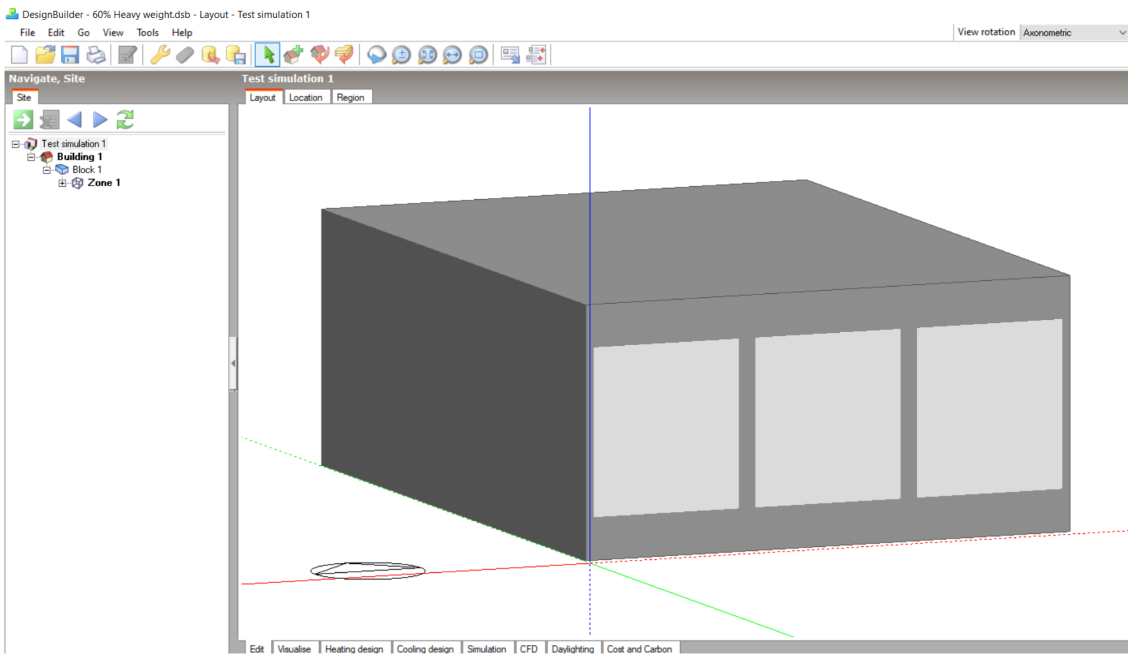


Fig.23. Design builder representation of the 3D Model used for simulations

3. Following the creation of the 3D model, the next step is to make the remaining walls, roof, and floor adiabatic to exclude them from the simulation calculations. This is accomplished by selecting each individual surface and accessing the construction tab. Under the adjacency settings, the adiabatic option is selected for the respective surfaces. When a surface is set to adiabatic, the text associated with it turns red in the navigation panel, and red arrows are displayed on the surface within the modelling space, indicating its adiabatic status.

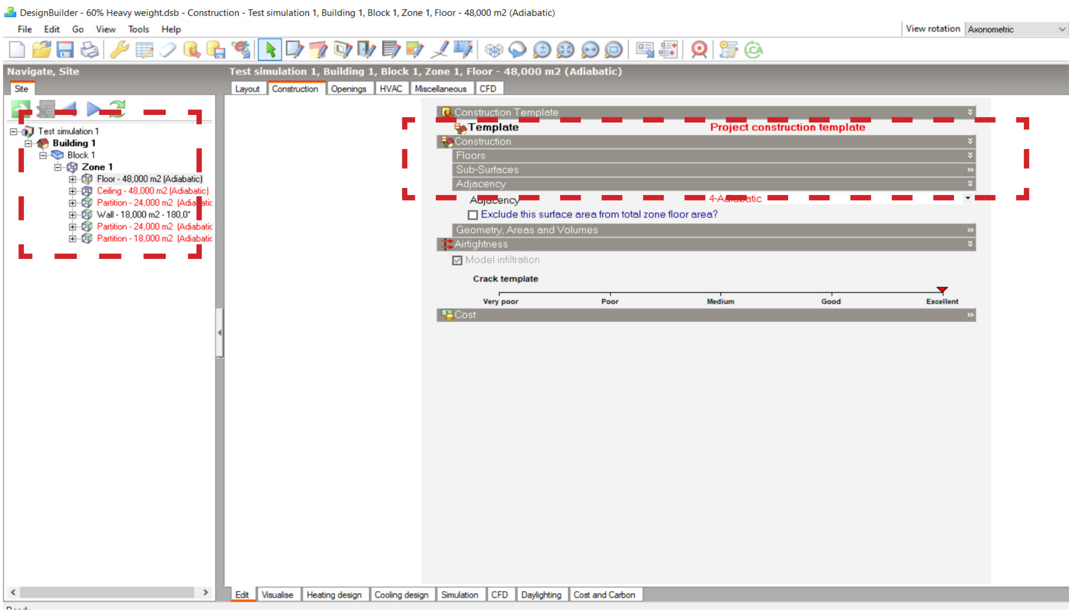


Fig.24. Design builder window for setting the adjacency for particular surfaces

4. The next step is to set the activity tab in DesignBuilder. In this tab, a suitable template is selected, such as the generic office template. Under the occupancy section, the "occupied" checkbox is checked, and a standard office schedule is chosen. This schedule specifies the occupied hours, typically from 8:00 to 19:00 on weekdays. Additionally, a metabolic factor of 1 and a clothing value of 0,5 are entered, which are standard values for occupants in office spaces. The ventilation set point temperatures section, both options are unchecked. This means that the ventilation in the simulation will depend solely on the window operation models and will not be influenced by pre-defined set point temperatures.

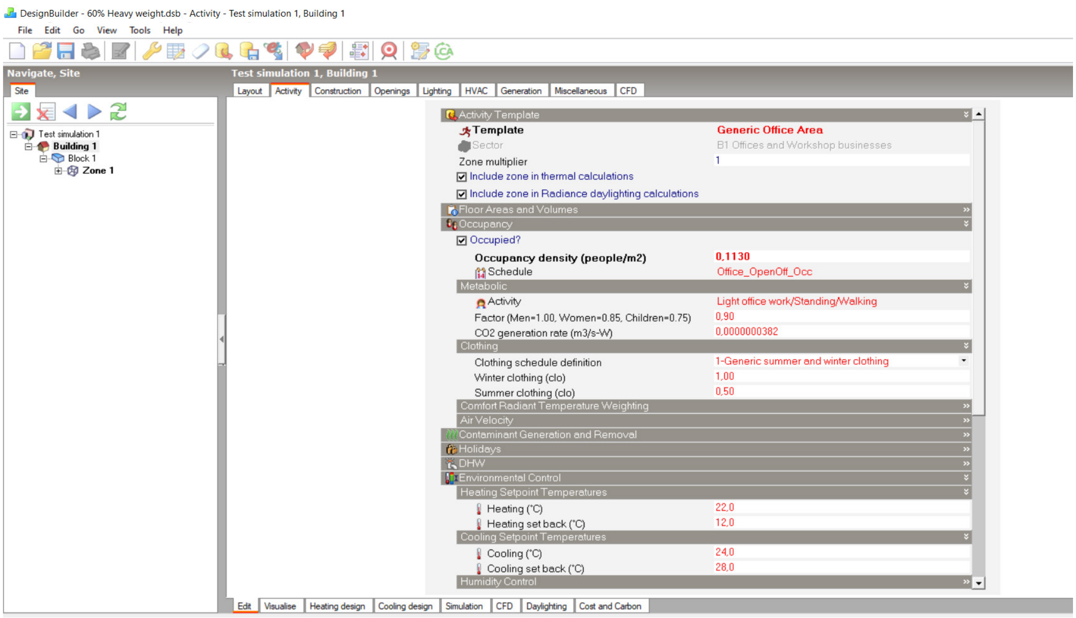


Fig.25. Design builder activity tab

5. In the openings tab of DesignBuilder, the glazing type can be specified to meet the project requirements. In this research, the glazing type remains consistent across all scenarios, while the window to wall ratio varies. A glazing template is chosen, and for this project, the most commonly used glazing type is selected, which is double glazed clear glass. The specific configuration for the glazing consists of two glass panes, each with a thickness of 6mm, separated by a 13mm air gap.

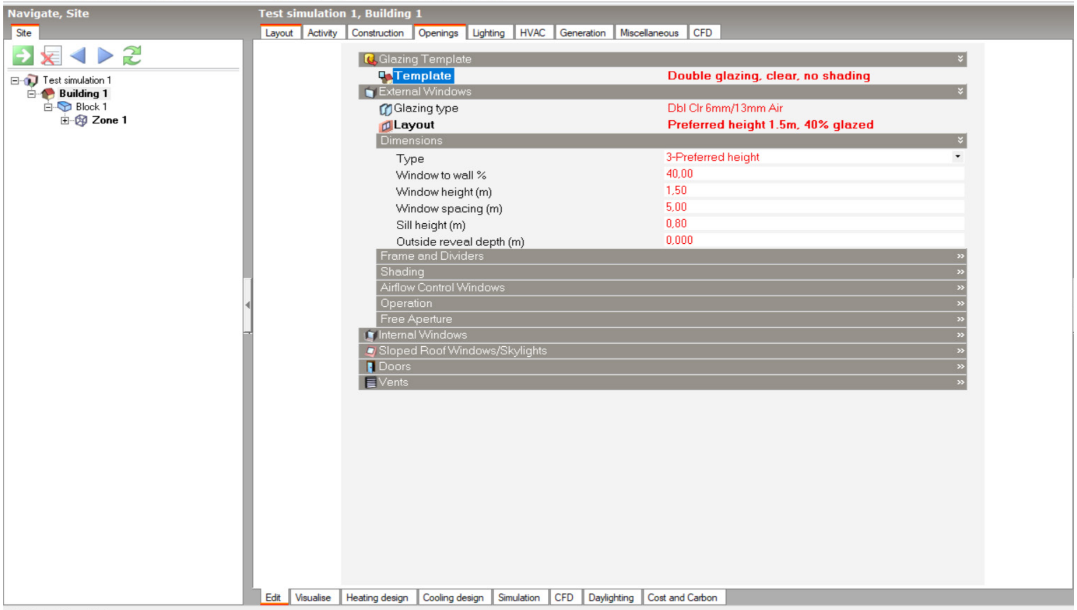


Fig.26. Design builder openings tab

6. In the HVAC tab of DesignBuilder, the details of the HVAC system can be defined. For this project, the HVAC template is left as "none," indicating that no mechanical heating, cooling, or DHW (domestic hot water) systems are present. Only natural ventilation is enabled to simulate the desired naturally ventilated condition. In the lighting tab, the generic office lighting template is used to represent the lighting conditions in the office space during the simulation.

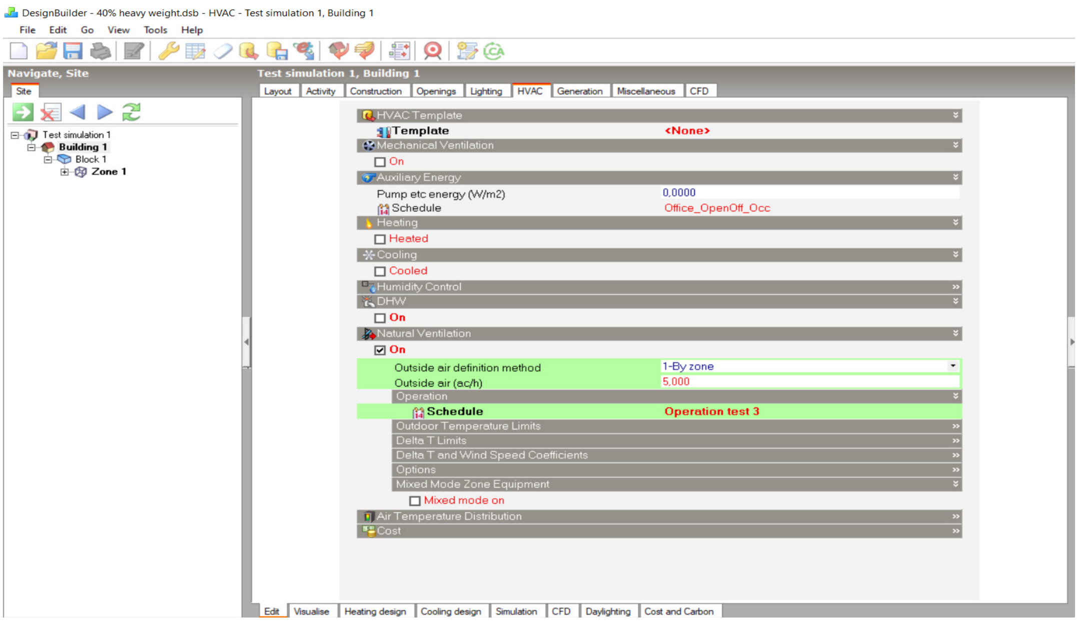


Fig.27. Design builder HVAC tab

The six steps mentioned above are applied to all the simulation models. The variations between the models are in terms of the window-to-wall ratio and the construction typology. First, the three models with different window-to-wall ratios are created, specifying the desired proportions of windows in relation to the total wall area. Next, for each model, both heavy-weight and light-weight construction templates are created to represent the different construction typologies. In the construction tab, the materials for each template are defined, including the number of layers, materials, and thicknesses.

These templates are then applied to the respective models, resulting in the desired combinations of window-to-wall ratio and construction typology. The resulting models for the three window-to-wall ratios and the two construction typologies are depicted in the following figures (28,29,30). Along with these settings, the weather file for Amsterdam is used at site level to obtain accurate weather data for the simulations.

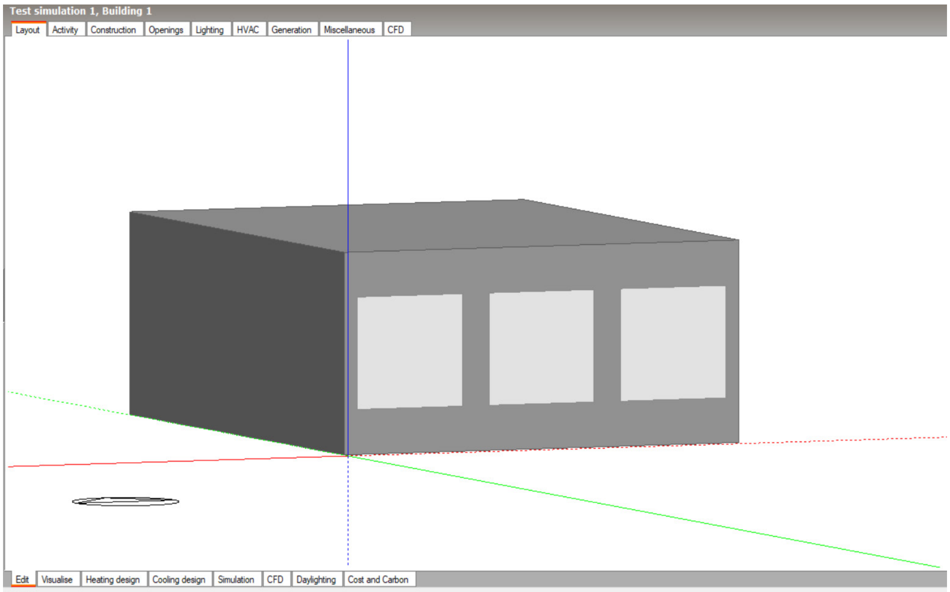


Fig.28. 3D model in design builder for the facade archetype with 40% window to wall ratio

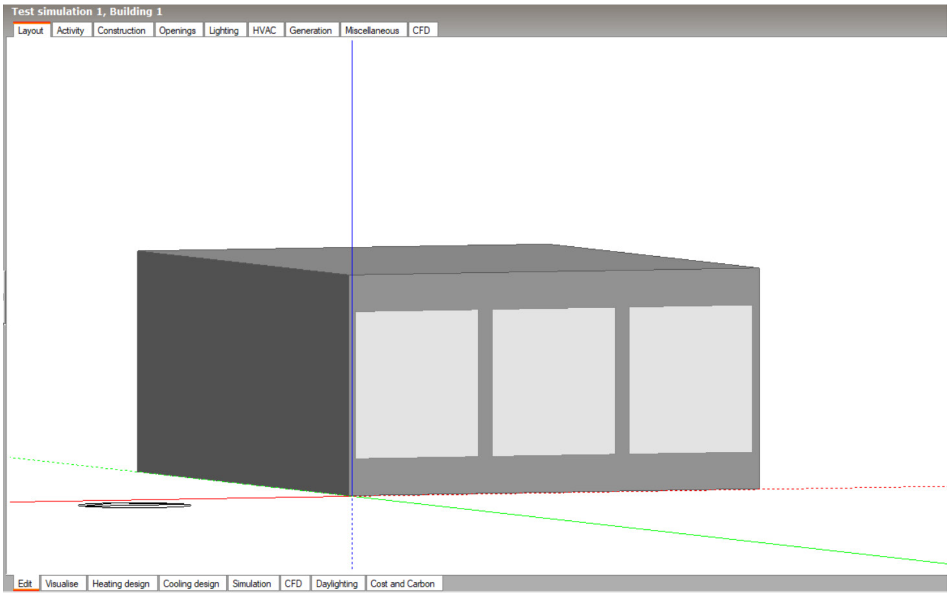


Fig.29. 3D model in design builder for the facade archetype with 60% window to wall ratio

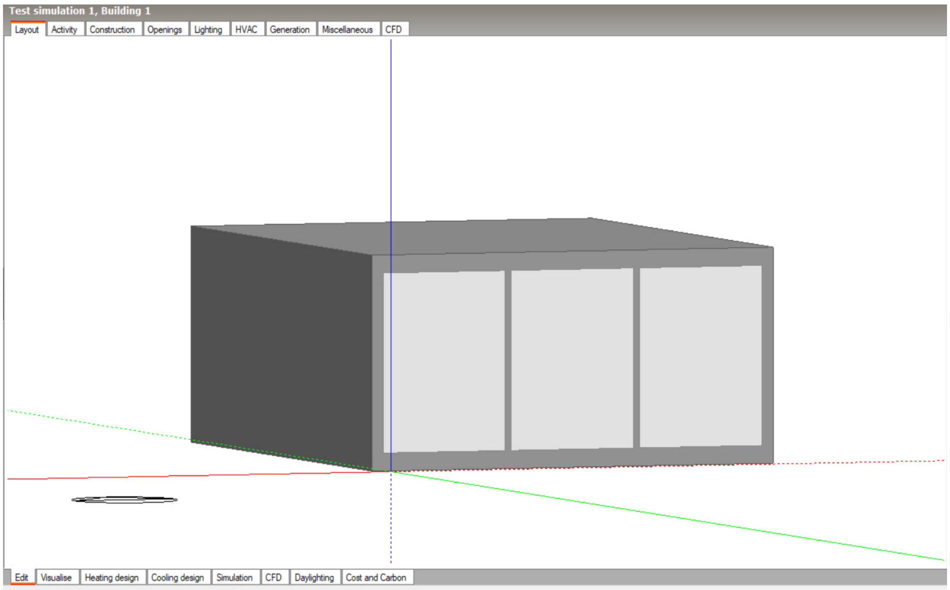


Fig.30. 3D model in design builder for the facade archetype with 80% window to wall ratio

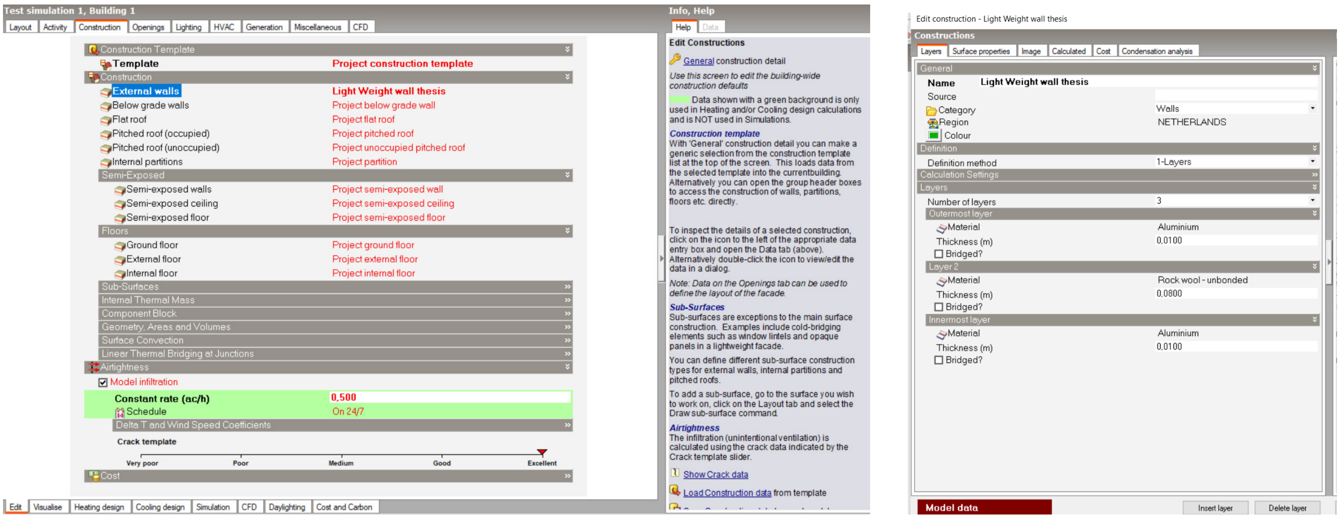


Fig.31 & 32. Settings and details used to define the light weight construction typology in design builder

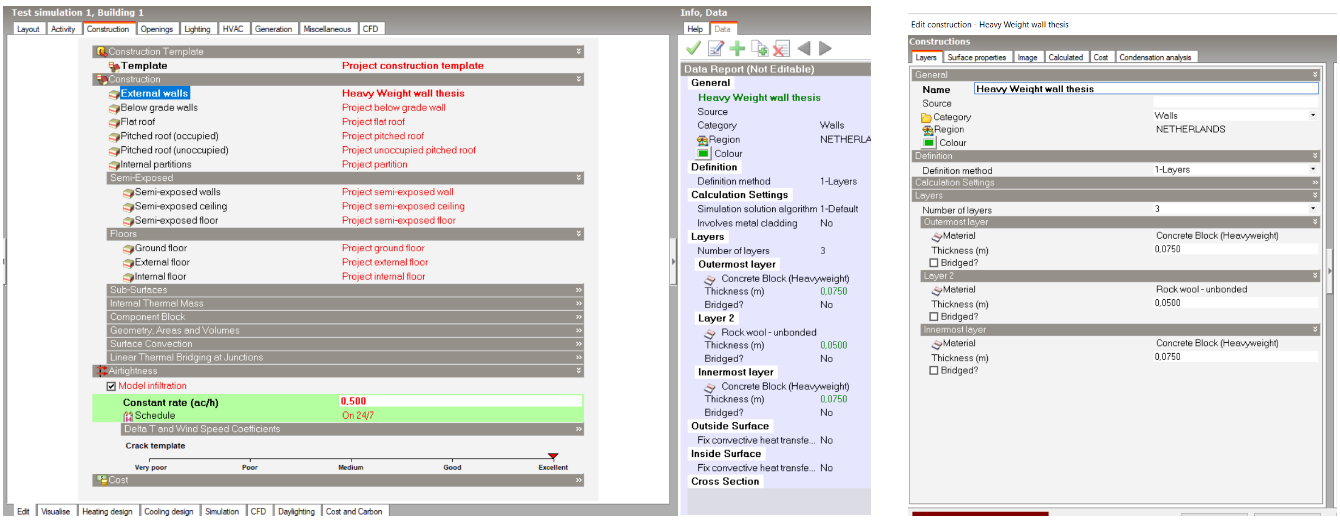


Fig.33 & 34. Settings and details used to define the heavy weight construction typology in design builder

4.3.2 Method to incorporate occupant behaviour models in design builder

Generally in Design Builder, schedules are used to specify and control various aspects of the simulation models. Schedules allow for the definition of time-dependent parameters, such as occupancy schedules, lighting schedules, and HVAC setpoint schedules. These schedules can be defined with a preferred time step, which can be set to either daily or hourly. This allows for more detailed and granular control over the variation of parameters throughout the day or week. By utilizing schedules in Design Builder, users can accurately represent the dynamic nature of occupant behaviour, energy usage, and environmental conditions within the simulated models. This helps in analyzing the performance of the building under different scenarios and optimizing its energy efficiency and thermal comfort.

When attempting to incorporate occupant behaviour models into Design Builder, the author initially experimented with compact schedules. Compact schedules are a feature in Design Builder that allows for more intricate and detailed scheduling. The idea was to use these schedules to input the hourly window operation values predicted by the occupant behaviour models. However, it quickly became evident that using compact schedules for modelling occupant behaviour, particularly window operation, was not the most efficient approach. Occupant behaviour models often capture the dynamic nature of occupant actions, including window opening and closing, on an hourly or even shorter time scale. This means that for each hour of the simulation period, a value for window operation would need to be manually inputted into the compact schedule.

Considering the potentially long simulation periods and the large number of hourly values involved, this method became laborious and time-consuming. It was not practical to manually input values for every hour, especially considering the need to repeat the process for multiple simulations and scenarios.Therefore, an alternative approach was sought to streamline the process of incorporating occupant behaviour models. The focus shifted to using scripts or external programs to automate the generation of window operation schedules based on the predictions of the occupant behaviour models. By leveraging scripting capabilities or external tools, the task of generating hourly window operation schedules could be simplified and expedited, making the modelling process more efficient.

In conclusion, while compact schedules initially seemed promising for modelling occupant behaviour in Design Builder, the dynamic and hourly nature of window operation predictions necessitated a more efficient approach. This led to the exploration of scripting or external program solutions to automate the generation of window operation schedules based on the occupant behaviour models. Using EMS runtime scripting within design builder was the next best solution.

Energy management system Runtime Language

EMS (Energy Management System) runtime language is a scripting language developed within EnergyPlus, a widely used energy simulation software. EMS allows users to define custom logic and control strategies to implement complex simulations and automate various aspects of the simulation process.In recent years, EMS scripting has been made available in Design Builder, providing users with the ability to harness the power and flexibility of EMS within the Design Builder interface. This integration has expanded the capabilities of Design Builder and has gained popularity among Design Builder users.

With EMS scripting, users can create custom scripts to manipulate simulation inputs, control system behaviour, and capture complex interactions between building components, occupant behaviour, and environmental conditions. By leveraging EMS scripting, users can further enhance the simulation capabilities of Design Builder and tailor their simulations to specific research objectives or design scenarios (Big Ladder Software LLC, n.d.).

The window operation models, which describe the behaviour of occupants in relation to window opening and closing, will be implemented using EMS scripting within Design Builder. This allows for the dynamic and realistic modelling of occupant interactions with the windows based on various influencing factors. By leveraging EMS scripting, the window operation models can be programmed to consider factors such as outdoor temperature, indoor temperature, occupant presence, and previous window state, among others. These models will use EMS to calculate the probability or binary state of window operation for each simulation time step, reflecting the dynamic nature of occupant behaviour. Using EMS for implementing the window operation models enables a more accurate representation of occupant interactions with the facade, allowing for a comprehensive analysis of the impact of window operation on thermal comfort and energy performance.

EMS scripting in Design Builder, while sharing similar syntax with EnergyPlus EMS, has some differences in terms of its implementation within the software. Design Builder has its own implementation of EMS scripting that is tailored to its interface and simulation capabilities.While EnergyPlus EMS is a widely-used scripting language in the energy simulation domain, Design Builder has developed its own version of EMS scripting that is specific to its software. The syntax and structure of EMS scripting in Design Builder may closely resemble EnergyPlus EMS, but there are variations and additional features specific to Design Builder.

In EMS (Energy Management System) scripting within Design Builder, sensors and actuators play a crucial role in capturing and controlling the behaviour of building systems and components. Sensors act as inputs to the EMS, providing information about the building's environment and conditions, while actuators are used to control and manipulate various building systems. These sensors and actuators are already predefined in design builder and can be directly used by selecting the blocks. Predefined sensors and actuators are readily available and can be conveniently utilized by selecting the corresponding blocks. To enable EMS, the enable program checkbox needs to be ticked in the program window.

Sensors in EMS serve to collect data from the simulation environment. These sensors can be defined to monitor parameters such as temperature, humidity, occupancy, solar radiation, and other relevant variables. Sensors extract information from the simulated building model, allowing the EMS to access and utilize this data for decision-making and control purposes (Big Ladder Software LLC, n.d.).

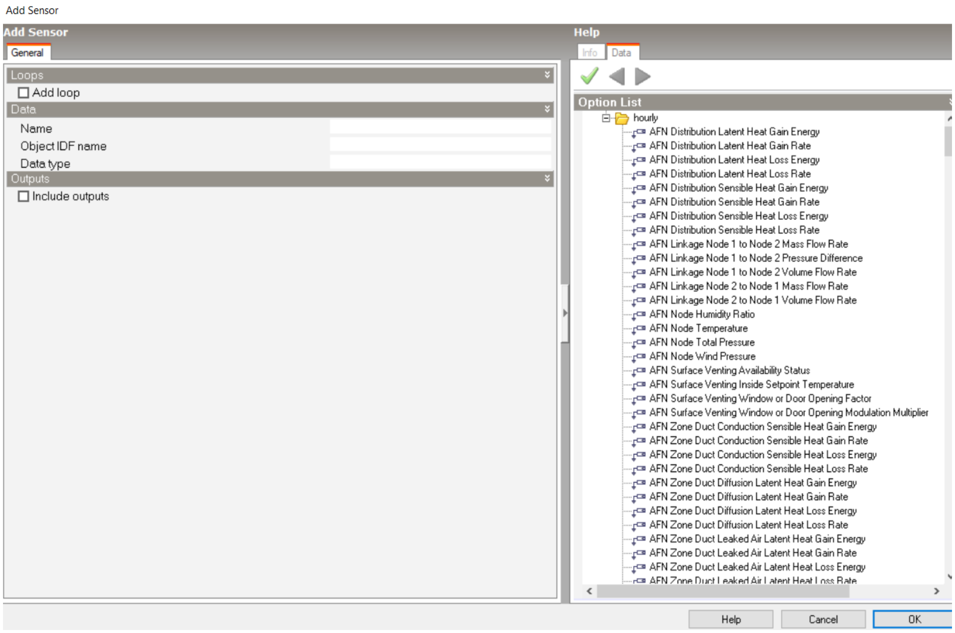


Fig.35. Sensor dialogue box within design builder EMS option, to define the sensors required for the script

Actuators, on the other hand, enable the EMS to interact with and control specific aspects of the simulated building systems. Actuators can be used to modify setpoints, adjust schedules, activate or deactivate equipment, and trigger certain actions based on the logic defined within the EMS script. They act as the interface between the EMS and the simulated building systems, allowing the EMS to influence the behaviour of the systems.

These blocks simplify the process of collecting data from the simulation environment using sensors and controlling building systems using actuators. This streamlined approach allows for efficient implementation of EMS scripting without the need for extensive manual configuration (Big Ladder Software LLC, n.d.).

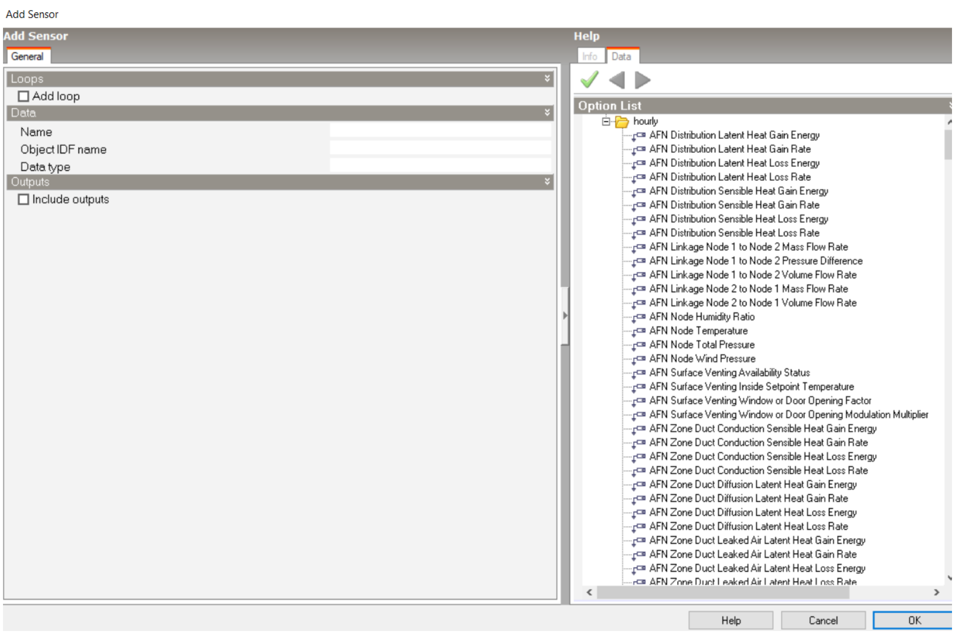


Fig.36. Actuator dialogue box within design builder EMS option, to define the sensors required for the script

4.3.3 Occupant behaviour model 1 simulation

To implement the occupant behaviour model developed by Zhou et al. (2018c) in Design Builder, an EMS script is created. This script utilizes a schedule and people occupant count as the sensors and the window venting factor as the actuator. The schedule is linked to a CSV file that contains the equation implemented per hour for the specified simulation period (June 1st - September 10th). It's important to note that when using schedules in EMS, the CSV file should contain values for the entire year, regardless of the simulation period. This means that the file must include 8760 hourly values.

The EMS code for defining a schedule includes specifying the schedule name, the location of the CSV file, the number of hours of data, the column number in the CSV file to be considered, and the number of rows to be skipped from the top, if necessary. By setting up the schedule in this manner, the occupant behaviour model can be effectively implemented in Design Builder for simulating window states based on outdoor temperature. A script for the program is given below with comments on the side indicating what it stands for.

```
Schedule:File,
 vent_value,                                                        ! Name
 Any Number,                                                        ! Schedule Type
C:\ProgramData\DesignBuilder\Schedule files\Model_1 copy.csv,       ! Name of File
 1,                                                                 !Column number
 0,                                                                 ! Rows to Skip at Top
 8760,                                                              ! Number of Hours of Data
 Comma;                                                             !Column Separator

<ForAllExternalWindows>
EnergyManagementSystem:Actuator,
  Venting_Opening_Factor_<LoopWindowVariableName>,                  !Actuator Block
  <LoopWindowIDFName>,
  AirFlow Network Window/Door Opening,
  Venting Opening Factor;
<LoopNextWindow>

EnergyManagementSystem:Sensor,
  Schedule_Value_Sensor,
  vent_value,                                                       !Sensor Block
  Schedule Value;

<ForAllExternalWindows>
EnergyManagementSystem:Sensor,                                      !Sensor Block
  Zone_People_Occupant_Count_<LoopWindowVariableName>,
  <LoopWindowZoneIDFName>,
  Zone People Occupant Count;
<LoopNextWindow>

EnergyManagementSystem:ProgramCallingManager,
  Window_Operation,                                                 !Program Code
  BeginTimestepBeforePredictor,
   WindowOperation;

EnergyManagementSystem:Program,
   WindowOperation,
<ForAllExternalWindows>

If Zone_People_Occupant_Count_<LoopWindowVariableName> > 0,
   Set Venting_Opening_Factor_<LoopWindowVariableName> = Schedule_Value_Sensor,

   ElseIf Zone_People_Occupant_Count_<LoopWindowVariableName> <= 0,
      Set Venting_Opening_Factor_<LoopWindowVariableName> = 0,
EndIf,
<LoopNextWindow>
  ;
```

```
Output:Variable, *, AFN Surface Venting Window or Door Opening Factor, Timestep;
Output:Variable, *, AFN Surface Venting Window or Door Opening Factor, Hourly;
Output:Variable, *, AFN Surface Venting Window or Door Opening Modulation Multiplier, Timestep;
Output:Variable, *, AFN Surface Venting Window or Door Opening Modulation Multiplier, Hourly;
Output:Variable, *, Zone Operative Temperature, Timestep;
Output:Variable, *, Zone Operative Temperature, Hourly;
Output:Variable, *, Zone Outdoor Air Drybulb Temperature, Timestep;
Output:Variable, *, Zone Outdoor Air Drybulb Temperature, Hourly;
```

EMS script for occupant behaviour model 1

In the program script, loops are used to iterate through each window and time step. The script instructs Design Builder to first check the occupant count. If the count is greater than 0, indicating that the office space is occupied, the venting opening factor is set to the corresponding value from the CSV file for that specific hour. On the other hand, if the building is unoccupied, the venting opening factor is set to 0.

After the execution of the program, it is necessary to define output variables in order to obtain the desired results. These output variables can be specified based on the specific parameters and data that need to be captured for analysis and evaluation.

Another version of the script includes the consideration of night ventilation. In this case, when the occupant count is zero (indicating an unoccupied period), the venting factor value is set to 0.4. This activation of night ventilation during unoccupied hours introduces an interesting variation to the model and allows for a comparison between scenarios with and without night ventilation. By adjusting the venting factor value during unoccupied periods, the model can simulate the impact of night ventilation on the window operation behaviour and its influence on the indoor thermal conditions.

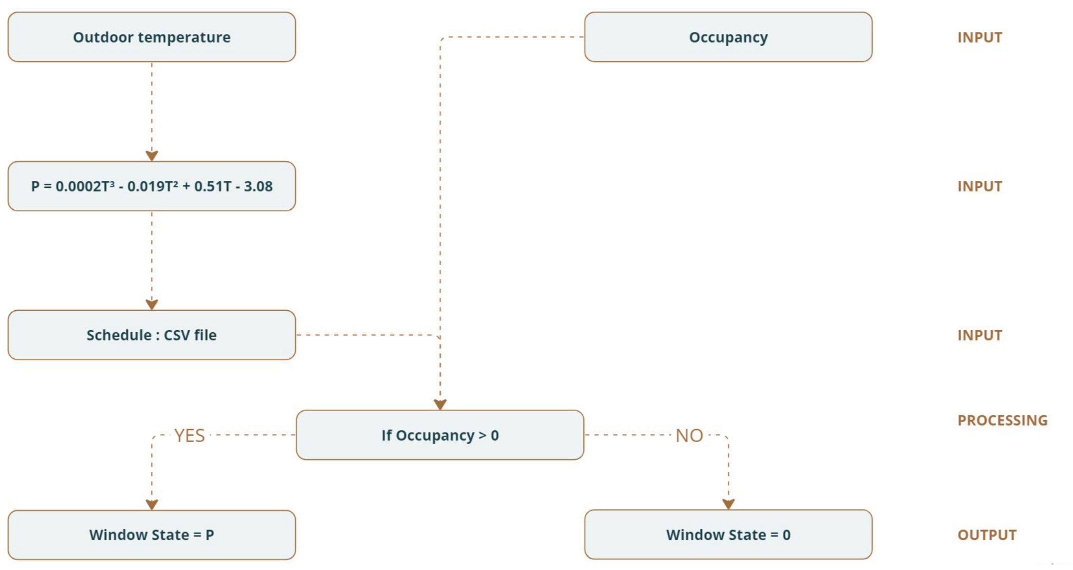


Fig.37. Graphical representation of the algorithm used to implement occupant behaviour model 1 in EMS programing tool

4.3.4 Occupant behaviour model 2 simulation

The occupant behaviour model developed by Rijal et al. (2007) is more comprehensive and considers multiple variables such as indoor temperature, outdoor temperature, occupant presence, and indoor thermal state. Despite these additional variables, the actuator for this model remains the venting opening factor. To implement this model in Design Builder, the sensors defined include the operative temperature, outdoor temperature, and people count. Additionally, a schedule is defined to incorporate a CSV file containing random numbers. This model requires comparing the probability of window opening with a random number to produce realistic results.

```
Schedule:File,
 Random_Number,                                          ! Name
 Any Number,                                             ! Schedule Type
 C:\ProgramData\DesignBuilder\Schedule files\Model_2_Random.csv,   ! Name of File
 1,                                                      !Column number
 0,                                                      ! Rows to Skip at Top
 8760,                                                   ! Number of Hours of Data
 Comma;                                                  !Column Separator

<ForAllExternalWindows>
EnergyManagementSystem:Actuator,                         !Actuator Block
  Venting_Opening_Factor_<LoopWindowVariableName>,
  <LoopWindowIDFName>,
  AirFlow Network Window/Door Opening,
  Venting Opening Factor;
<LoopNextWindow>

<ForAllExternalWindows>
EnergyManagementSystem:Sensor,                           !Sensor Block
  Zone_Operative_Temperature_<LoopWindowVariableName>,
  <LoopWindowZoneIDFName>,
  Zone Operative Temperature;
<LoopNextWindow>

<ForAllExternalWindows>                                  !Sensor Block
EnergyManagementSystem:Sensor,
  Zone_People_Occupant_Count_<LoopWindowVariableName>,
  <LoopWindowZoneIDFName>,
  Zone People Occupant Count;
<LoopNextWindow>

<ForAllExternalWindows>                                  !Sensor Block
EnergyManagementSystem:Sensor,
  Zone_Outdoor_Air_Drybulb_Temperature_<LoopWindowVariableName>,
  <LoopWindowZoneIDFName>,
  Zone Outdoor Air Drybulb Temperature;
<LoopNextWindow>


EnergyManagementSystem:Sensor,
  Schedule_Value_Sensor,
  Random_Number,
  Schedule Value;


EnergyManagementSystem:ProgramCallingManager,            !Program Code
  Model_2,
  BeginTimestepBeforePredictor,
  Model_2;

EnergyManagementSystem:Program,
   Model_2,
<ForAllExternalWindows>
Set Tp = Zone_Operative_Temperature_<LoopWindowVariableName>,
Set To = Zone_Outdoor_Air_Drybulb_Temperature_<LoopWindowVariableName>,
Set e = 2.718281821828459,
```

```
Set Rand = Schedule_Value_Sensor,
Set Tc = (0.33*To) + 18.8,
Set A = (0.171*Tp) + (0.166*To) - 6.4,
Set P = (e^A)/(1 + e^A),
Set Oc = Zone_People_Occupant_Count_<LoopWindowVariableName>,

If (Oc > 0) && (Tp > (2 + Tc)) && (Rand < P),
      Set Venting_Opening_Factor_<LoopWindowVariableName> = 1,

   ElseIf (Oc > 0) && (Tp < (Tc - 2)) && (Rand > P),
      Set Venting_Opening_Factor_<LoopWindowVariableName> = 0,

   ElseIf (Oc <= 0),
      Set Venting_Opening_Factor_<LoopWindowVariableName> = 0,
ENDIF,
<LoopNextWindow>;

Output:Variable, *, AFN Surface Venting Window or Door Opening Factor, Timestep;
Output:Variable, *, AFN Surface Venting Window or Door Opening Factor, Hourly;
Output:Variable, *, AFN Surface Venting Window or Door Opening Modulation Multiplier, Timestep;
Output:Variable, *, AFN Surface Venting Window or Door Opening Modulation Multiplier, Hourly;
Output:Variable, *, Zone Operative Temperature, Timestep;
Output:Variable, *, Zone Operative Temperature, Hourly;
Output:Variable, *, Zone Outdoor Air Drybulb Temperature, Timestep;
Output:Variable, *, Zone Outdoor Air Drybulb Temperature, Hourly;
```

EMS script for occupant behaviour model 2

The program code for this occupant behaviour model begins by setting the required variables to their respective values, including sensors, constant values, and equations. This helps simplify the writing of the program code. Once all the values are set, the main program code is written. In this model, binary values are predicted for window opening (1) and closing (0).

The program first checks if the office space is occupied. If it is occupied and the thermal state is classified as "hot" (operative temperature greater than 2 K above the comfort temperature), the model compares the probability of window opening with a random number. If the probability is lower than the random number, the window state is set to 1, indicating an open window. On the other hand, if the office is occupied and the thermal state is classified as "cold" (operative temperature less than 2 K below the comfort temperature), the model compares the probability of window opening with a random number. If the probability is higher than the random number, the window state is set to 0, indicating a closed window. Finally, if the office is unoccupied, the window remains closed.

By incorporating these conditions and probabilities, the occupant behaviour model simulates the decision-making process for window operation based on the thermal state and occupant presence, providing a realistic representation of window behaviour in response to indoor comfort conditions. Similar to the previous case, another script for occupant behaviour model 2 is created to include night ventilation, by setting the venting opening factor to 0,4.

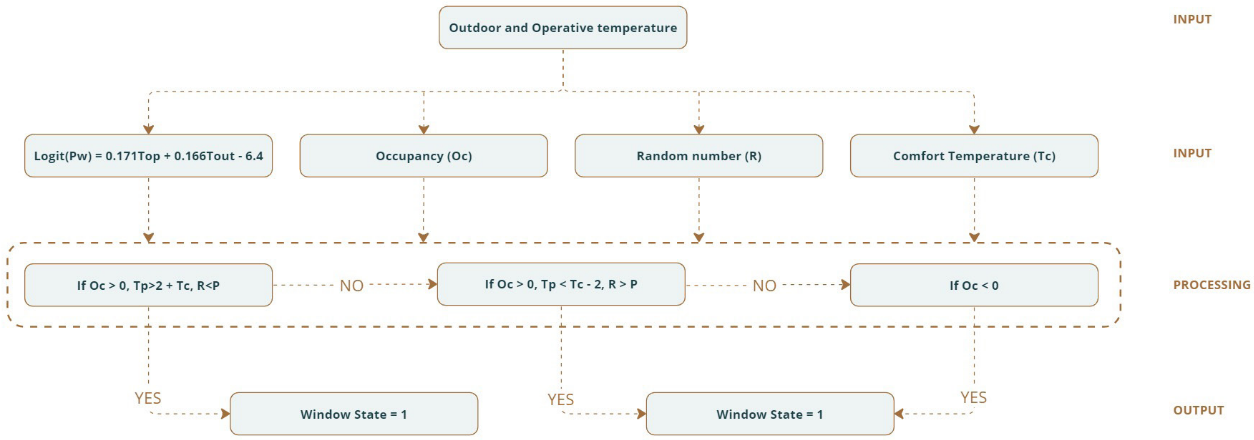


Fig. 38. Graphical representation of the algorithm used to implement occupant behaviour model 2 in EMS programing tool

4.3.5 Base case models

For the purpose of analyzing and comparing the occupant behaviour models, two additional models are set up for each facade archetype: one with windows always open and the other with windows always closed. These models serve to provide insights into the influence of using occupant behaviour models and the impact of window operation on indoor thermal comfort.

In the script for the model with windows always open, the venting opening factor is set to 1. This means that the windows are constantly open, allowing maximum ventilation throughout the simulation period. This scenario represents a situation where occupants have no control over the window operation and the windows remain open regardless of the indoor thermal conditions.

In contrast, the script for the model with windows always closed sets the venting opening factor to 0. In this case, the windows are kept closed at all times, resulting in minimal or no natural ventilation. This scenario represents a situation where the windows are non-operable or occupants choose to keep them closed consistently, disregarding the indoor thermal conditions.

By including these two extreme models, the research aims to highlight the importance of occupant behaviour models in simulating realistic window operation and its impact on indoor thermal comfort. It allows for a comprehensive analysis of the different scenarios and provides insights into the potential benefits and drawbacks of different window operation strategies.

All the simulations were carried out for a period of three and a half months, from June 1st to September 10th 2022.

05 | Results and Analysis

5.1 Introduction

The following chapter presents the results and analysis obtained from the simulations conducted in this research study. The simulations were performed for the period between June 1st and September 10th, which corresponds to the summer months when the cooling load is typically high. The focus of the analysis is on the operative temperature, which is a key indicator of indoor thermal comfort.

The analysis aims to evaluate the performance of different window operation strategies and occupant behaviour models in terms of their impact on indoor thermal conditions. The key performance indicators considered for analysis include the operative temperature and overheating degree.

Operative temperature is a comprehensive metric that takes into account the combined effect of air temperature, radiant temperature, and air velocity on occupant comfort. It provides a holistic assessment of the thermal conditions experienced by occupants in the simulated spaces (ASHRAE Standard 55). The overheating degree is a measure of the extent to which the operative temperature exceeds a specified comfort threshold. It helps identify the occurrences and duration of thermal discomfort, particularly when the indoor temperature rises above the desired comfort range (Nicol, Humphreys, & Roaf, 2012).

The relationship beween window state and operative temperature will also be analysed, to understand the importance of window operation as a passive strategy. This analysis can also give rise to possible recommendations on controlled window operation to maintain comfort levels.

The analysis will include statistical evaluation of the operative temperature data, comparative assessment of different window operation strategies and occupant behaviour models, and examination of temporal patterns. Additionally, the analysis will explore the influence of various factors, such as window to wall ratios, construction typologies, and occupant behaviour, on the thermal performance of the simulated spaces. Through the analysis of the results, valuable insights will be gained into the influence of occupant behaviour on indoor thermal conditions, and the overall performance of the simulated office spaces during the summer months.

The results obtained from the simulations in Design Builder can be viewed and analyzed using the Design Builder Results Viewer. This tool allows for a more detailed understanding of the output variables, including operative temperature values, window state values, and comfort temperature values. To facilitate further analysis and processing of the data, these values are exported from the Design Builder Results Viewer into Excel.

5.2 Assessment of thermal comfort

This section is divided into four sub sections that describe the analysis of operative temperature variation across all scenarios, the analysis of operative temperature and window state, the analysis of operative temperature and outdoor temperature and the analysis of discomfort hours and indoor overheating degree respectively.

5.2.1 Analysis of operative temperature variations

This section focuses on analyzing the hourly operative temperature values for the various facade archetypes and occupant behaviour models. The maximum and minimum operative temperature values are calculated for each combination and compare them among the different models and facade archetypes. Additionally, these values are compared with the operative temperature when the windows are fully closed and fully open. By examining these comparisons, we can gain insights into the impact of different occupant behaviour models and window states on the operative temperature, allowing us to assess their influence on indoor thermal comfort. To depict the results , bar graphs and a box plot are used which are explained in this section.

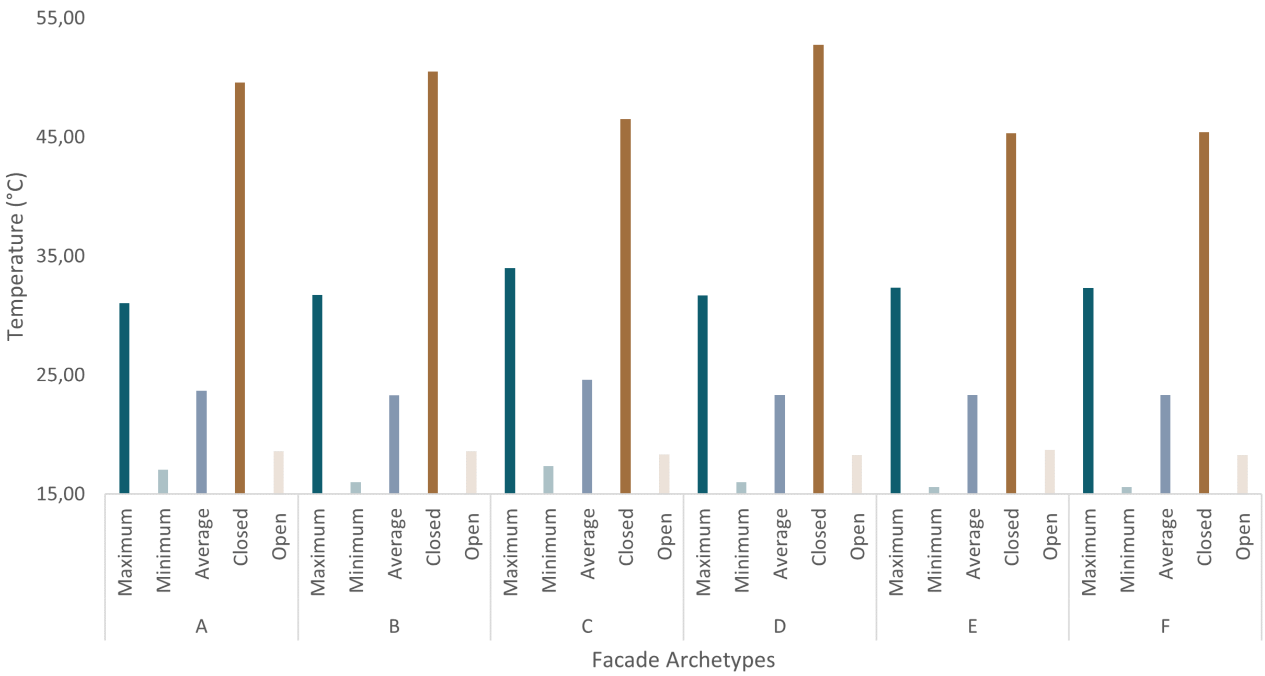


Fig. 39. Bar graph depicting the maximum, minimum and average values of operative temperatures obtained from the simulations for the six archetypes, for the scenario with occupant behaviour model 1 without night ventilation, along with the average operative temperature values for scenarios with windows always open and closed.

Where,
A - 40% Window to wall ratio, Light weight construction
B - 40% Window to wall ratio, Heavy weight construction
C - 60% Window to wall ratio, Light weightt construction
D - 60% Window to wall ratio, Heavy weight construction
E - 80% Window to wall ratio, Light weightt construction
F - 80% Window to wall ratio, Heavy weight construction

Occupant behaviour model 1 without night ventilation

Figure 39 illustrates the bar graph depicting the maximum, minimum and average values of operative temperatures obtained from the simulations for the six archetypes, for the scenario with occupant behaviour model 1 without night ventilation, along with the average operative temperature values for scenarios where windows are always open and closed. Across all the facade archetypes, the maximum operative temperatures fall within the range of 31°C to 34°C. Among the six archetypes, archetype C exhibits the highest maximum temperature(33.98°C), while archetype A has the lowest maximum temperature(31.02°C). On the other hand, the minimum operative temperatures for the six archetypes range from 15°C to 18°C. Archetype C once again shows the highest minimum temperature, while archetypes E and F have the lowest minimum temperatures. The graphs also show the average temperature values recorded for every scenario. It can be observed that although the maximum temperatures across all the archetypes go above 30°C, the average temperature remains between 23 - 25°C, which means that a large percentage of the operative temperatures are within comfort range. These findings provide insights into the variation of operative temperatures across different facade archetypes in the specific scenario of occupant behaviour model 1without night ventilation. The higher percentage of window-to-wall ratio (WWR) and the lightweight construction in archetype C could contribute to the higher maximum and minimum temperatures observed. The lower thermal mass of the lightweight construction allows for faster heat transfer, resulting in increased heat gain and potentially higher temperatures.

However, it is interesting to note that archetypes D, E, and F, which also have the same or higher WWR, exhibit lower temperatures compared to archetype C. There could be several factors contributing to this. Archetypes E and F, with 80% WWR, have such a high percentage of glazing that the opaque part of the facade has less influence on indoor temperatures. As a result, the overall thermal performance improves, leading to lower maximum and minimum temperatures. On the other hand, archetype D, with a heavy-weight construction consisting of concrete blocks, offers higher thermal mass. The increased thermal mass allows for greater heat storage capacity and slower heat transfer, resulting in lower temperature fluctuations and lower maximum and minimum temperatures compared to archetype C.

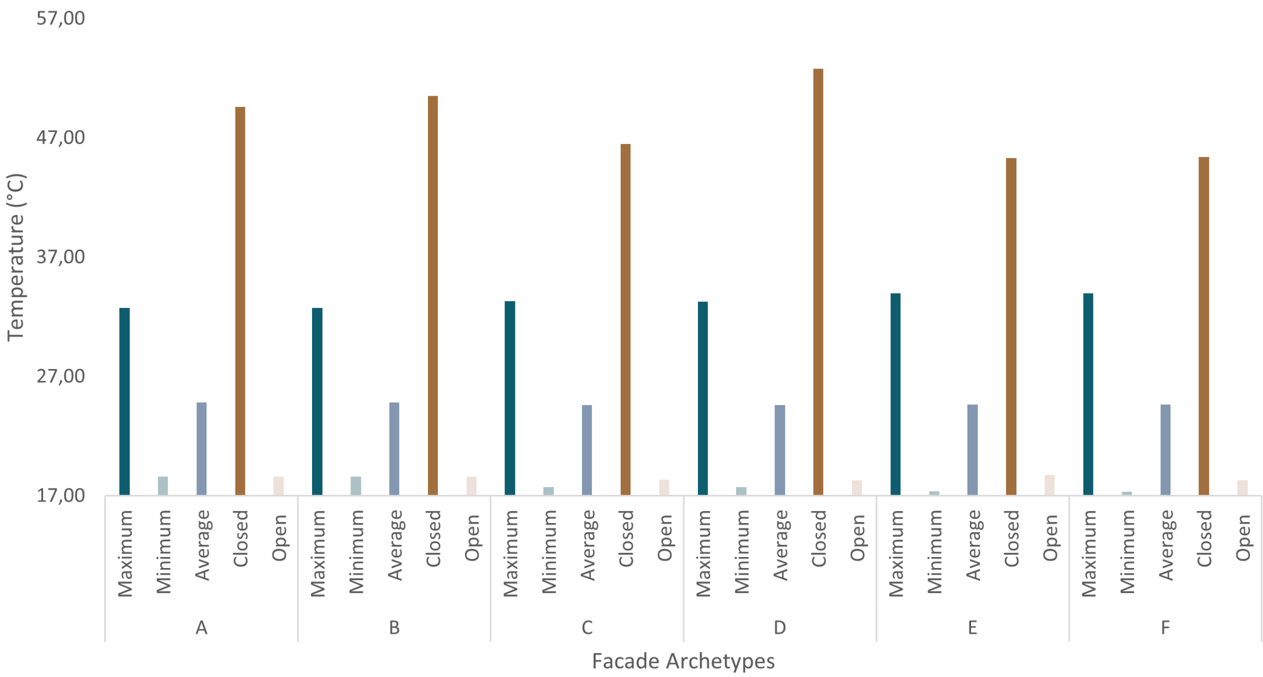


Fig. 40. Bar graph depicting the maximum, minimum and average values of operative temperatures obtained from the simulations for the six archetypes, for the scenario with occupant behaviour model 2 without night ventilation , along with the average operative temperature values for scenarios with windows always open and closed.

Where,
A - 40% Window to wall ratio, Light weight construction
B - 40% Window to wall ratio, Heavy weight construction
C - 60% Window to wall ratio, Light weightt construction
D - 60% Window to wall ratio, Heavy weight construction
E - 80% Window to wall ratio, Light weightt construction
F - 80% Window to wall ratio, Heavy weight construction

Occupant behaviour model 2 without night ventilation

Figure 40 depicts the bar graph the maximum, minimum and average values of operative temperatures obtained from the simulations for the six archetypes, for the scenario with occupant behaviour model 2 without night ventilation , along with the average operative temperature values for scenarios with windows always open and closed. The maximum temperatures for the different archetypes range from 32°C to 34°C, and the minimum temperatures rage between 17°C - 18°C, showing a relatively narrow temperature range among the archetypes. This uniformity in temperatures can be attributed to the characteristics of model 2, which integrates both outdoor and indoor temperatures in its calculations.

Unlike model 1, which considers only the outdoor temperature for window operation, model 2 takes into account the indoor thermal state as well. This integration of indoor temperature allows the model to make window operation decisions based on the prevailing indoor conditions. As a result, the temperatures across the archetypes in model 2 are closely aligned, indicating a more considerate approach to maintaining the desired indoor thermal comfort. Among the six archetypes, E and F exhibit the highest maximum temperatures and the lowest minimum temperatures. This can be attributed to their high glazing percentage of 80%. The significant amount of glazing in these archetypes allows for greater solar heat gain during the day, leading to higher maximum temperatures. Conversely, during cooler periods or at night, the reduced insulation provided by the extensive glazing results in greater heat loss, leading to lower minimum temperatures. Again it is seen that although the maximum temperatures are quite high, the average temperatures are between 24-25°C , which is still an acceptable range for operative temperatures.

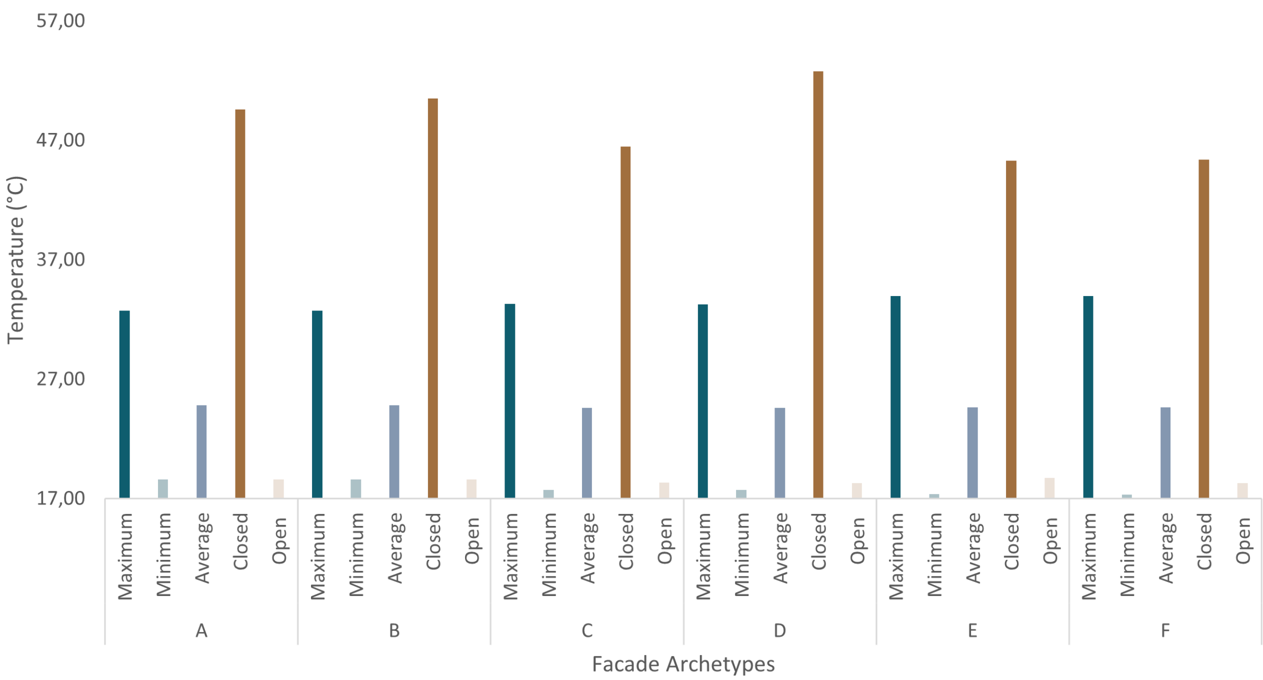


Fig. 41 Bar graph depicting the maximum, minimum and average values of operative temperatures obtained from the simulations for the six archetypes, for the scenario with occupant behaviour model 1 with night ventilation, along with the average operative temperature values for scenarios with windows always open and closed.

Where,
A - 40% Window to wall ratio, Light weight construction
B - 40% Window to wall ratio, Heavy weight construction
C - 60% Window to wall ratio, Light weightt construction
D - 60% Window to wall ratio, Heavy weight construction
E - 80% Window to wall ratio, Light weightt construction
F - 80% Window to wall ratio, Heavy weight construction

Occupant behaviour model 1 with night ventilation

Figure 41 showcases bar graph depicting the maximum, minimum and average values of operative temperatures obtained from the simulations for the six archetypes, for the scenario with occupant behaviour model 1 with night ventilation, along with the average operative temperature values for scenarios with windows always open and closed. The maximum temperatures observed across the six archetypes range from 29°C to 30.5°C. Notably, these temperatures are lower compared to the scenarios without night ventilation for the same model. This finding demonstrates that night ventilation can effectively reduce indoor temperatures during the summer period.

In contrast, the minimum temperatures recorded range from 11.9°C to 13.2°C, which is significantly lower than in the model without night ventilation. This can be attributed to the fact that the temperature measurements are taken throughout the day and into the night. As the outdoor temperatures decrease during the night time, the opening of windows for night ventilation leads to a drop in operative temperatures indoors. Among the six archetypes, archetype E exhibits the highest maximum temperatures and lowest minimum temperatures. This can be attributed to its high Window-to-Wall Ratio (WWR) of 80%. The extensive glazing in archetype E allows for more solar heat gain, resulting in higher maximum temperatures. Once again, archetype F, which also has an 80% WWR, shows temperature patterns similar to archetype E. This can be explained by the dominance of glazing in both archetypes, where the opaque part of the facade plays a relatively smaller role in influencing the indoor temperatures. As a result, the temperature differences between archetypes E and F are minimal. The average temperatures observed in this case are much lower than the one's observed without night ventilation, they range from 18 - 20°C. This again proves that the use of night

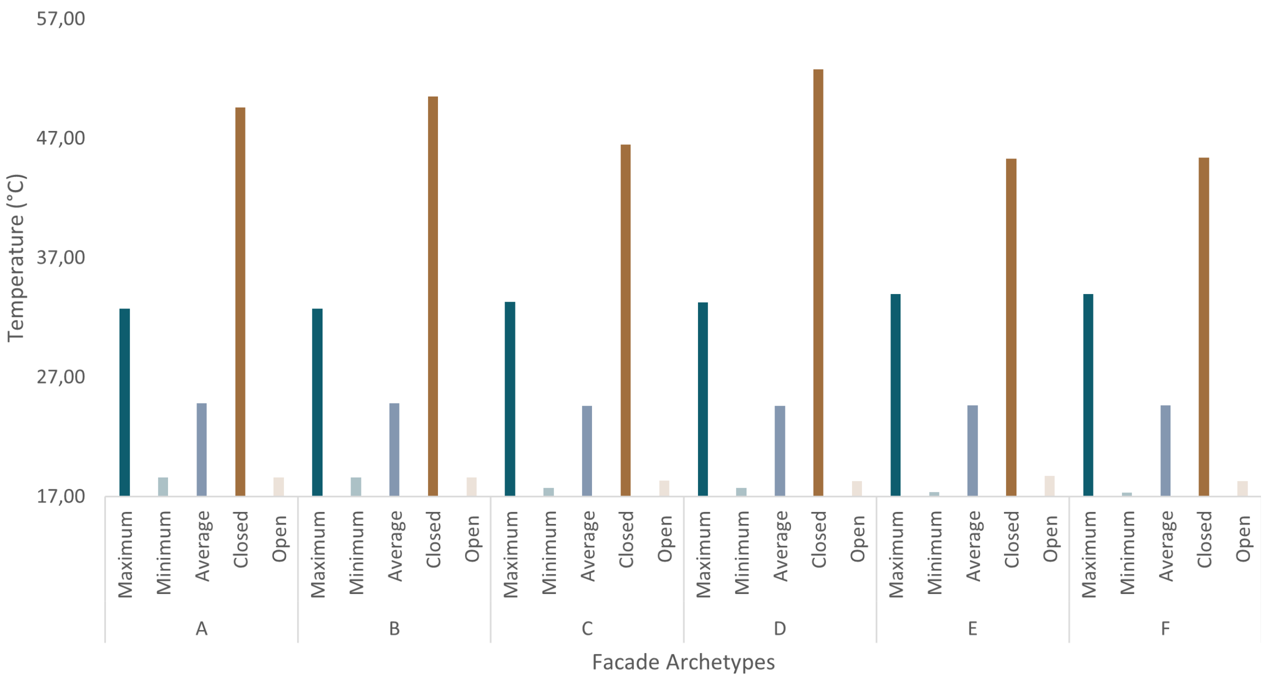


Fig.42. Bar graph depicting the maximum, minimum and average values of operative temperatures obtained from the simulations for the six archetypes, for the scenario with occupant behaviour model 2 with night ventilation, along with the average operative temperature values for scenarios with windows always open and closed.

Where,
A - 40% Window to wall ratio, Light weight construction
B - 40% Window to wall ratio, Heavy weight construction
C - 60% Window to wall ratio, Light weightt construction
D - 60% Window to wall ratio, Heavy weight construction
E - 80% Window to wall ratio, Light weightt construction
F - 80% Window to wall ratio, Heavy weight construction

Occupant behaviour model 2 with night ventilation

Figure 42 presents bar graph depicting the maximum, minimum and average values of operative temperatures obtained from the simulations for the six archetypes, for the scenario with occupant behaviour model 2 with night ventilation, along with the average operative temperature values for scenarios with windows always open and closed. The maximum temperatures recorded across the six archetypes range from 28.8°C to 30.4°C and the average temperatures range between 19 °C - 20.2 °C. Compared to the model without night ventilation, it is evident that the use of night ventilation has led to lower maximum temperatures during the simulation period. This indicates the effectiveness of night ventilation in reducing indoor temperatures and improving thermal comfort.

The combination of occupant behaviour model 2 and night ventilation proves to be effective in mitigating excessive heat and improving indoor thermal comfort. These findings highlight the potential of utilizing occupant behaviour models and night ventilation strategies to optimize energy efficiency and enhance occupants' comfort in buildings.

The analysis of the different occupant behaviour models for window operation clearly demonstrates their significant impact on operative temperatures. Comparing the results with scenarios where windows are fully open or fully closed, it is evident that window operation can effectively reduce indoor temperatures. The operative temperature values recorded in scenarios with windows always closed were alarmingly high, exceeding 50°C. Although the temperatures in the windows always closed scenario were closer to the other models, this approach is not practical or conducive to occupant comfort.

The inclusion of night ventilation in occupant behaviour model 1 proves to be an effective strategy for mitigating indoor heat buildup during hot summer days. By allowing for natural night time cooling, the indoor temperatures are brought down, contributing to improved thermal comfort. This finding emphasizes the importance of considering night ventilation strategies in building design to enhance occupant comfort and reduce reliance on mechanical cooling systems.

The findings emphasize the importance of considering occupant behaviour and window operation strategies to achieve optimal thermal comfort and energy efficiency in buildings. By incorporating occupant behaviour models, such as those examined in this study, the indoor thermal environment can be better regulated, resulting in more comfortable and healthier spaces. Window operation, when aligned with occupant preferences and outdoor conditions, plays a crucial role in maintaining comfortable indoor temperatures and improving overall thermal comfort.

However, examining only the maximum and minimum temperatures is insufficient for understanding the overall thermal comfort experienced during the simulation period. These extreme values may occur during specific isolated instances and might not represent the prevailing conditions throughout the day. Therefore, it is essential to analyze the complete set of hourly data points to identify the most common temperature ranges and gain a comprehensive understanding of thermal comfort. To achieve this, a box plot is employed, as depicted in figure 43. The box plot provides a visual representation of the statistical distribution of operative temperatures. It presents key insights into the central tendency, spread, and skewness of the temperature data. By analyzing the box plot, we can observe the range of temperatures within which the majority of the hourly data points fall. This information helps us identify the most common temperature ranges experienced by the occupants. Moreover, we can compare the temperature distributions across different scenarios and occupant behaviour models

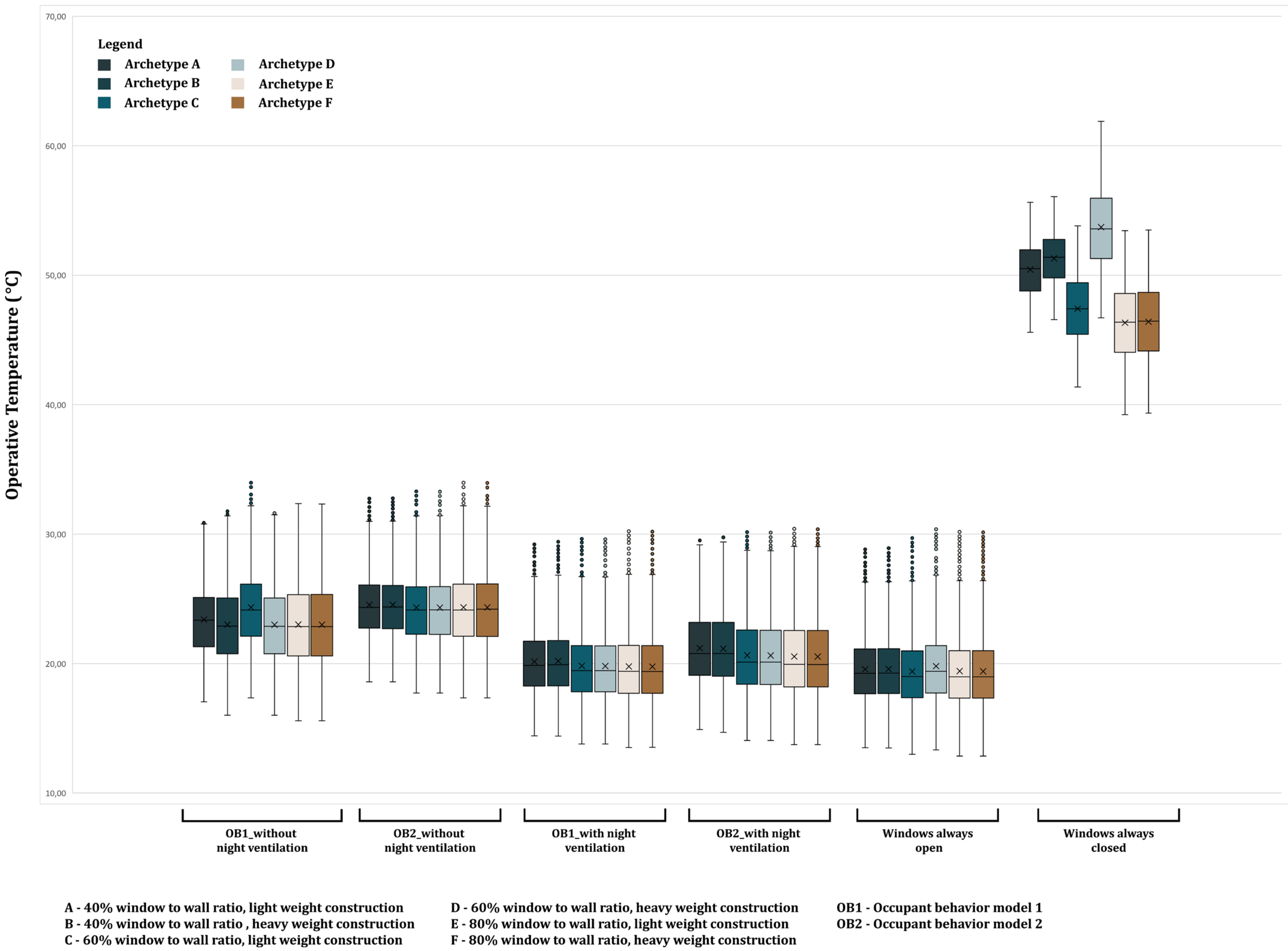


Fig. 43. Box plot depicting the operative temperatures obtained from the simulations for the 36 scenarios. In the box plot, the shaded box represents the interquartile range (IQR), which encompasses the middle 50% of the data points. The whiskers extend from the edges of the box to depict the range of the data, excluding outliers. The horizontal line within the box represents the median, which is the midpoint of the data distribution. The "X" symbol typically represents the mean value. Outliers, which are data points that fall significantly outside the range of the whiskers represent extreme values that may be noteworthy for further investigation (Yi, 2019).

The box plot in figure 43 was constructed using only the operative temperature values during the occupied hours. This approach focuses specifically on the time when occupants are present in the space and experiencing thermal conditions. By excluding the unoccupied hours from the analysis, the box plot provides a more accurate representation of the thermal comfort experienced by occupants during their active periods. Analyzing the operative temperatures specifically during occupied hours allows for a more targeted assessment of thermal comfort. It enables a closer examination of the temperature ranges that occupants are likely to encounter during their time in the building and helps identify potential areas of concern or improvement.

Upon closer examination of the box plot, several important observations can be made. Firstly, it is evident that the operative temperature values without night ventilation are significantly higher compared to the models with night ventilation. This reinforces the advantage of incorporating night ventilation strategies to reduce indoor temperatures, as previously mentioned. The substantial temperature difference between the scenarios with windows fully closed and those using occupant behaviour models further highlights the effectiveness of considering occupant behaviour for window operation.

Additionally, while the previous bar graphs displayed relatively high maximum temperatures, the box plots reveal that 50% of the temperature values are actually much lower than the highest recorded value. This indicates a more favourable distribution of temperatures, with a significant portion falling within a comfortable range. This finding is reassuring and suggests that the models and occupant behaviour strategies considered have successfully maintained thermal comfort for the majority of the simulation period.

Upon analyzing the individual sets of box plots, some interesting observations can be made. In the case of occupant behaviour model 1 without night ventilation, archetype C stands out due to its higher values of the interquartile range compared to the other archetypes. This behaviour can be attributed to the combination of a higher window-to-wall ratio (WWR) and a lightweight construction typology. The higher WWR allows for increased solar gain, while the lightweight construction leads to faster heat transfer, resulting in a wider range of operative temperatures within the archetype. On the other hand, for occupant behaviour model 2 without night ventilation, all the box plots exhibit a similar distribution of temperatures. This uniformity can be attributed to the model's ability to consider both indoor and outdoor temperatures, allowing for more efficient and accurate prediction of window operation. By integrating indoor temperature data, the model can better regulate the indoor thermal conditions, resulting in a narrower range of operative temperatures across the archetypes.

These findings highlight the impact of different occupant behaviour models on the distribution of operative temperatures. While occupant behaviour model 1 without night ventilation shows variations in thermal performance among the archetypes, occupant behaviour model 2 without night ventilation demonstrates more consistent and controlled thermal conditions. This suggests that considering both indoor and outdoor temperatures in the modelling approach improves the accuracy of predicting and regulating window operation, leading to more stable and comfortable indoor environments.

Upon closer examination of the box plots, it is evident that three sets, namely OB2_WO, OB2_W, and OB2_W, exhibit similar behaviour patterns. Archetypes A and B show similar temperature distributions, while archetypes C, D, E, and F demonstrate comparable patterns. This similarity can be attributed to the influence of the opaque area on temperature variations. As the opaque area decreases, the impact of construction on temperature becomes less significant, leading to similar temperature distributions within these groups of archetypes.

In the case of the windows always open and windows always closed scenarios, archetype D stands out with higher interquartile range values. This behaviour can be attributed to the combination of a higher window-to-wall ratio (WWR) and a heavy-weight construction. The higher WWR allows for increased solar gain, while the heavy-weight construction has a higher thermal mass, resulting in slower heat transfer. Additionally, the lack of regulation of window operation in these scenarios contributes tohigher temperatures within archetype D.

Table. 8. List of Anova tests conducted for analysis.

ANOVA tests			
1	All archetypes with OB1 without nightt ventilation	7	Archetype A with all window operation models
2	All archetypes with OB2 without nightt ventilation	8	Archetype B with all window operation models
3	All archetypes with OB1 with nightt ventilation	9	Archetype C with all window operation models
4	All archetypes with OB2 with nightt ventilation	10	Archetype D with all window operation models
5	All archetypes with windows always closed	11	Archetype E with all window operation models
6	All archetypes with winsdows always open	12	Archetype F with all window operation models

To gain a deeper understanding of the variations in operative temperatures among different scenarios, an ANOVA (Analysis of Variance) test is conducted. This statistical test allows for the comparison of mean temperatures across multiple groups, such as different occupant behaviour models and facade archetypes.

12 ANOVA tests were conducted for the different combinations, the table 8 shows the ANOVA tests conducted.

The ANOVA test provides a summary of different groups of data, including their average values, sample sizes, variances, and sums of values. It calculates a P-value to assess the statistical significance between these groups. If the obtained P-value is greater than 0.05 (commonly chosen significance level), it suggests that there is insufficient evidence to reject the null hypothesis. In other words, the groups are not significantly different, and any observed differences could be due to random chance or sampling variability. Conversely, if the obtained P-value is less than or equal to 0.05, it indicates that the observed differences between the groups are statistically significant. This suggests that the null hypothesis is unlikely to be true, and the groups are considered significantly different.

In table 9, the ANOVA test conducted for occupant behaviour model 1 shows that although the average values across the six scenarios are similar, the extremely small P-value (close to 0) indicates a highly significant difference between the groups. This suggests that the archetypes have a significant impact on the operative temperature in this scenario, highlighting the influence of WWR and construction typology.

Similarly, ANOVA tests 3 to 6 also yield very small P-values, confirming significant differences between the archetypes within each group. This further supports the notion that both the window-to-wall ratio (WWR) and construction typology influence operative temperatures when the same occupant behaviour model is applied. In contrast, for occupant behaviour model 2 without night ventilation (test 2, table 8), the obtained P-value is 0.107, which is greater than the chosen significance level of 0.05. This indicates that the operative temperature values are not significantly different among the scenarios. This observation can be attributed to the fact that model 2 considers indoor temperature as well, resulting in better temperature regulation across all scenarios compared to the other models.

However, when occupant behaviour model 2 is combined with night ventilation (test 4) in the analysis, the differences become significant again. This suggests that the effect of night ventilation has a noticeable impact on the operative temperatures. In summary, the ANOVA test results indicate that the archetypes have significantly different effects on the operative temperature for occupant behaviour model 1. The influence of WWR and construction typology is evident. Model 2 without night ventilation shows less variability in operative temperatures, likely due to its consideration of indoor temperature. Night ventilation reintroduces significant differences in operative temperatures.

Table. 9 ANOVA test 1 - Table representing the summary of data used for the anova test conducted for all archetypes with occupant behaviour model 1 without night ventilation

Groups	Count	Sum	Average	Variance
A_OB1_WO	1224	28634,78	23,39	8,58
B_OB1_WO	1224	28154,43	23,00	10,52
C_OB1_WO	1224	29794,35	24,34	9,34
D_OB1_WO	1224	28147,38	23,00	10,52
E_OB1_WO	1224	28168,50	23,01	11,95
F_OB1_WO	1224	28162,52	23,01	11,94

Table. 10 ANOVA test 1 - Table representing the anova test conducted for all archetypes with occupant behaviour model 1 without night ventilation

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1765,04	5	353,01	33,70	3,84499E-34	2,22
Within Groups	76871,08	7338	10,48			
Total	78636,12	7343				

The ANOVA results for tests 7-12 (shown in appendix) indicate that all scenarios have a p-value of 0, which implies highly significant differences. This finding supports the notion that different occupant behaviour models applied to the same facade archetype result in distinct operative temperatures. It reinforces the understanding that window operation models and patterns can have a significant impact on thermal comfort. The p-value of 0 indicates that the differences observed in the operative temperatures are not due to chance and can be attributed to the specific occupant behaviour models employed and their window opperation patterns.

Table. 11 ANOVA test 2 - Table representing the summary of data used for the anova test conducted for archetype A with occupant model 1 with and without night ventilation, occupant model 2 with and without night ventilation, windows always open and windows always closed

Groups	Count	Sum	Average	Variance
A_OB1_WO	1224	28634,78	23,39	8,58
A_OB2_WO	1224	30035,78	24,54	6,96
A_OB1_W	1224	24662,00	20,15	7,76
A_OB2_W	1224	25936,47	21,19	8,44
A_O	1224	23940,62	19,56	8,12
A_C	1224	61741,91	50,44	4,89

Table. 12 ANOVA test 2 - Tables representing the anova test conducted for archetype A with occupant model 1 with and without night ventilation, occupant model 2 with and without night ventilation, windows always open and windows always closed

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	861011,83	5	172202,37	23086,28	0	2,215317
Within Groups	54734,72	7338	7,46			
Total	915746,55	7343				

5.2.2 Analysis of operative temperature and window state

In this particular section, the focus is on analyzing the connection between the state of the windows and the operative temperatures. To effectively convey this relationship, heat maps are employed as a visual tool. Heat maps offer a comprehensive view of temperature patterns and fluctuations over a given duration. They allow researchers and readers to quickly grasp the overall temperature range and observe any notable changes or trends.

In addition to illustrating the temperature data, the heat maps in this study also incorporate information about the window state. By including this aspect, the heat maps provide a comprehensive representation of how the window state influences the operative temperatures. This integration of window state information allows for a more detailed analysis of how temperature variations correspond to different window states.

The provided heatmaps, shown in figure 44 and 45, depict the relationship between operative temperatures and window state for facade archetype A, specifically considering occupant behaviour model 1 without night ventilation. A color legend on the right side of the heatmaps indicates the range of colors used to represent different temperature values.Upon analyzing the heatmaps, it becomes evident that during occupied periods when the windows are operated, the operative temperatures tend to decrease. This indicates that opening the windows has a cooling effect on the indoor environment. However, it is important to note that the impact of window state on operative temperatures is also influenced by outdoor temperatures.

In particular, the heatmaps reveal a pattern between the window state and operative temperatures. When the windows are opened, the operative temperatures generally show a decrease. However, the extent of this temperature reduction varies depending on the outdoor temperatures. For instance, in the month of August, the temperatures are highest, which may be attributed to the elevated outdoor temperatures compared to other months. Interestingly, the heatmaps also provide insights into the optimal window operation strategy for maintaining thermal comfort. It is observed that keeping the windows open continuously may not yield the best results in terms of indoor thermal comfort. This is particularly evident when the outdoor temperatures are high, as opening the windows under such conditions can lead to indoor spaces becoming overheated, counteracting the intended cooling effect.

Figures 46 and 47 illustrate the heatmaps showcasing the operative temperatures and window states when the windows are always closed. By comparing these figures with figures 44 and 45, which represent scenarios where occupant behavior is considered, a clear influence of window operation on indoor temperatures can be observed. The heatmaps demonstrate that implementing occupant behavior leads to a reduction in operative temperatures compared to the scenario where windows are consistently closed. This highlights the importance of considering occupant behavior in building design and operation to achieve improved thermal comfort.

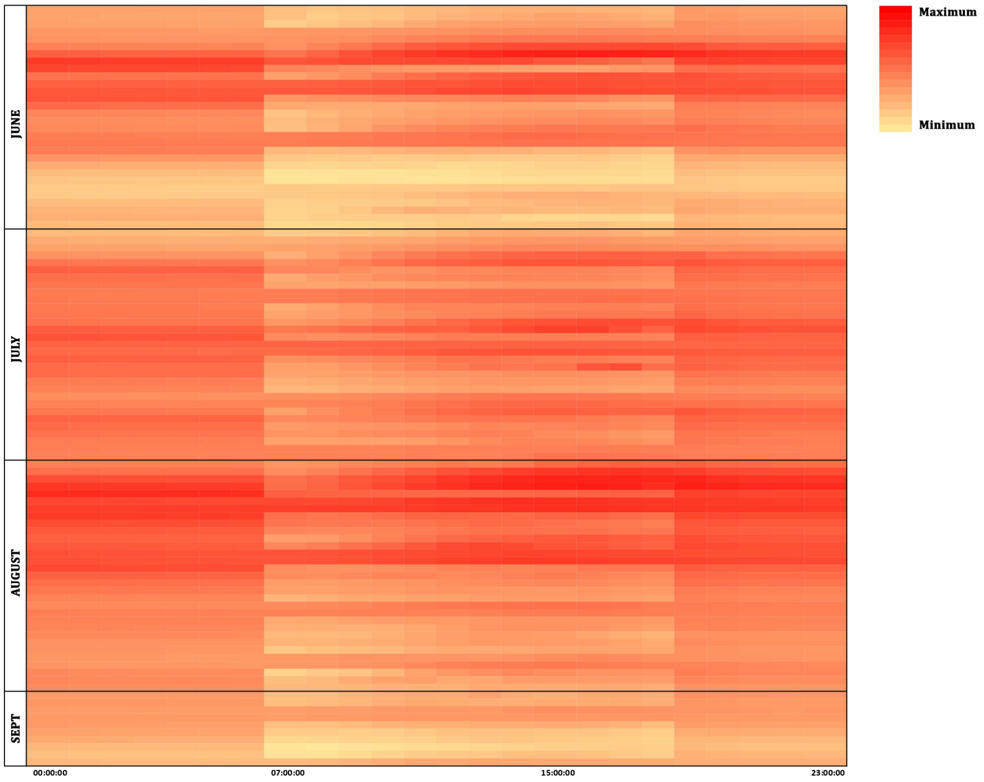


Fig. 44. Heat map depicting the operative temperatures for facade archetype A , with occupant behaviour model 1 without night ventilation

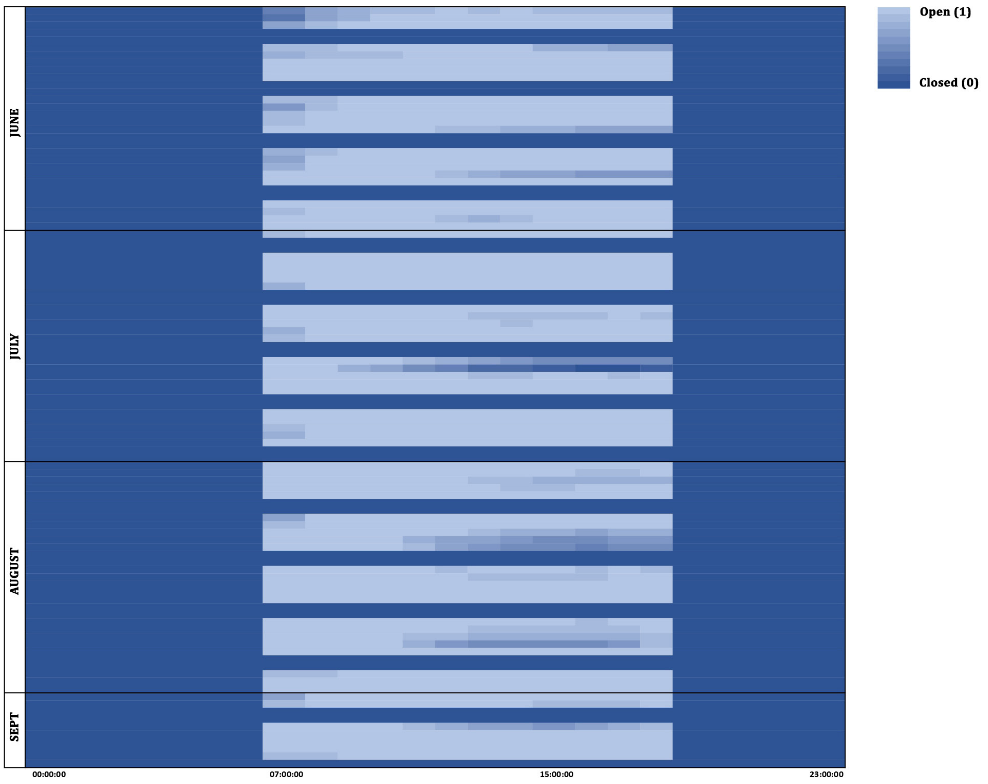


Fig. 45. Heat map depicting the window state for facade archetype A , with occupant behaviour model 1 without night ventilation

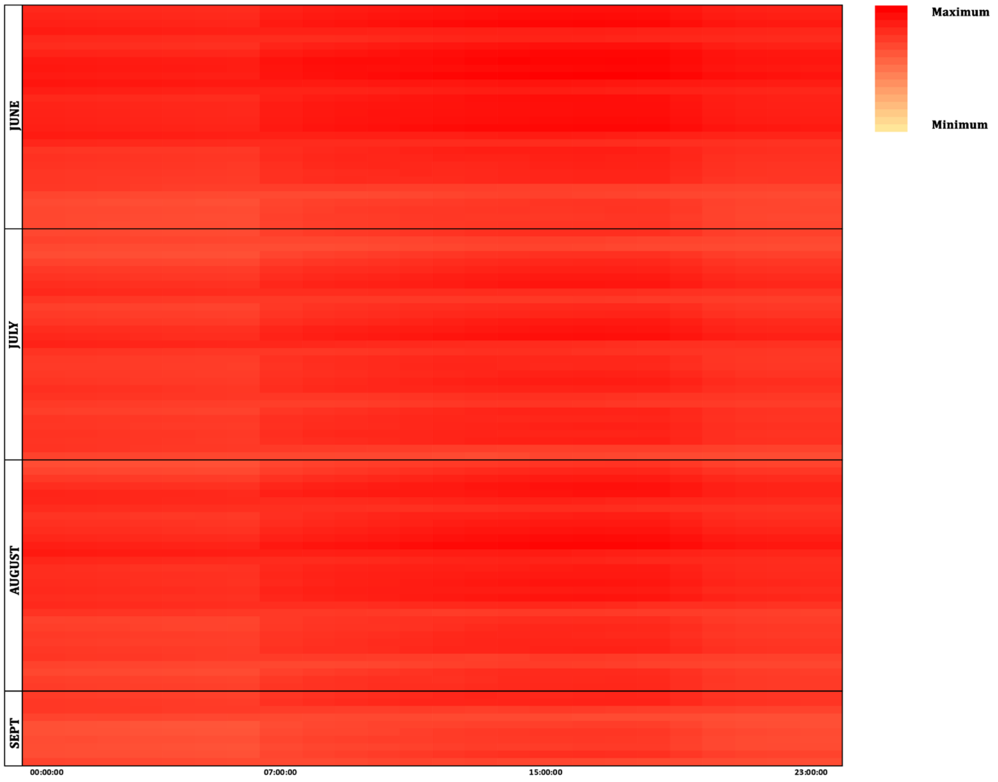


Fig. 46. Heat map depicting the operative temperatures for facade archetype A , with windows always closed

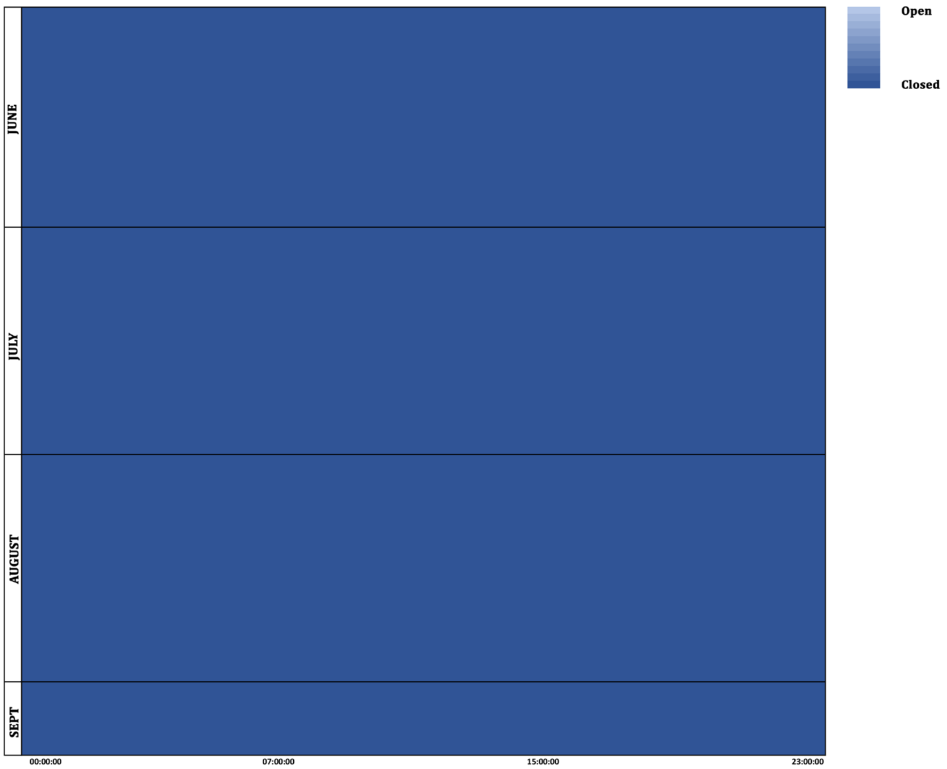
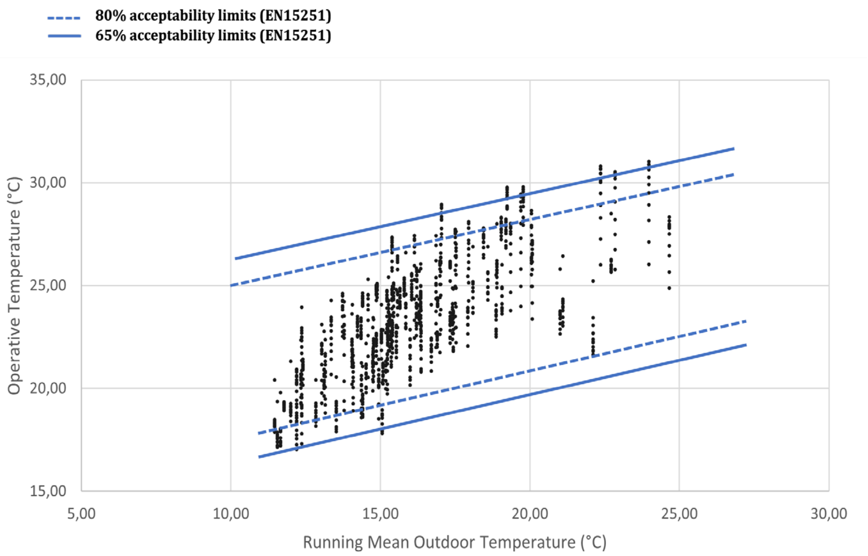


Fig. 47. Heat map depicting the window state for facade archetype A , with windows always closed

5.2.3 Analysis of operative temperature and outdoor temperature

In the next section, scatter plots are used to explore the relationship between outdoor temperature and operative temperature. The operative temperature is plotted on the y-axis, while the outdoor running mean temperature is plotted on the x-axis for all 36 different combinations. This analysis aims to understand how indoor operative temperatures vary in response to outdoor temperatures in each scenario. By visualizing the data in scatter plots, patterns and trends can be identified, providing insights into the relationship between indoor and outdoor temperatures for different scenarios. The scatter plots take the operative tempertures only for the occupied hours.



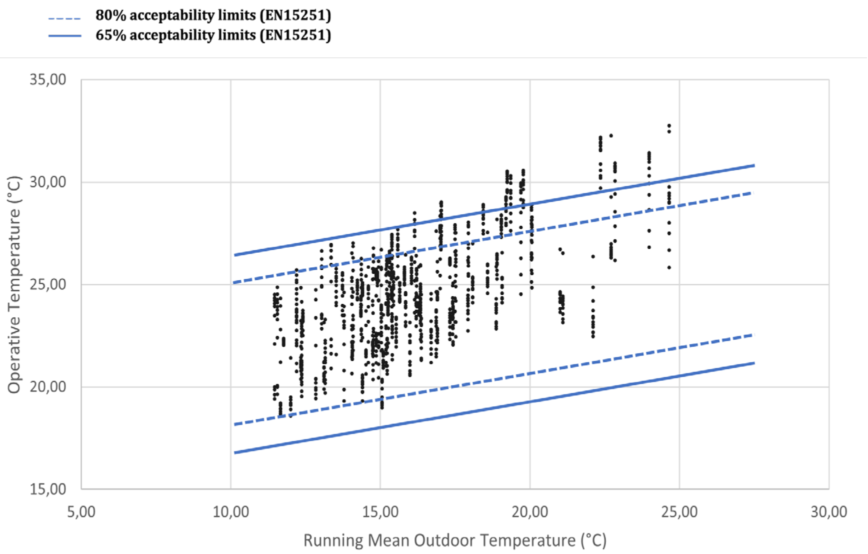


Fig.48. Scatter plots depicting operative temperatures on the X axis and running mean outdoor temperature on the Y axis . The graph also depicts the thermal comfort acceptability limits defined by EN 15251 standard.
a) Scatter plot of archetype A with occupant bhaviour model 1 without night ventilation
b) Scatter plot of archetype A with occupant bhaviour model 2 without night ventilation

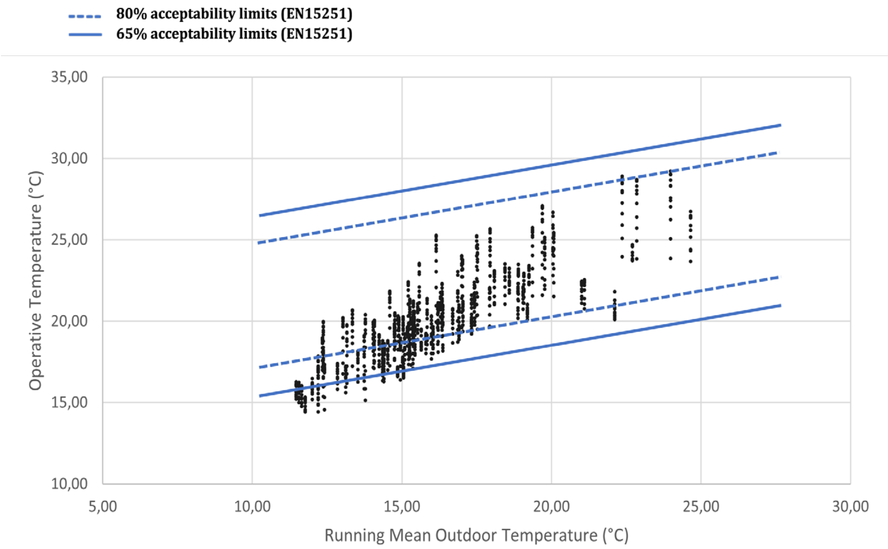


Fig.49a

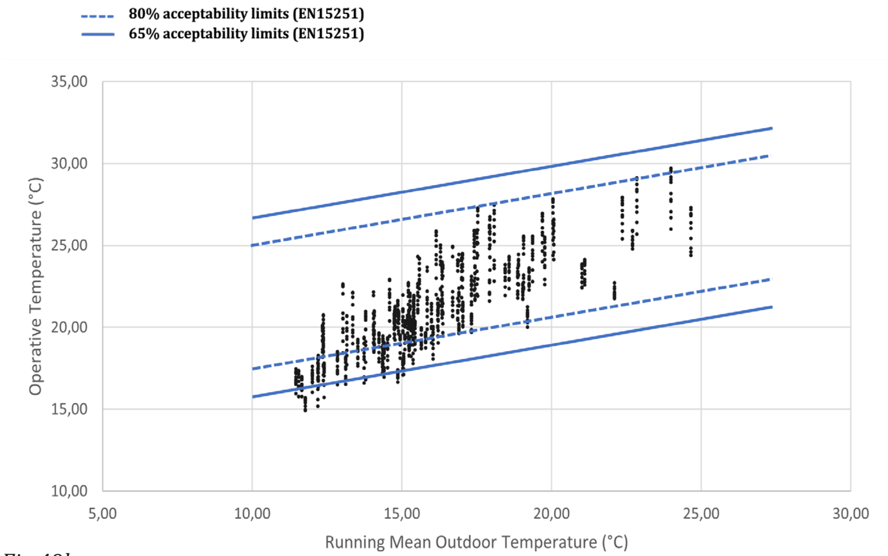


Fig.49b

Fig.49. Scatter plots depicting operative temperatures on the X axis and running mean outdoor temperature on the Y axis . The graph also depicts the thermal comfort acceptability limits defined by EN 15251 standard.
a) Scatter plot of archetype A with occupant bhaviour model 1 with night ventilation
b) Scatter plot of archetype A with occupant bhaviour model 2 with night ventilation

The provided scatter plots in figures 48 and 49 depict the relationship between outdoor temperature and operative temperature for facade archetype A with different occupant behaviour models and window operation scenarios. The plots also indicate the acceptable comfort range according to the EN15251 standard, specifically the 80% and 65% ranges. By visually examining these graphs, we can determine the number of data points that fall within the comfort band (i.e., within the acceptable temperature range) and the number of points that fall outside the comfort band. This analysis allows us to assess the extent to which the indoor operative temperatures align with the specified comfort criteria for each scenario.

From the analysis of the scatter plots, it is evident that there exists a moderately strong positive linear relationship between operative temperature and outdoor temperature. This implies that as the outdoor temperature increases, the majority of the operative temperature points also increase. Upon closer examination of the plots, it can be observed that a significant number of data points fall within the 65% acceptability range for all four scenarios, indicating that a considerable portion of the data lies within the specified comfort range. Additionally, approximately 70% of the data points fall within the 80% acceptability range in all four plots.

However, the distribution and behaviour of the data points vary among the different scenarios. In the cases of OB1_WO and OB2_WO, the data points are more spread out across the comfort bands. Conversely, in the case of OB1_W and OB2_W, the data points are clustered closer to one another and inclined towards the lower thresholds of the comfort bands. This could be due to night ventilation which reduces the indoor temperatures.

Overall, we can see that OB2_WO has most number of data points outside the comfort band on the higher side, while OB_WO has the most number of points within the comfort range of 80% accepttability and is evenly spread across tthe band. A notable observation from the plots is that in the scenarios with night ventilation, when the outdoor temperatures are lower, the operative temperatures also decrease significantly and can fall below the comfort band. This trend is more prominent in the case of OB1 compared to OB2. This discrepancy can be attributed to the different approaches taken by the two occupant behaviour models. OB2 considers indoor temperature as well, aiming to maintain comfort levels. As a result, it adjusts window operation based on the indoor thermal state, leading to a more regulated and controlled response to outdoor temperature variations. On the other hand, OB1 solely relies on outdoor temperature, and the lack of indoor temperature consideration may result in larger fluctuations and deviations from the comfort band when outdoor temperatures are low.

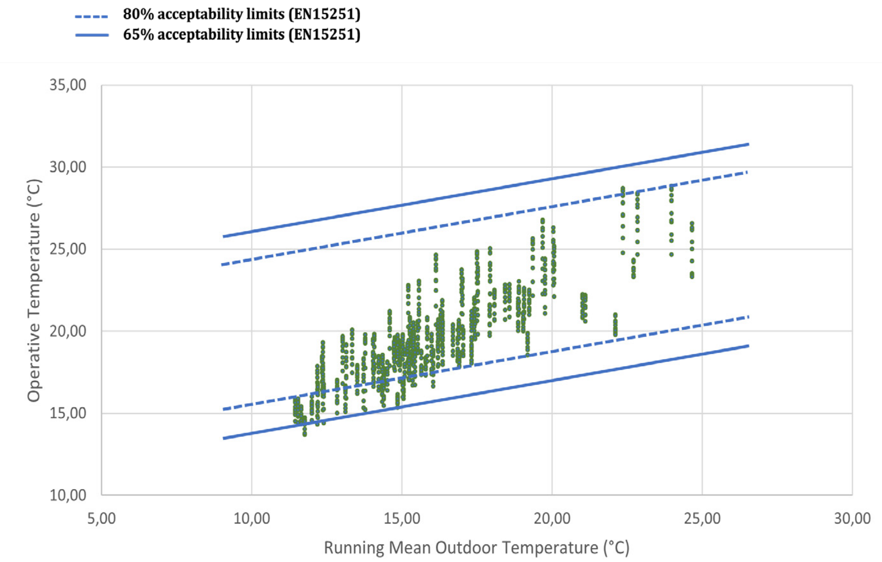


Fig.50a

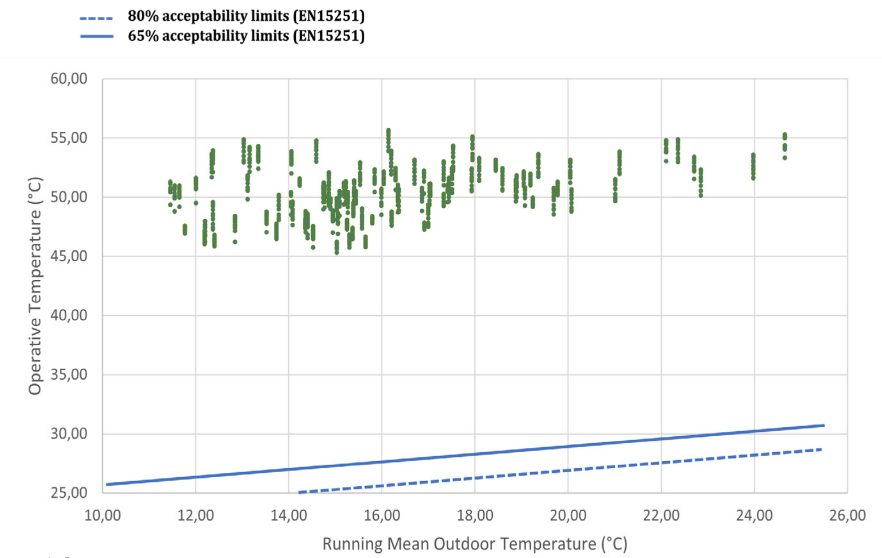


Fig.50b

Fig.50. Scatter plots depicting operative temperatures on the X axis and running mean outdoor temperature on the Y axis . The graph also depicts the thermal comfort acceptability limits defined by EN 15251 standard.
a) Scatter plot of archetype A with scenario where windows are always open
b) Scatter plot of archetype A with scenario where windows are always closed

Figure 50 illustrate the operative temperatures for archetype A with windows fully open and fully closed, respectively, to compare the performance when occupant behaviour models are used. From the graphs, it is evident that when the windows are fully closed, the operative temperatures are exceptionally high, sometimes exceeding 60°C. In contrast, when the windows are fully open, the operative temperatures decrease and can even fall below the comfort band. This indicates that regulating window operation, as facilitated by the occupant behaviour models, generally helps maintain operative temperatures within acceptable limits, in contrast to the extreme values observed in the two base cases.

Similar scatter plots are generated for the other five archetypes to analyze the relationship between outdoor temperature and operative temperature.

Based on the observations made across the six archetypes, it can be concluded that similar patterns are observed within each archetype. One notable pattern is that as the Window-to-Wall Ratio (WWR) increases, the operative temperatures also tend to increase. This is particularly evident in the cases of OB1 and OB2 without night ventilation, where more data points lie above the comfort band. Furthermore, the inclusion of night ventilation leads to lower operative temperatures, especially when the outdoor temperatures are lower. This can be attributed to the cooling effect of night ventilation.

Additionally, the similarities in operative temperatures among archetypes D, E, and F further support the previous analysis, indicating that the high glazing area dominates the thermal performance and the influence of the opaque area (based on construction typology) is relatively minimal.

An interesting observation from the graphs is that the low temperatures in the case with windows always open are slightly higher compared to the cases employing occupant behavior models with night ventilation. This can be attributed to the fact that when the windows are constantly open and the outdoor temperatures rise, there is a possibility of the indoor temperatures also increasing. In contrast, in the cases with occupant behavior and night ventilation, the cooling effect of night ventilation helps to lower the indoor temperatures. This observation highlights the impact of window operation and the use of night ventilation on indoor thermal conditions, indicating that occupant behavior combined with passive cooling strategies can contribute to maintaining lower indoor temperatures.

5.2.4 Analysis of discomfort hours and overheating degree

In this section, the thermal performance of the different scenarios is evaluated by calculating the number of hours that fall outside the comfort limits for each archetype and scenario during the occupied hours in the simulation period. Additionally, the degree of indoor overheating is calculated to enable a comparison between the scenarios. These analyses provide insights into the extent and severity of thermal discomfort experienced in each case.

Table.13. Number of discomfort hours

Archetype	Total Number of hours	OB1_WO	OB2_WO	OB1_W	OB2_W	open	closed
A	1224	19	46	0	0	0	1224
B	1224	28	49	0	1	0	1224
C	1224	62	49	0	2	0	1224
D	1224	28	49	0	1	7	1224
E	1224	40	62	5	12	3	1224
F	1224	40	61	4	12	3	1224

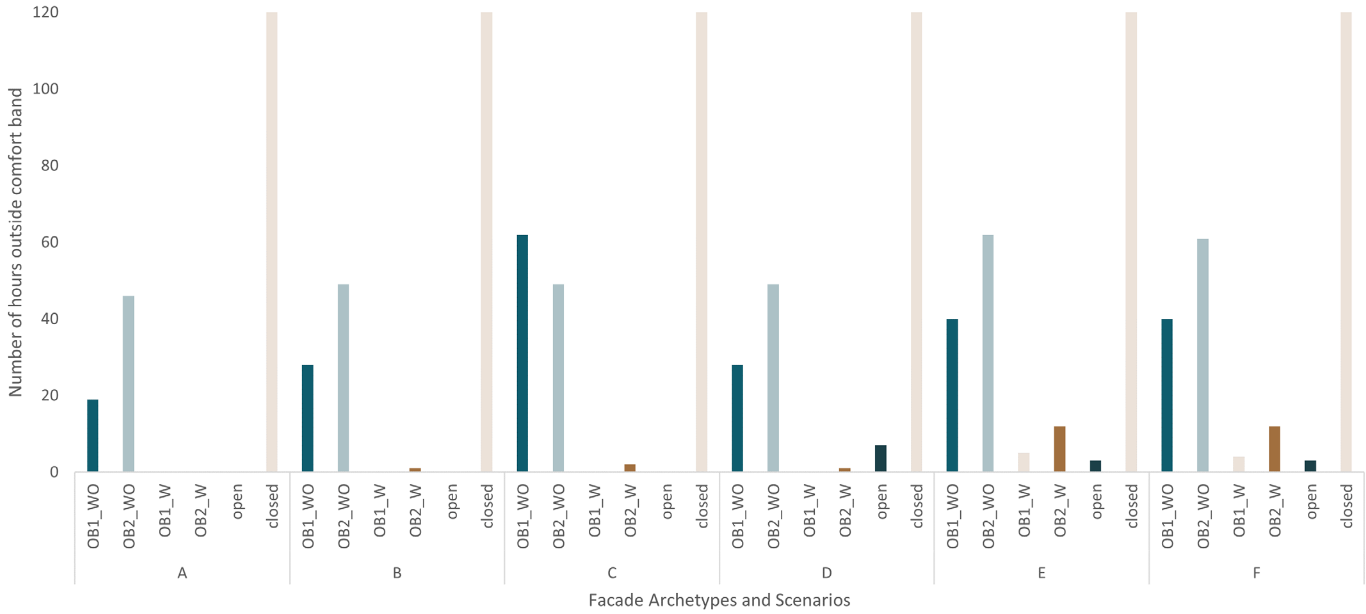


Fig.51. Bar graph of number of discomfort hours

The above table 13 and figure 51 provides the total number of hours in which occupants experience thermal discomfort, calculated according to the CEN standard. The calculation is specifically performed for the occupied hours within the simulation period, which amounts to a total of 1224 hours spanning from June 1st to September 10th. The Y-axis represents the number of discomfort hours, while the X-axis displays the different scenarios. The bar graph is divided into six sub-graphs, each corresponding to a specific archetype. Within each archetype, information is provided for OB1 and OB2 without night ventilation, OB1 and OB2 with night ventilation, as well as scenarios with windows always closed and windows always open. This representation allows for a comprehensive comparison of the thermal performance across different scenarios and archetypes.

The hours presented in the table and figure represent only the overheating hours, specifically the number of hours during which the operative temperature exceeds the upper limit of 80% acceptability according to the CEN standard. The focus of this research is on assessing and comparing the thermal performance in terms of overheating, and therefore the calculation includes only the hours above the upper limit. The underheating hours, which refer to the hours below the lower limit of acceptability, are not considered in this particular study.

The table clearly shows that in all archetypes, the number of overheating hours is 1224 out of 1224 hours when windows are always closed. This means that without window operation, all hours exceed the comfort band, highlighting the need for window ventilation to reduce overheating. This observation underscores the importance of utilizing window operation as a means to mitigate overheating, particularly when mechanical HVAC systems are not in use.

In Archetype A, the highest number of overheating hours is observed in the case of OB2 without night ventilation, totaling 46 hours out of the 1224 hours. Although this may not be considered severe, it is still a significant number of hours. To put it in perspective, if we consider the simulation period of 1224 hours as equivalent to 110 days, this calculation suggests that approximately 4 working days during the simulation period experience overheating. It's important to note that these hours are typically distributed across multiple days, but this method of calculation provides a comparative measure. On the other hand, OB1 without night ventilation shows a total of 1.7 days (19 hours) of overheating, which is lower than what was calculated for OB2. However, as discussed earlier, OB2 provides a more realistic prediction of window operation by considering indoor temperature as well. Therefore, although OB1 performs better in terms of reducing overheating, OB2 shows a more realistic prediction. It is also noteworthy that OB1 and OB2 with night ventilation show 0 overheating hours, which is a positive outcome. However, it should be noted that the operative temperature drops below the comfort band when using night ventilation, which can lead to underheating.

In archetype B, the highest number of overheating hours is observed again in OB2 without night ventilation, corresponding to approximately 4 days of overheating (46 hours), compared to OB1 without night ventilation, which shows 2.5 days of overheating (28 hours). Archetype B exhibits a higher number of overheating hours for OB1 compared to archetype A, which could be attributed to its higher thermal mass and the fact that this model only operates with outdoor temperature. Once again, scenarios without night ventilation show low overheating hours, indicating the importance of window operation to mitigate overheating in this context.

In the case of archetype C, it is surprising to see that OB1 without night ventilation exhibits higher overheating hours of 5.6 days (62 hours) compared to OB2 without night ventilation, which shows 4.5 days (49 hours) of overheating. This drastic difference could be attributed to the increase in window-to-wall ratio (WWR) and the use of lightweight construction typology. The higher WWR allows more solar radiation to enter the space, leading to increased overheating, while the lightweight construction may have lower thermal mass and less ability to absorb and store heat. These factors contribute to the higher overheating hours in OB1 without night ventilation in archetype C. Another observation is that OB2 without night ventilation shows similar temperatures across all scenarios, with archetypes E and F exhibiting higher values. This can be attributed to the use of indoor temperatures in the calculation, which helps regulate the operative temperature more effectively in OB2 models compared to OB1. The inclusion of indoor temperatures allows for better control and adjustment of the operative temperature, resulting in more consistent values across different scenarios.

It is interesting to observe that archetype E and F perform identically. The number of overheating hours for each scenario is nearly the same. Additionally, it is seen that the number of overheating hours for scenarios with night ventilation has increased to 12 hours. This can be attributed to the high window-to-wall ratio (WWR) and low opaque surface area in these archetypes. It highlights that even with the implementation of night ventilation, there can still be overheating if the thermal performance of the facade is lower.

Overall, when considering OB1 without night ventilation, archetype C has the highest number of overheating hours. On the other hand, when considering OB2 without night ventilation, scenario E exhibits the highest overheating hours. In the scenarios with night ventilation, most archetypes have values below 5 overheating hours, except for archetypes E and F with OB2, which show 12 overheating hours.

Table.14. Table showing the monthly and total indoor overheating degree values for all the scenarios

Archetype	Month	OB1_WO	OB2_WO	OB1_W	OB2_W
A	June	1,72	2,25	1,10	0,89
	July	1,28	1,62	0,58	0,95
	August	2,12	2,13	1,31	1,37
	September	0,00	0,81	0,00	0,00
	Total	1,72	1,92	1,13	1,14
B	June	2,02	2,27	1,18	0,98
	July	1,36	1,57	0,55	0,91
	August	2,40	2,17	1,38	1,43
	September	0,00	0,95	0,00	0,00
	Total	1,93	1,94	1,16	1,17
C	June	2,53	2,27	1,55	1,29
	July	1,97	1,82	0,64	1,05
	August	2,80	2,53	1,81	1,60
	September	1,38	1,23	0,00	0,00
	Total	2,37	2,15	1,43	1,31
D	June	2,03	2,27	1,52	1,26
	July	1,37	1,82	0,61	1,03
	August	2,38	2,54	1,78	1,63
	September	0,00	1,30	0,00	0,00
	Total	1,93	2,16	1,39	1,31
E	June	2,28	2,53	1,78	1,55
	July	1,63	1,97	0,82	1,41
	August	2,67	2,80	2,01	1,87
	September	0,00	1,38	0,00	0,00
	Total	2,19	2,37	1,59	1,60
F	June	2,27	2,53	1,75	1,49
	July	1,64	1,94	0,80	1,37
	August	2,69	2,81	1,99	1,85
	September	0,00	1,40	0,00	0,00
	Total	2,20	2,36	1,57	1,57

Table 14 shows the indoor overheating degree(IOD) for each of the scenarios, this is calculated for each month of the simulation period. Indoor overheating degree is calculated using the formula below which is given by CEN 15251 standard. The comfort temperature in this equation is also calculated according to the EN 15251 standard, and the operative temperatures are taken from the simulations.

$$IOD = \frac{\Sigma \Delta T}{\text{Total number of hours}} = \frac{\text{Operative temperature} - \text{Comfort temperature}}{\text{Total number of hours}}$$

Among all the different building archetypes analyzed, it was observed that archetype E with occupant behaviour model 2 and without night ventilation, as well as archetype C with occupant behaviour model 1 without night ventilation, exhibited the highest Indoor Overheating Degree (IOD) during the month of August. This can be attributed to the high outdoor temperatures experienced during that month. Additionally, both archetype C and E have a high percentage of window-to-wall ratio and are constructed with lightweight materials, which can result in higher heat gains compared to other archetypes.

The presence of higher IOD values in these scenarios emphasizes the need for effective cooling strategies. It is noteworthy that the overheating degrees were significantly lower in scenarios where night ventilation was present, indicating that night ventilation can serve as an efficient cooling strategy.

Furthermore, it is evident that the month of August consistently exhibits the highest IOD across all archetypes, which can be attributed to the elevated outdoor temperatures during this time. This highlights the importance of carefully planning window operation strategies, particularly when outdoor temperatures are higher. It also suggests that relying solely on window operation may not be sufficient to achieve thermal comfort, and a hybrid cooling system incorporating other strategies may be necessary.

While the presence of overheating is evident from the data, it is crucial to consider the distribution of overheating periods. As previously analyzed in terms of overheating hours, it is important to note that the number of hours outside the comfort level is not excessively high. However, the existence of overheating indicates the potential need for additional strategies to ensure that no overheating occurs and to maintain comfortable indoor conditions.

Overall, the analysis highlights the significance of outdoor temperature, window operation strategies, and the influence of building characteristics in determining indoor overheating. It underscores the importance of implementing effective cooling strategies, such as night ventilation, and considering a hybrid cooling system approach to mitigate overheating and ensure optimal thermal comfort.

5.3 Assessment of indoor air quality

In this thesis, occupant-window interaction is studied as a passive strategy for cooling during the summer periods, however, along with thermal comfort, window operation can have a significant effect on indoor air quality, especially due to the fact that no other mechanical ventilation systems are being used in this case. A comfortable indoor environment relies not only on achieving suitable thermal conditions but also on maintaining a high level of air quality. Therefore, understanding the interplay between window operation, thermal comfort, and indoor air quality is crucial for ensuring occupants' overall comfort and well-being.

To analyse the CO_2 concentration levels, an output function is added to the EMS script which returns the hourly CO_2 levels in ppm. These values are analysed in different ways by looking at the range of values including the range containing the most number of values for every scenario and the number of hours above the acceptability limit. A detailed analysis is explained in the following sections. It is also improtant to note that the following graphs depict values only for the occupied periods according to the defined occupancy schedule.

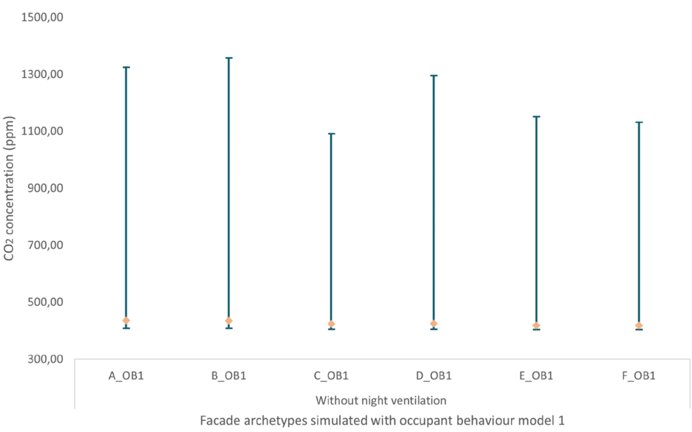


Fig.52. Graphical representation of the maximum,minimum and average values of CO_2 levels for the facade archetypes with occupant behaviour model 1, without night ventilation

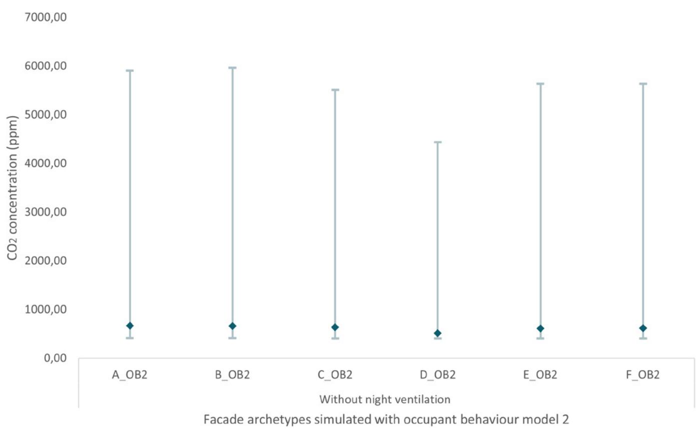


Fig.53. Graphical representation of the maximum,minimum and average values of CO_2 levels for the facade archetypes with occupant behaviour model 2, without night ventilation

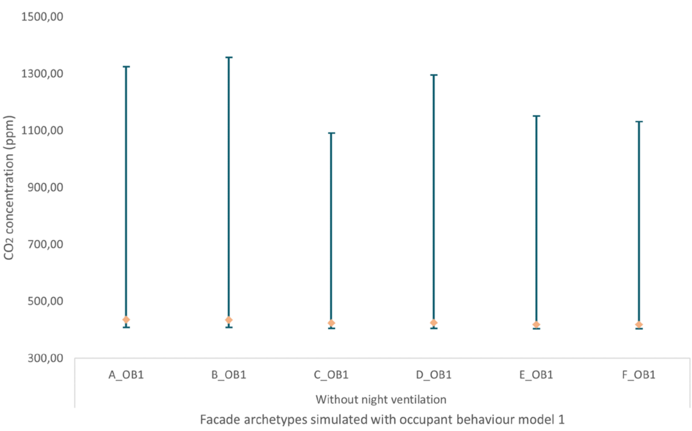


Fig.54. Graphical representation of the maximum,minimum and average values of CO_2 levels for the facade archetypes with occupant behaviour model 1, with night ventilation

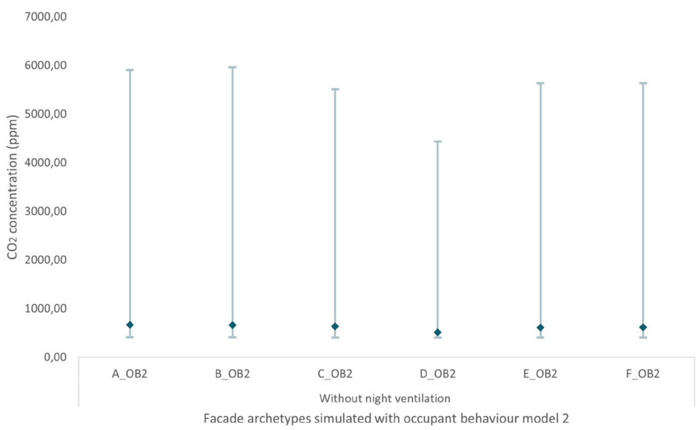


Fig.55. Graphical representation of the maximum,minimum and average values of CO_2 levels for the facade archetypes with occupant behaviour model 2, with night ventilation

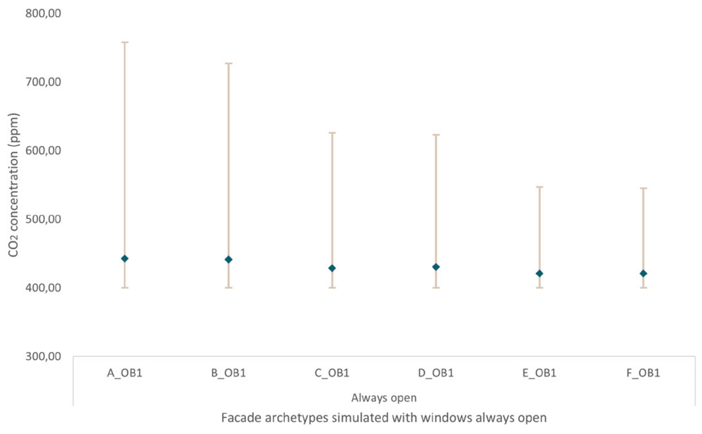


Fig.56. Graphical representation of the maximum,minimum and average values of CO_2 levels for the facade archetypes with windows always open

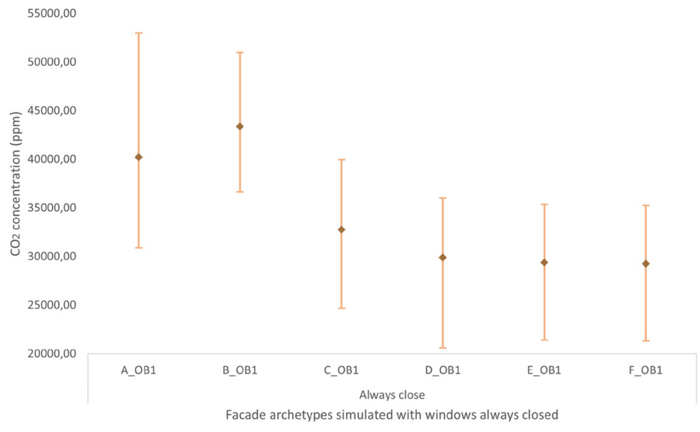


Fig.57. Graphical representation of the maximum,minimum and average values of CO_2 levels for the facade archetypes with windows always closed

Figures 52 to 57 present comprehensive insights into the CO_2 concentration levels across different scenarios. These graphs depict maximum, minimum, and average CO_2 concentrations for various occupant behaviour models.

In Figure 52, which corresponds to occupant behaviour model 1 without night ventilation, it is evident that the maximum CO_2 concentration values exceed the acceptable limit defined by EN 15251 (800 ppm). However, the average CO_2 concentrations remain within the acceptable range, indicating that the majority of data points fall within the acceptable limit. Additionally, an interesting observation is that higher window-to-wall ratios result in lower maximum CO_2 concentrations. This outcome is expected since larger window sizes provide greater ventilation and air exchange.

Figure 53 reveals significantly higher maximum CO_2 concentration levels for occupant behaviour model 2 without night ventilation compared to occupant behaviour model 1. This disparity can be attributed to the fact that occupant behaviour model 2 considers both outdoor and indoor temperatures for window operation. As a result, the window state is more influenced by temperature, leading to a higher probability of closed windows and elevated indoor CO_2 levels. Furthermore, the proportional window state values in occupant behaviour model 1 contribute to lower CO_2 levels when windows are partially open as oposed to occupant behaviour model 2 where the window state is binary (either fully closed or open).

When night ventilation is introduced in conjunction with occupant behaviour model 1 (figure 54), the CO_2 values remain similar to those without night ventilation. This similarity can be attributed to the fact that occupant behaviour model 1 only considers outdoor temperature for window operation, so the use of night ventilation does not directly impact the window state. However, it does affect indoor temperature.

In contrast, for occupant behaviour model 2 with night ventilation, a distinct difference in behaviour is observed compared to the case without night ventilation. The implementation of night ventilation typically leads to cooling of the indoor space. As occupant behaviour model 2 considers both outdoor and indoor temperatures for window operation, this cooling effect may result in a lower frequency of "open" window states, consequently leading to increased indoor CO_2 levels.

Figures 56 and 57 showcase the CO_2 levels when the windows are always open and always closed, respectively. As expected, the CO_2 levels remain within the acceptable limit when the windows are consistently open. Conversely, when the windows are consistently closed, the CO_2 levels are exceptionally high. Considering that window operation is the primary means of providing ventilation in these scenarios, these results are consistent with expectations.

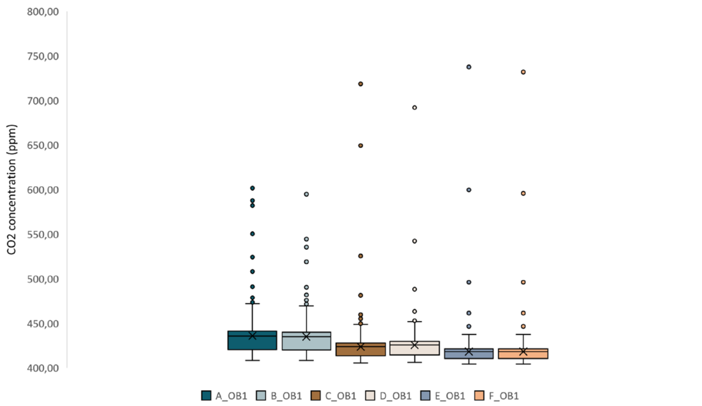


Fig.58. Box plot representation of CO2 levels for the facade archetypes with occupant behaviour model 1, without night ventilation

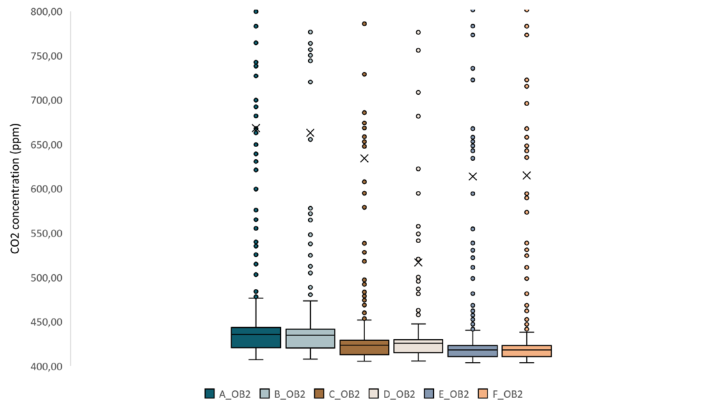


Fig.59. Box plot representation of CO2 levels for the facade archetypes with occupant behaviour model 2, without night ventilation

The box plots, as depicted in Figures 50 and 51, provide a visual representation of the CO_2 concentration levels for occupant behaviour models 1 and 2 without night ventilation across the six different facade archetypes. To enhance clarity, the box plots are capped at 800 ppm, meaning that data points or outliers above this value are not shown but are still considered in the analysis.

Upon initial observation, it is apparent that the average CO_2 concentration values for occupant behaviour model 2 are higher compared to those for occupant behaviour model 1. This difference aligns with the explanation that occupant behaviour model 2 takes into account both outdoor and indoor temperatures, leading to variations in the window state and, subsequently, higher CO_2 levels indoors. Additionally, occupant behaviour model 2 exhibits a greater number of outliers, indicating more instances of CO_2 concentration exceedances.

Moreover, the box plots demonstrate that scenarios with higher window-to-wall ratios tend to have lower average CO_2 concentrations. This outcome is attributed to the increased ventilation rates facilitated by larger window sizes, which allow for greater air exchange and subsequently reduce CO_2 buildup indoors.

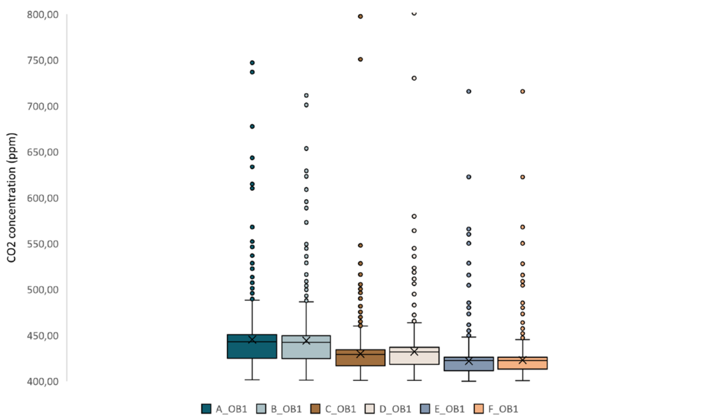


Fig.60. Box plot representation of CO2 levels for the facade archetypes with occupant behaviour model 1, with night ventilation

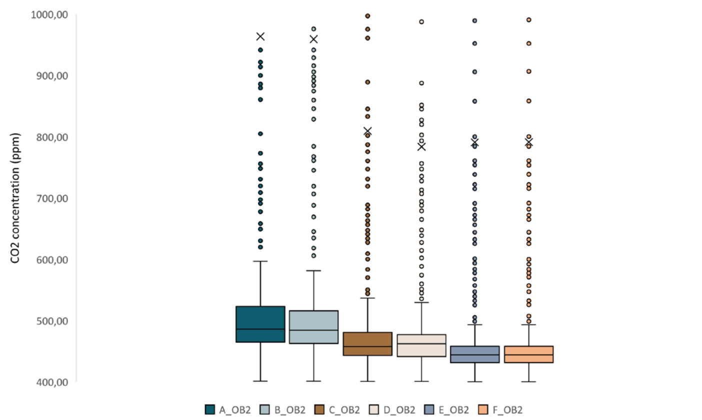


Fig.61. Box plot representation of CO2 levels for the facade archetypes with occupant behaviour model 2, with night ventilation

The influence of night ventilation on the simulations is evident when comparing the results for occupant behaviour models 1 and 2. Figure 52 shows that the inclusion of night ventilation has minimal impact on the CO_2 concentration levels in simulations with occupant behaviour model 1. This again reinforces the fact that occupant behaviour model 1 primarily considers outdoor temperature for window operation, and night ventilation does not directly affect the window state since it is not based on indoor temperature.

On the other hand, figure 53 highlights the significant difference in CO_2 concentration levels when night ventilation is incorporated in simulations with occupant behaviour model 2. The average CO_2 values are notably higher compared to simulations without night ventilation. This result aligns with the explanation that occupant behaviour model 2 takes into account both outdoor and indoor temperatures, resulting in a higher probability of windows being closed, thereby increasing CO_2 levels indoors.

An interesting observation is that as the window-to-wall ratio increases, leading to larger window sizes, the average CO_2 values decrease. However, the size of the boxes (representing the interquartile range) also decreases. This pattern can be observed across all the graphs, suggesting that with larger windows, when they are opened, the cooling effect is more pronounced, prompting occupants to close the windows more frequently, consequently leading to higher CO_2 levels indoors.

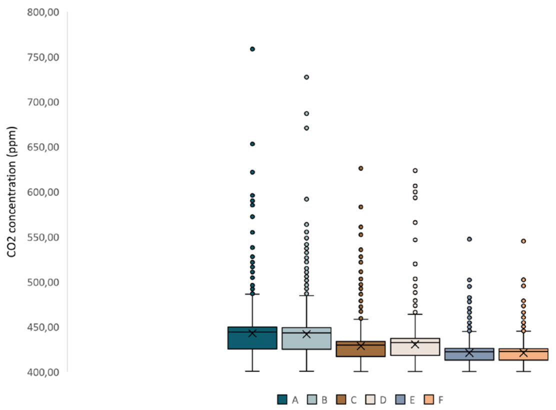


Fig.62. Box plot representation of the range of CO_2 levels for the facade archetypes with windows always open

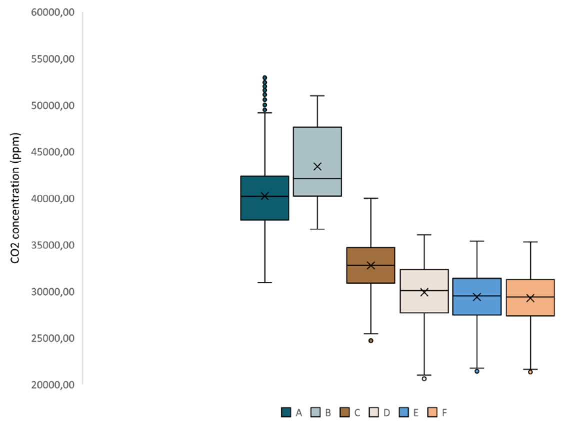


Fig.63. Box plot representation of the range of CO_2 levels for the facade archetypes with windows always closed

Figures 54 and 55 present the box plots for scenarios where the windows are always open and always closed, respectively. As anticipated, the CO_2 concentration values for the windows always open scenario are consistently below the acceptability limit of 800ppm. This outcome aligns with the understanding that open windows allow for natural ventilation, facilitating the exchange of indoor and outdoor air and effectively reducing CO_2 levels.

Conversely, the box plots for the windows always closed scenario reveal significantly higher CO_2concentration values. This finding is to be expected since, in the absence of any mechanical air supply, the accumulation of CO_2 becomes inevitable when windows remain closed. The lack of fresh outdoor air intake hampers ventilation and exacerbates the buildup of CO_2 indoors.

These results underscore the crucial role of window operation in maintaining acceptable indoor air quality. Properly utilizing windows for natural ventilation can effectively mitigate CO_2 levels and contribute to a healthier and more comfortable indoor environment.

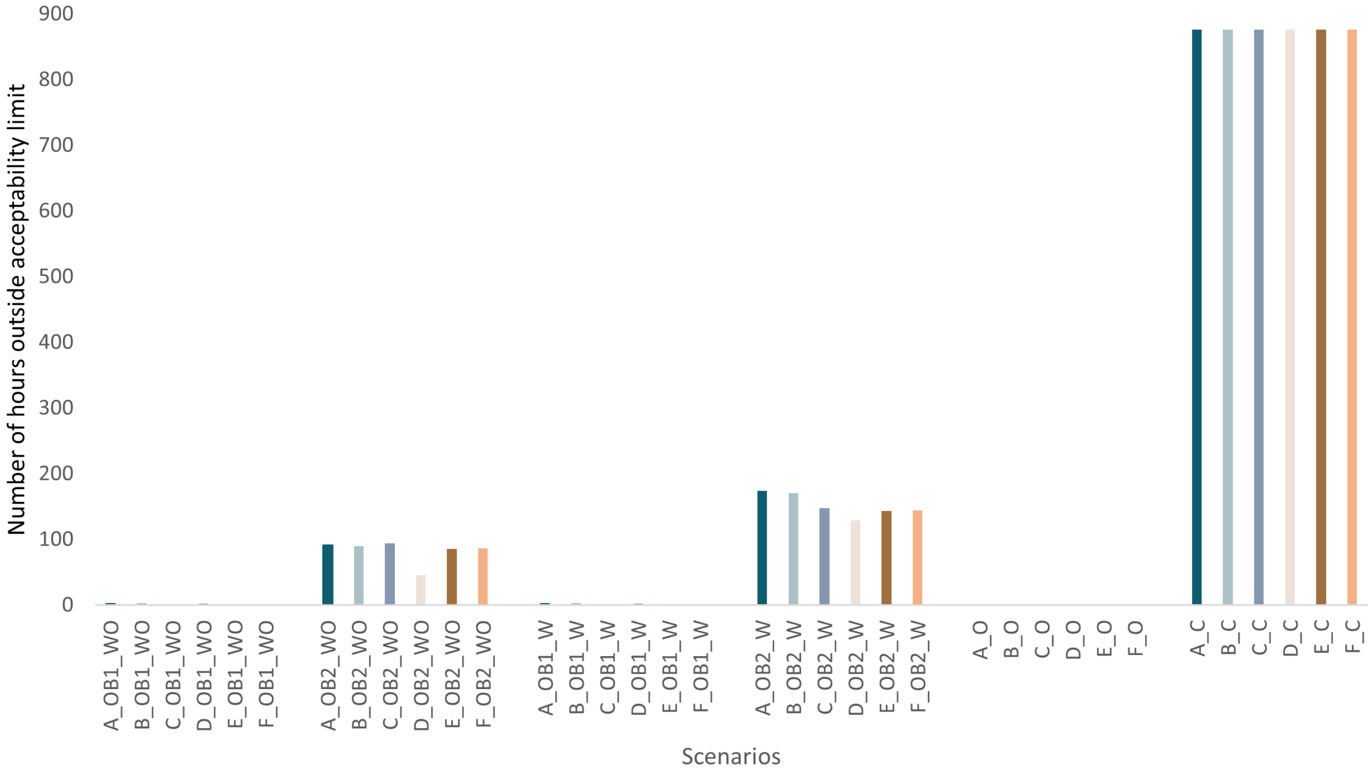


Fig.64. Graphical representation of the number of hours which have CO2 concentration levels higher than the acceptable limit defined by EN 15251

Figure 56 provides an overview of the number of hours during which CO_2 concentrations exceed the acceptability limit of 800ppm, as defined by EN 15251 (category III). The graph encompasses all occupied hours throughout the simulation period, which totals 876 hours. Notably, the results demonstrate that in scenarios where the windows are always closed, CO_2 levels surpass the acceptability limit for the entire duration of occupancy. Conversely, in scenarios with windows always open, the number of hours outside the acceptability limit is zero. This emphasizes the crucial role of window operation and natural ventilation in maintaining satisfactory indoor air quality with regards to CO_2 levels.

Further analysis of the scenarios involving occupant behaviour models reveals that although some hours exceed the acceptability limit, the overall extent of the issue is not severe in comparison to the total number of occupied hours. A closer examination reveals that scenarios employing occupant behaviour model 2 tend to exhibit a greater number of hours outside the acceptability limit compared to those utilizing model 1. This observation aligns with the previous discussions regarding the impact of occupant behaviour models on window operation and subsequent CO_2 levels. Moreover, within the context of occupant behaviour model 2, simulations without night ventilation result in fewer hours outside the acceptability limit when compared to simulations with night ventilation. This observation further underscores the influence of night ventilation on window operation and CO_2 concentrations.

When analyzing the individual archetypes, some intriguing patterns emerge. Archetypes A and B, both characterized by a 40% window to wall ratio, consistently exhibit the highest number of hours outside the acceptability limit. This can be attributed to their smaller window sizes, which limit ventilation rates and contribute to higher CO_2 levels. Conversely, archetypes E and F, with an 80% window to wall ratio, outperform archetypes A and B in terms of CO_2 levels due to their larger window sizes and higher ventilation rates.

However, a closer examination reveals an interesting exception: archetype D consistently demonstrates the lowest number of hours outside the acceptability limit, regardless of whether night ventilation is considered. To understand this phenomenon, it is crucial to scrutinize the characteristics of the archetypes. Archetypes A and B, with their 40% window to wall ratio and lightweight and heavyweight construction, respectively, suffer from higher CO_2 levels due to their smaller window sizes. In contrast, archetypes E and F, with their larger window sizes and higher window to wall ratio, enjoy improved CO_2 levels owing to enhanced ventilation rates.

An interesting discrepancy arises when comparing archetypes C and D, both featuring a 60% window to wall ratio. According to the previous logic, archetypes C and D should exhibit higher numbers of hours outside the acceptability limit compared to archetypes E and F. However, this is not the case. One possible explanation for this discrepancy is that archetypes E and F, with their higher window to wall ratio, cool the indoor space more rapidly, leading to reduced reliance on frequent window opening. As a result, CO_2 levels may increase in these archetypes despite their favourable window to wall ratio.

Looking at archetypes C and D, both having a 60% window to wall ratio, we can attribute the lower number of hours outside the acceptability limit in archetype D to its heavy weight construction. The increased thermal mass of archetype D, combined with the 60% window to wall ratio, influences window operation patterns that effectively reduce indoor CO_2 levels. The heavier construction typology of archetype D contributes to a more stable indoor temperature, reducing the need for frequent window operation to regulate temperature. As a result, occupants may be less inclined to open and close windows as frequently, which helps maintain lower CO_2 levels indoors.

It's important to note that the analysis of window operation patterns and their impact on CO_2 levels can be complex and context-dependent. Multiple factors interact to influence occupant behaviour and the resulting indoor air quality. Further investigation and consideration of specific case studies may be necessary to gain a more comprehensive understanding of the dynamics between window operation, thermal performance, and CO_2 levels in different building archetypes.

5.4 Analysis of sensitivity and robustness of facade archetypes

The analysis of the operative temperature data revealed interesting findings regarding the sensitivity of different archetypes to occupant behavior. To assess the sensitivity and robustness of the six facade archetypes to the occupant behavior models, two methods were employed. The first method involved comparing the average operative temperature values obtained for each archetype between the two occupant behavior models: model 1 and model 2. By calculating the differences between the average temperatures for each archetype and behavior model combination, insights into the magnitude of variation caused by different occupant behavior models were obtained. Figure 65 presents the calculated differences in average operative temperature values for each archetype across the two occupant behavior models. The differences highlight the degree of variation in thermal performance resulting from the implementation of different occupant behavior models. Larger differences indicate a higher sensitivity of the archetypes to the specific occupant behavior model used.

The second method utilized an analysis of variance (ANOVA) test to further examine the significance of the differences observed. The ANOVA test evaluated whether the differences in average operative temperatures between the two behavior models were statistically significant. The resulting P-values from the ANOVA tests are presented in table 15, providing an indication of the significance of the differences observed for each archetype.

Among the six studied archetypes, Archetype C, characterized by a 60% window-to-wall ratio and lightweight construction, exhibited the least difference in operative temperatures between the two occupant behavior models. The small difference of 0.02 indicates a relatively lower sensitivity to variations in occupant behavior. This finding suggests that Archetype C is more robust and less affected by changes in occupant behavior. In contrast, Archetype B, featuring a 40% window-to-wall ratio and heavy weight construction, demonstrated the maximum difference in operative temperatures, with a value of 1.51. This significant difference indicates a higher sensitivity to variations in occupant behavior. Archetype B is more influenced by changes in occupant behavior models, making it more susceptible to fluctuations in thermal performance.

In conclusion, the combined analysis using both methods confirms that Archetype C is the most robust among the studied archetypes, as it shows minimal sensitivity to changes in occupant behavior models. On the other hand, Archetype B exhibits the highest sensitivity, indicating that its thermal performance is strongly influenced by variations in occupant behavior.

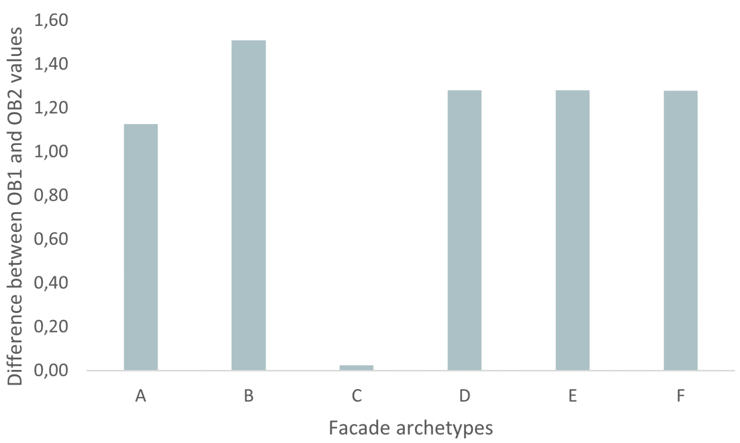


Fig.65. Graphical representation of the calculated operative temperature differences between the two occupant behaviour models for the six archetypes.

Façade archetype	P - value
A	2,83E-50
B	2,61E-77
C	0,752062
D	2,93E-54
E	8E-48
F	1,06E-47

Table 15. Table showing the P values obtained from the anova tests performed on the operative temperatures for the six archetypes.

Similar to the analysis conducted for operative temperatures, the sensitivity and robustness of the six archetypes towards occupant behavior models were also evaluated using average CO_2 concentration levels. The first method involved calculating the differences between the average CO_2 levels for each archetype and behavior model combination.

Among the archetypes, archetype C consistently displayed the lowest difference in CO_2 levels, indicating its lower sensitivity to changes in occupant behavior. On the other hand, Archetype A exhibited the highest difference, suggesting its greater sensitivity to variations in occupant behavior. These differences are illustrated in figure 66, which presents the calculated differences in average CO_2 concentration levels for each archetype across the two occupant behavior models.

However, the ANOVA tests revealed that all the archetypes exhibited significant differences in CO_2 concentration levels between the two behavior models. The P-values obtained from the ANOVA tests, as shown in table 16, indicate that the observed differences are statistically significant.

These findings indicate that while all the archetypes show sensitivity to changes in occupant behavior regarding CO_2 levels, Archetype C demonstrates a relatively lower sensitivity compared to the other archetypes. This implies that Archetype C is more robust and less influenced by variations in occupant behavior in terms of CO_2 concentration levels. On the other hand, Archetype A exhibits the highest sensitivity, indicating that it is more affected by changes in occupant behavior models with respect to CO_2 levels.

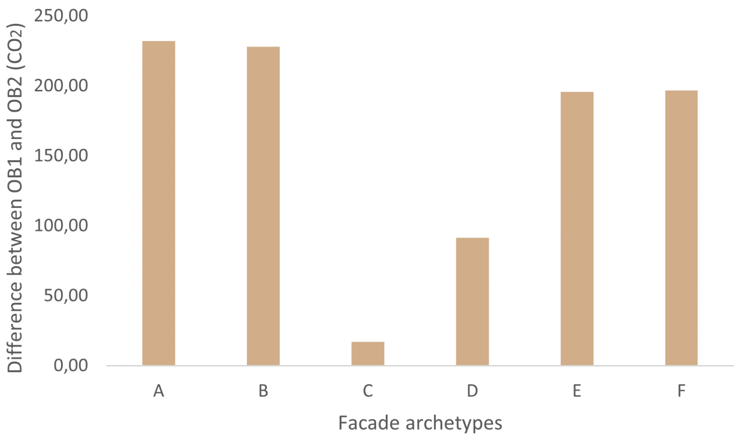


Fig.66. Graphical representation of the calculated CO_2 concentration levels differences between the two occupant behaviour models for the six archetypes.

Façade archetype	P - value
A	1,74E-20
B	5,37E-21
C	1,82E-22
D	9,3E-11
E	7,35E-20
F	5,71E-20

Table 16. Table showing the P values obtained from the anova tests performed on the CO_2 concentration levels for the six archetypes.

5.5 Overall comparision of scenarios in terms of thermal comfort and air quality

To evaluate the performance of the six facade archetypes in terms of thermal comfort and indoor air quality, several key metrics were analyzed. The analysis aimed to determine the best-performing archetype across various scenarios and provide valuable insights for future design considerations.

For thermal comfort assessment, two metrics were considered: discomfort hours and indoor overheating degree. Table 13 presents the number of hours exceeding the comfort limits (80% acceptability limit as per EN15251) for each facade archetype. By examining the values in the table, it becomes evident that archetype A consistently demonstrates the best performance across all scenarios, while archetype C exhibits the highest number of discomfort hours. Archetypes B and D show similar performance, with archetype B performing slightly better, especially in the scenario with windows always open. Following archetype D, archetypes F and E exhibit similar performance with slight differences. The overall rating of the six facade archetypes, based on discomfort hours, is summarized in table18.

To assess indoor overheating, table 14 presents the monthly indoor overheating degree for each archetype in all scenarios. The table reveals that archetype A outperforms the other archetypes in terms of total indoor overheating degree, closely followed by archetype B. Archetypes D and C exhibit comparable performance, with archetype D showing slightly better results. Finally, archetypes E and F demonstrate similar levels of overheating. The rating of archetype performance in terms of overheating degree is provided in table 18.

To assess the performance of the archetypes in relation indoor air quality, the CO_2 levels are evaluated by analyzing the number of hours exceeding the CO_2 concentration acceptability limit, as defined by EN15251. The results, shown in table 17, indicate that archetype D performs the best in terms of maintaining acceptable CO_2 levels, while archetype A exhibits the highest number of hours exceeding the limit. The rating of the six archetypes based on CO_2 concentration levels is illustrated in figure 18.

Overall, the analysis of thermal comfort and indoor air quality metrics reveals that archetype A consistently performs well for thermal comfort, while archetype D demonstrates the best performance in terms of CO_2 levels.

Table 17. Table showing the number of hours that exceed the acceptable CO_2 concentration levels as defined by EN 15251 for all the scenarios

Archetype	Total Number of hours	OB1_WO	OB2_WO	OB1_W	OB2_W	open	closed
A	**876**	3	91	3	174	0	876
B	**876**	3	90	3	170	0	876
C	**876**	1	94	1	147	0	876
D	**876**	2	45	2	129	0	876
E	**876**	1	85	1	143	0	876
F	**876**	1	86	1	144	0	876

Table 18. Table showing the ranking of the facade architypes in terms of thermal comfort and indoor air quality. The ranking depicts 1 as the best performing archetype and 5 as the worst performing archetype.

Ranking of façade archetypes			
Rank	**Discomfort hours**	**Overheating degree**	**CO_2 concentration**
1	A	A	D
2	B	B	E
3	D	D	F
4	F	C	C
5	E	E and F	B
6	C		A

Upon analyzing the rankings presented in table 18, it is evident that archetype D emerges as the best-performing facade archetype in terms of both thermal comfort and indoor air quality. Across the three ranking categories, archetype D consistently ranks within the top three, indicating its strong performance in maintaining occupant comfort and ensuring satisfactory indoor air quality. This finding highlights the robustness and effectiveness of archetype D in meeting the desired performance criteria and suggests its suitability for future design considerations. By prioritizing archetype D, designers and architects can optimize building performance and enhance occupants' well-being in terms of thermal comfort and indoor air quality.

5.6 Conclusions

The results and analysis chapter focused on evaluating the thermal performance of different scenarios and their impact on operative temperatures, along with the CO_2 concentration levels. Several key observations were made.

5.6.1 Observations made for thermal comfort

- Occupant behaviour models - different occupant behaviour models (OB1 and OB2) were compared. Occupant behaviour model 2, which considers indoor temperature in addition to outdoor temperature, provides a better descriptive of window operation and resultant operative temperatures since it is usually common for occupants to react to indoor conditions as a stimulus to operate windows.

- Relationship between outdoor temperature and operative temperature - scatter plots were used to analyze the relationship between outdoor temperature and operative temperature for different scenarios. A moderate positive linear relationship was observed, indicating that as outdoor temperature increases, so does the operative temperature. It is also found that a large percentage of the operative temperature data points lie within the comfort band, when compared to the total number of data points.

- Archetype analysis - different archetypes (A to F) were evaluated. It was observed that as the window-to-wall ratio (WWR) increases, operative temperatures also increase. Archetypes D, E, and F, with high glazing percentages, showed similar thermal performance, indicating that the opaque area has less influence on operative temperatures in these cases.

- Window operation and thermal comfort - the impact of window operation on thermal comfort was assessed. The bar graph displayed the number of discomfort hours, focusing on overheating. It was evident that keeping windows always closed led to continuous overheating, emphasizing the importance of window operation to reduce overheating when mechanical HVAC systems are not present.

- Scenario comparison - the performance of different scenarios within each archetype was compared. It was observed that scenarios without night ventilation generally had higher overheating hours compared to scenarios with night ventilation. However, scenarios with night ventilation sometimes led to underheating, as operative temperatures dropped below the comfort band.

- Scenario specific observations - several scenario specific observations were made. For example, archetype B showed higher overheating hours for OB1 compared to archetype A, possibly due to higher thermal mass. Archetype C exhibited higher overheating hours for OB1 without night ventilation compared to OB2, potentially due to increased WWR and lightweight construction.

5.6.2 Observations made for air quality

- Window to wall ratio - the size of windows and their proportion to the wall area significantly influenced CO_2 levels. Archetypes with larger window to wall ratios, such as E and F, exhibited lower CO_2 levels due to increased ventilation rates.

- Occupant behaviour models - two occupant behaviour models were compared, and it was found that the model considering both outdoor temperature and indoor temperature (OB model 2) resulted in higher CO_2 levels compared to the model considering only outdoor temperature (OB model 1).

- Night ventilation - the addition of night ventilation had a notable impact on CO_2 levels, particularly in simulations using OB model 2. The implementation of night ventilation as a cooling strategy effectively lowers indoor temperatures during the day. However, the relationship between occupant behavior models and temperature influences the probability of windows being closed, resulting in higher CO_2 levels indoors. As the indoor spaces become cooler due to night ventilation, occupants are more likely to keep the windows closed, limiting the natural exchange of fresh outdoor air and leading to a buildup of CO_2.

- Individual archetypes - different archetypes demonstrated varying CO_2 levels. Archetypes A and B, with a 40% window to wall ratio and smaller window sizes, consistently exhibited higher CO_2 levels. Conversely, archetypes E and F, with an 80% window to wall ratio and larger windows, showed improved CO_2 levels due to enhanced ventilation rates.

- Construction typology - the construction typology of archetypes also influenced CO_2 levels indirectly. Archetype D, with a heavy weight construction and a 60% window to wall ratio, consistently demonstrated overall the lowest CO_2 levels. The higher thermal mass of archetype D, combined with its window operation patterns, contributed to reducing indoor CO_2 levels.

In summary, the analysis highlighted the importance of window operation in regulating operative temperatures and reducing overheating. The analysis highlighted the importance of window size, occupant behaviour models, night ventilation, and construction typology in influencing thermal comfort and CO_2 levels.

Larger window sizes and higher window to wall ratios generally led to improved CO_2 levels due to enhanced ventilation rates. However, the interplay of factors such as occupant behaviour, thermal mass, and window operation patterns could create exceptions to this trend, as seen in archetype D. Understanding these factors is crucial for designing buildings that effectively manage CO_2 levels and ensure satisfactory indoor air quality.

06 | Conclusion

6.1 Conclusion

The thesis addresses the research question "what is the impact of occupant-facade interaction on thermal comfort during the cooling season?", by exploring the complex and dynamic nature of occupant behaviour and its implementation in building performance simulations.

The thesis begins with a literature review that focuses on the conventional and novel passive strategies used during the cooling season to maintain thermal comfort. Through this literature review, it is identified that existing passive facade strategies often overlook the role of occupant behaviour. This study aims to fill the research gap and shed light on the importance of considering occupant-facade interaction strategies, particularly window operation, when evaluating passive strategies for maintaining thermal comfort.

The study focuses on office spaces and reviews work on occupant behaviour in buildings, which encompasses various factors such as window and shade operation, lighting preferences, and occupant presence. Among the various adaptive behaviours, window operation is selected for further study. A second literature review is carried out on window operation models and their implementation in simulation software. The next step involved developing scenarios to conduct the simulations, six facade archetypes are identified based on window to wall ratio and construction typology for the Netherlands. Along with this two window operation models are selected from the literature review, and two base cases are considered where windows are always open and always closed respectively. Additionally, considering the benefits of night ventilation identified in the literature, night ventilation is included as a passive strategy.

To conduct simulations, 36 scenarios are generated by combining the identified archetypes, window operation models, and night ventilation. Energy Management System Runtime Language (EMS) is employed in DesignBuilder software to script the occupant behaviour models. Individual DesignBuilder models are created for each scenario, and scripts are developed for the base cases and night ventilation. Simulations are performed for all 36 scenarios, and the results are collected for further analysis. The simulation results are then used to assess the impact of window operation on thermal comfort and indoor air quality. Operative temperatures and overheating degree are considered as key indicators for evaluating thermal comfort. Additionally, these results are complemented with the analysis of indoor air quality by computing the related CO_2 concentration levels for each scenario.

By analyzing the collected results, the study provides insights into the effects of different window operation strategies on thermal comfort and indoor air quality. The findings contribute to a better understanding of the importance of occupant-facade interaction in maintaining comfortable and healthy indoor environments during the cooling season.

The analysis of the implemented occupant behaviour models yields several important conclusions which contribute to answering the research question:

- The results highlight the significant impact of window operation on thermal comfort. The operative temperatures obtained for each scenario and archetype differ significantly, emphasizing the importance of considering both facade typology and window operation patterns in determining indoor thermal conditions. Furthermore, comparing the window operation models with scenarios where windows are always closed or always open reveals that considering occupant behaviour leads to improved thermal comfort performance.

- The results of the study demonstrate the effectiveness of night ventilation as a passive cooling strategy for reducing indoor temperatures during the summer season. By allowing cooler outdoor air to enter the indoor spaces during the night, the need for mechanical cooling systems is reduced, thereby resulting in energy savings. The analysis of the data reveals that the implementation of night ventilation successfully lowers the operative temperatures, contributing to improved thermal comfort for the occupants. This reduction in indoor temperatures can lead to a more sustainable and energy-efficient approach to cooling, as it minimizes the reliance on energy-intensive air conditioning systems.

- It is important to note that the impact of window operation on indoor air quality is influenced by the window to wall ratio and construction typology of the building. The findings suggest that larger window sizes, represented by a higher window to wall ratio, generally lead to improved ventilation rates and lower CO_2 levels. Additionally, the construction typology, such as lightweight or heavyweight construction, may not have a direct influence on the ventilation rates but interacts with the window operation pattern, potentially affecting the indoor air quality outcomes.

- The analysis of the results demonstrates that facade archetype C, characterized by a 60% window-to-wall ratio and lightweight construction, exhibits the highest robustness to variations in occupant behavior models in terms of both thermal comfort and indoor air quality. Despite changes in occupant behavior, archetype C consistently maintains relatively stable operative temperatures and CO_2 levels compared to the other archetypes. This indicates that the design attributes of archetype C, such as the higher window-to-wall ratio and lightweight construction, contribute to its ability to mitigate the impact of occupant behavior on indoor conditions. On the otehr hand archetype B proves to be most sensitive towards ocuupant behaviour in terms of thermal comfort and archetype A is the most sensitive in terms of air quality.

- While archetype C demonstrates the highest robustness to changes in occupant behavior models, it is important to note that archetype D emerges as the best performer in terms of both thermal comfort and indoor air quality. Archetype D consistently achieves favourable outcomes across various scenarios, exhibiting superior performance in terms of operative temperatures, CO_2 concentrations, and overall occupant satisfaction.

- One intriguing finding of this study is the interplay between thermal comfort and indoor air quality influenced by the use of occupant behavior models. The temperature dependency of these models implies a higher likelihood of windows being kept closed to maintain indoor thermal comfort. While this contributes to optimal thermal conditions, it also leads to the accumulation of CO_2 indoors due to limited ventilation.This observation highlights the inherent trade-off between thermal comfort and indoor air quality. The prioritization of thermal comfort through closed windows can inadvertently result in compromised air quality, specifically in terms of elevated CO_2 levels. It emphasizes the need to strike a balance between these two aspects to ensure occupants' well-being and health within indoor environments. To address this challenge, future design strategies should aim to integrate both thermal comfort and indoor air quality considerations.

In conclusion, the research conducted in this thesis demonstrates that occupant-facade interaction, particularly window operation, has a positive impact on thermal comfort during the cooling season. By actively involving occupants in the control of windows, such as adjusting their opening and closing based on their comfort preferences and external conditions, indoor thermal conditions can be optimized. The findings of this study emphasize the potential of occupant-facade interaction as a passive strategy to maintain thermal comfort without relying heavily on mechanical cooling systems. By encouraging occupants to actively engage in window operation, buildings can achieve better thermal performance while reducing energy consumption.The results of this research provide valuable insights for building designers, practitioners, and researchers, highlighting the importance of considering occupant behaviour as a key factor in achieving optimal thermal conditions in buildings.

The findings emphasize the need for integrated design approaches that consider occupant behaviour and promote energy-efficient strategies in building design and operation. Further research is recommended to explore additional occupant behaviour models, assess the impact of other factors such as shading devices, and evaluate the long-term sustainability implications of occupant-facade interaction strategies. By acknowledging these findings, building designers and practitioners can make informed decisions regarding window operation strategies and the integration of mechanical air supply systems to enhance both thermal comfort and indoor air quality in office spaces during the cooling season.

6.1.1 Design conclusions

This thesis offers several design conclusions that can guide architects and designers in making informed decisions regarding future building and facade design.

- It is concluded that window operation can serve as an effective cooling strategy without relying solely on mechanical methods. While a large percentage of operative temperatures fall within the thermal comfort range, it is essential to acknowledge that some overheating still occurs. Therefore, completely eliminating mechanical cooling may not be practical for ensuring occupant comfort. To optimize energy consumption, a balance must be struck between mechanical cooling and considering occupant behaviour, as only a small percentage of hours fall outside the comfort range.

- The results further demonstrate that window operation plays a crucial role in maintaining indoor air quality. However, it is observed that when the windows are closed, the absence of mechanical air supply leads to increased CO_2 levels. This highlights the potential need for incorporating a mechanical air supply system to ensure continuous and effective ventilation, thus mitigating elevated CO_2 levels indoors.

- The thesis also underscores the importance of adaptive behaviour in reducing energy consumption. Allowing occupants control over their thermal environment promotes comfort and enables individuals to adapt to varying climatic conditions. In contrast, constant conditioning at a specific temperature hampers adaptive capabilities and energy efficiency. (add personal control)

- The results also show that overall archetype D performs the best in terms of both thermal comfort as well as air quality. Individually, archetype A performs the best in terms of thermal comfort and archetype D shows the best perfromance in terms of air quality. By understanding the performance ranking of the archetypes, designers and architects can optimize building performance and enhance occupants’ well-being in terms of thermal comfort and indoor air quality.

- Further, the research highlights the importance of continuously monitoring and evaluating indoor environmental conditions, including operative temperatures and CO_2 concentrations, to ensure the effectiveness of design strategies. Architects can incorporate sensors and monitoring systems into buildings to gather real-time data, enabling them to make informed decisions and adapt design strategies based on occupants’ needs and changing environmental conditions.

6.2 Limitations

The present section discusses the limitations encountered during the course of this thesis project. While extensive efforts were made to address the research questions and achieve the objectives, it is important to acknowledge the constraints and challenges that influenced the scope and outcomes of the study. By understanding these limitations, it becomes possible to provide a comprehensive assessment of the project's findings and offer insights into areas for future improvement.

- The occupant behaviour models utilized in this project are based on field studies conducted in diverse climatic regions. Since the thesis focuses on a hypothetical office space in the Netherlands, there may be limitations in accurately predicting occupant behaviour in this specific region. For instance, one of the selected models relies on outdoor temperature, which may differ significantly between China (where the model was developed) and the Netherlands, potentially leading to variations in the obtained results.

- The use of software tools posed a limitation in this study. DesignBuilder, along with EMS coding language, was employed for simulations. While EMS coding in DesignBuilder is a relatively new tool, it required a learning curve to understand and utilize effectively. Additionally, data analysis was performed using Excel, which, although proficient for statistical analysis, may have imposed constraints on conducting more in-depth analyses compared to alternative programming languages like Python.

- Knowledge was a constraint during the thesis, particularly regarding statistical analysis. As a student with a background in architecture and design, statistical analysis was a new and unfamiliar aspect. This limitation may have influenced the depth and extent of the statistical analyses conducted in the study.

- Time constraints were also a factor in the project. Initially, the aim was to simulate both window and shade operation to analyze their effects on thermal comfort. However, due to the considerable amount of time required to comprehend and implement window operation models, shading devices were not included in the final research. Given more time, extending the thesis to encompass shading devices and exploring scenarios with combined window and shading operations would have been valuable.

- The research was conducted on a hypothetical office space, and the sample size used for the occupant behaviour models was limited. A larger sample size would provide a more representative understanding of occupant behaviour and its impact on thermal comfort.

- The models and simulations used in this thesis project relied on certain simplifying assumptions, such as uniform occupant behaviour and consistent climate conditions. These assumptions may not fully capture the complexities and variations that exist in real-world scenarios, leading to potential discrepancies between the simulated results and actual occupant behaviour.

- The occupant behaviour models employed in this study relied on predefined schedules and inputs. However, in real-world scenarios, occupants receive real-time feedback from their environment and adjust their behaviour accordingly. The absence of such feedback mechanisms in the simulation may limit the accuracy and representativeness of the results.

6.3 Recommendations for further research

The findings of this research project have uncovered valuable insights into the influence of occupant-facade interaction on thermal comfort and energy performance. As a result, several recommendations for future research and development have emerged. By investigating these areas, researchers can contribute to the development of occupant-oriented design approaches, optimized passive strategies, and region-specific guidelines that prioritize thermal comfort, energy efficiency, and sustainable development. These recommendations pave the way for further advancements in the field of occupant-facade interaction and sustainable building design, ultimately leading to more comfortable, energy-efficient, and environmentally conscious built environments.

- Facade design can be further developed to prioritize occupant-oriented approaches, encouraging occupants to actively participate in controlling their thermal environment. This can be achieved by integrating user-friendly interfaces, smart technologies, and intuitive design features that empower occupants to make informed decisions about their comfort and energy consumption. Further research can explore innovative design strategies and evaluate their effectiveness in promoting occupant engagement and reducing energy consumption.

- While window operation has shown to contribute to maintaining thermal comfort without relying solely on mechanical systems, it is important to determine the extent to which window operation can effectively regulate indoor thermal conditions. Future research can investigate different window operation strategies and their impact on energy savings, and indoor air quality. This includes studying the relationship between window operation patterns and occupant satisfaction, as well as quantifying the energy savings achieved by utilizing window operation as a passive cooling strategy.

- Night ventilation has been identified as a beneficial strategy for reducing indoor temperatures during the summer months. However, it is essential to develop effective night ventilation strategies that strike a balance between temperature reduction and preventing underheating. Further research can explore optimized night ventilation techniques. This research can lead to the development of guidelines or recommendations for implementing night ventilation strategies that enhance overall thermal comfort and energy efficiency.

- While this study primarily focused on window operation, there is potential for further research to investigate other device controls, such as shading systems and lighting controls, as well as explore innovative passive strategies. Investigating the combined effects of various passive strategies on thermal comfort and energy performance can provide valuable insights for building design and operation. This research can contribute to the development of integrated design approaches that optimize multiple passive strategies for enhanced occupant comfort and energy efficiency.

- Building upon the findings of this study, future research can delve deeper into refining window control strategies or developing new window operation techniques and patterns to further improve indoor thermal comfort. Evaluating the effectiveness of these refined strategies through simulations and field studies can provide valuable knowledge on optimizing window operation for enhanced thermal comfort and energy efficiency.

- Although this study was conducted in the context of the Netherlands, similar research can be conducted in different climatic regions to analyze the performance and effects of occupant behaviour and natural ventilation on thermal comfort. Understanding the region-specific influences on occupant behaviour and the effectiveness of passive strategies in different climates can lead to tailored design guidelines and recommendations. Additionally, considering the increasing occurrence of heatwaves, investigating the role of window operation in mitigating heatwave impacts on indoor thermal comfort can be a valuable avenue for future research.

6.4 Reflections

Personal Reflection

Engaging in the master thesis was a transformative journey for me, filled with valuable experiences and knowledge gained. I am grateful for the unwavering support and guidance provided by my supervisors and the people around me, which played a significant role in successfully completing this project within the given timeframe. Their expertise and insights broadened my understanding and allowed me to delve into new areas of study.

Coming from an architectural and design background, this thesis provided a fresh perspective by immersing me in technical and research-oriented work. It was a challenge to delve into subjects that were previously unfamiliar to me, but it also sparked my curiosity and facilitated my growth as a researcher. Occupant behaviour, in particular, captured my interest due to its relevance and emerging prominence in the field of built environment. The complexity of this topic presented new challenges and pushed me to conduct thorough research before implementing the concepts in my project. Understanding the intricacies of occupant behaviour and its application in building performance analysis was a significant learning experience that further fueled my interest for this area of study.

This thesis only scratched the surface of the vast possibilities within the realm of occupant-façade interaction and its impact on thermal comfort. The research has revealed numerous avenues for future exploration and development, leaving me inspired to continue contributing to this field. The potential to create innovative design solutions and enhance energy efficiency by incorporating occupant behaviour models is both exciting and promising.

One of the significant challenges encountered during the implementation phase of the occupant behaviour models was the integration of these models into the DesignBuilder software. This required me to delve into the world of Energy Management System (EMS) language, a coding language used to customize simulations and model complex interactions. Initially, I had limited experience and interest in coding, but this obstacle provided an opportunity for personal growth. Learning EMS language and its application in DesignBuilder was a steep learning curve for me. As I delved deeper into the coding process, I realized the immense power and flexibility that EMS offered in implementing complex simulations and capturing detailed occupant behaviour patterns. It allowed me to refine and customize the simulations to accurately represent the dynamic nature of occupant-façade interaction.

Overcoming this challenge not only enhanced my technical skills but also opened my eyes to the possibilities and efficiencies that coding can bring to building performance analysis. It highlighted the importance of embracing new technologies and tools in the field of sustainable design. This experience served as a valuable lesson in adaptability and pushed me to broaden my skill set beyond my initial comfort zone. Overall, the master thesis has been a rewarding and enlightening experience, allowing me to expand my knowledge, develop research skills, and contribute to the discourse on sustainable building design. I am grateful for the opportunity to have worked on this project and look forward to further exploration and growth in the field of building technology and design.

1. The relation between graduation project topic and Master programme.

The relation between my graduation project topic and the Master programme in Building Technology is significant. The Building Technology master track, offered by the faculty of Architecture, is designed to bridge the gap between architecture and engineering, emphasizing sustainable design and technical innovation. It encourages students to think innovatively about design and focus on technical detailing.

My thesis topic, "The Influence of Occupant-Façade Interaction on Thermal Comfort," aligns well with the goals of the Building Technology program. It falls under two chairs of the program: design of construction and climate design. Under the guidance of Dr. Alessandra Luna Navarro and Dr.ir. Martin Tenpierik, I conducted research to explore the possibility of achieving thermal comfort in office buildings without excessive reliance on mechanical systems. The core of my thesis revolves around studying the interaction between occupants and the building façade, as the façade plays a crucial role in influencing thermal comfort. By understanding how occupants interact with the façade, we can design strategies to optimize thermal comfort. One aspect of my research involved studying occupant behaviour models for window operation. These models aim to accurately predict how occupants would interact with windows in real-world scenarios. By incorporating these models into simulations, we were able to analyze the impact of different occupant behaviour patterns on thermal comfort within office spaces.

Ultimately, the goal of my thesis was to contribute to mitigating climate change by promoting passive strategies and reducing energy consumption. By focusing on occupant-façade interaction and understanding its influence on thermal comfort, we aimed to provide insights and recommendations for designing more sustainable and comfortable office environments.

2. The value of the research approach and method chosen related to the graduation studio.

The chosen research approach and methodology in my thesis align well with the methodical line of approach followed in the graduation studio. The research methodology was systematic and followed a logical progression from problem statement to data analysis.

The research approach began by clearly defining the problem statement and research objectives. A literature review was conducted to identify the existing knowledge and research gap regarding passive façade strategies for maintaining indoor thermal comfort. This step allowed for a comprehensive understanding of the current state of the field and provided a foundation for the research. Building upon the literature review, further research was conducted to delve deeper into occupant behaviour and behaviour models. This step involved gathering relevant information and data about occupant behaviour models for window operation. By incorporating this aspect into the research, the study aimed to capture the influence of occupant behaviour on thermal comfort accurately.

The next stage of the research involved implementing the gathered information and behaviour models in simulations. This allowed for the evaluation and analysis of thermal comfort under different scenarios. The results obtained from the simulations were carefully analyzed and interpreted to address the main research question and sub-questions effectively. Conclusions were drawn based on the findings of the analysis, and recommendations for future research in this area are provided. This systematic approach ensured that the research process was well-structured, and the objectives of the study were addressed in a coherent manner. The chosen research methodology demonstrated a clear line of reasoning, starting from the identification of the research gap to the implementation of simulations and the analysis of results. It provided a foundation for addressing the research objectives and contributed to a better understanding of the influence of occupant-façade interaction on thermal comfort.

3. How are research and design related?

Research and design are closely related in this project, although it focusses more on simulation and analysis, the research conducted in this thesis provides valuable insights and knowledge that inform the design process. The research focused on understanding and exploring the influence of occupant-façade interaction on thermal comfort in office buildings.

Through the research, existing façade design strategies for reducing energy consumption and maintaining thermal comfort were identified and analyzed. However, it was observed that occupant behaviour and their active participation in maintaining thermal comfort were not adequately considered in many cases. This research gap led to the exploration of the possibility of occupants actively interacting with the built environment to achieve thermal comfort. The findings of the research highlight the importance of designing the façade in a way that encourages occupant engagement and active participation in maintaining thermal comfort. The results emphasize the need to consider occupant behaviour and preferences when designing the operation strategies for windows and other façade elements.

By bridging the gap between research and design, this project opens up opportunities to integrate the research findings into the design process. The insights gained from the research can be used to inform the design of office buildings with occupant-centric thermal comfort strategies. This could include designing façades that provide occupants with control over their immediate environment or incorporating intelligent systems that adapt to occupants' needs and preferences.

Societal Impact

4. To what extent are the results applicable in practice?

The results of this project have practical implications for the design and operation of office buildings. The findings demonstrate the potential of window operation as a strategy to maintain thermal comfort without relying heavily on mechanical systems. This is particularly relevant in the context of sustainable design and energy efficiency, as reducing the reliance on mechanical cooling can contribute to energy savings and lower environmental impact.

The research provides insights into the impact of different window operation patterns on thermal comfort. By analyzing the simulations and evaluating the operative temperatures, it is possible to identify effective window operation strategies that can regulate indoor temperatures and create a comfortable environment for occupants. These findings can be directly applied in practice when designing office buildings or retrofitting existing ones. Furthermore, the thesis highlights the importance of occupant behaviour models in building performance simulations. By incorporating occupant behaviour in the simulations, more accurate predictions of thermal comfort can be obtained. This aspect opens up opportunities for further development and implementation of occupant models in building performance simulation tools used in practice.

The concept of using natural ventilation and smart window operation patterns proposed in this thesis can be implemented in real-world scenarios. Designers, architects, and building professionals can leverage these findings to inform their design decisions and optimize the performance of office buildings in terms of thermal comfort and energy efficiency. However, it is important to note that the applicability of the results may vary depending on specific contextual factors such as climate, building design, and occupant preferences. Therefore, further studies and validation in different contexts are necessary to ensure broader applicability and to account for specific regional or building-specific conditions.

5. Did you encounter moral/ethical issues or dilemmas during the process? How did you deal with these?

During the process of conducting this thesis, several moral and ethical issues and dilemmas were encountered, particularly regarding occupant behaviour and their interaction with the built environment. Some of the key concerns and how they were addressed are as follows:

1. Subjectivity and Variability of Occupant Behaviour: Occupant behaviour is highly subjective and influenced by various factors such as cultural differences, personal preferences, and individual comfort thresholds. This raises the ethical dilemma of whether it is appropriate to generalize occupant behaviour models and impose specific window operation patterns on all occupants. To address this, the thesis acknowledged the variability of occupant behaviour and emphasized the need for context-specific approaches. It is suggested that future developments should focus on creating adaptable and customizable strategies that allow occupants to personalize their window operation while still maintaining thermal comfort.

2. Encouraging Active Occupant Participation: The thesis explores the concept of active occupant-façade interaction, where occupants play a role in maintaining thermal comfort through window operation. However, this raises questions about whether it is ethically acceptable to ask occupants to actively engage in this process, especially when the prevailing trend in office buildings is to rely on centralized and automated HVAC systems. To address this dilemma, the thesis highlights the potential benefits of active participation, such as energy savings and increased occupant satisfaction, while acknowledging the need for effective communication and education to encourage occupants to embrace their role in maintaining thermal comfort.

3. Sustainability Implications: The ethical considerations of promoting sustainable practices and mitigating climate change were significant drivers in this research. The potential for reducing energy consumption and greenhouse gas emissions through passive strategies, such as smart window operation, was recognized as a valuable contribution to sustainability. While ethical dilemmas related to occupant behaviour were acknowledged, the overall positive impact of promoting energy-efficient practices and reducing reliance on mechanical systems outweighed these concerns.

6. Does the project contribute to sustainable development?

This project makes a significant contribution to sustainable development by focusing on passive strategies to maintain thermal comfort, with a specific emphasis on window operation. The excessive use of mechanical systems for cooling and heating in buildings leads to high energy consumption and associated carbon emissions. By studying and promoting the role of occupants in actively interacting with the building envelope, particularly windows, this project explores the potential for reducing reliance on mechanical systems and achieving thermal comfort through natural means.

The findings of the project highlight the importance of considering occupants as active participants in maintaining thermal comfort. By designing appropriate window operation strategies and promoting natural ventilation, energy consumption can be reduced, leading to lower greenhouse gas emissions and a more sustainable built environment. This aligns with the principles of sustainable development, which aim to minimize environmental impact, conserve resources, and create healthier and more comfortable indoor spaces.Furthermore, the project addresses the need for more comprehensive occupant behaviour models in building performance simulations. By integrating these models into simulations, designers and architects can make more informed decisions about building design and operation, leading to more energy-efficient and sustainable buildings.

Overall, the project's focus on passive strategies, occupant behaviour, and the reduction of energy consumption aligns with the principles of sustainable development, contributing to a more sustainable and environmentally responsible built environment.

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Appendix

A.1 Scatter plots of operative temperature versus outdoor temperature

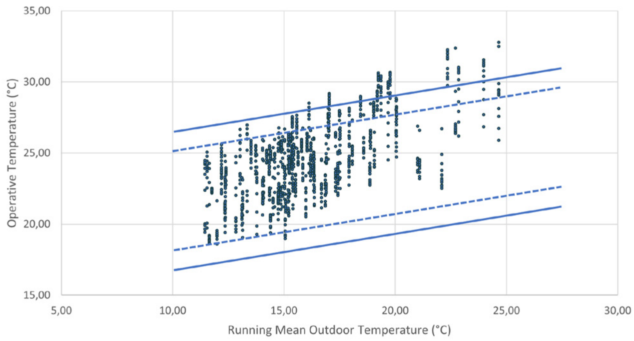

Fig.A1. Scatter plot of archetype B with occupant behaviour 1 without night ventilation

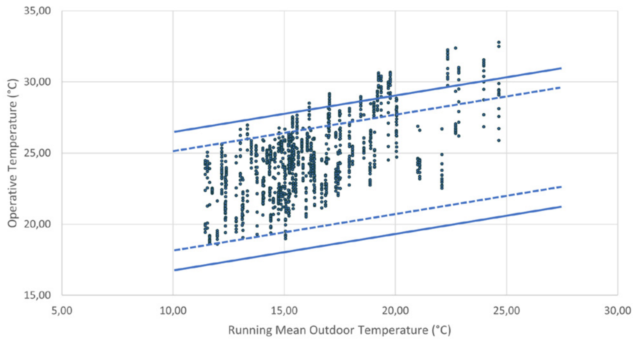

Fig.A2. Scatter plot of archetype B with occupant behaviour 2 without night ventilation

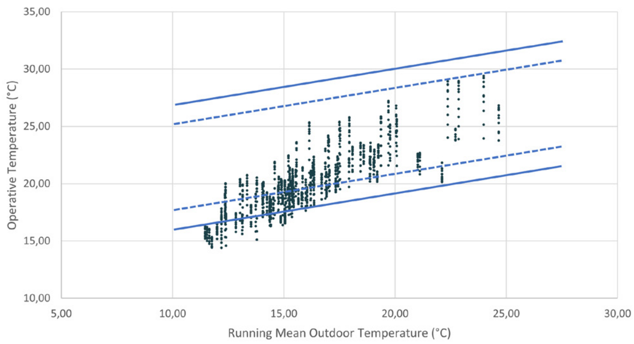

Fig.A3. Scatter plot of archetype B with occupant behaviour 1 with night ventilation

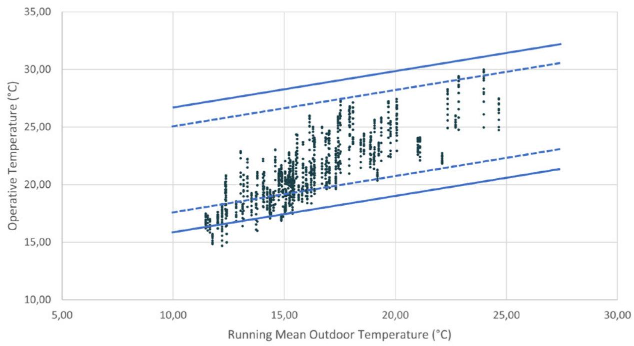

Fig.A4. Scatter plot of archetype B with occupant behaviour 2 with night ventilation

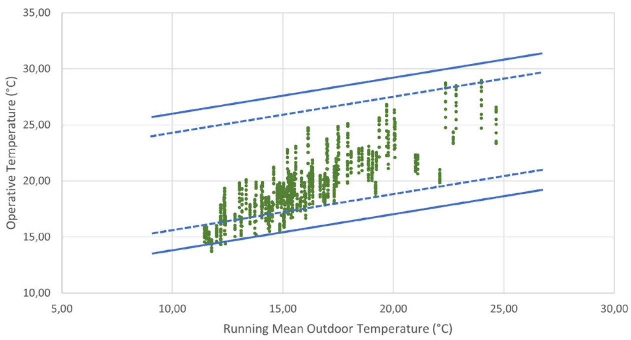

Fig.A5. Scatter plot of archetype B with windows always open

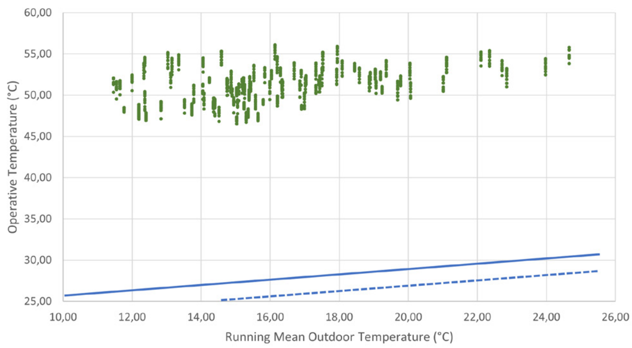

Fig.A6. Scatter plot of archetype B with windows always closed

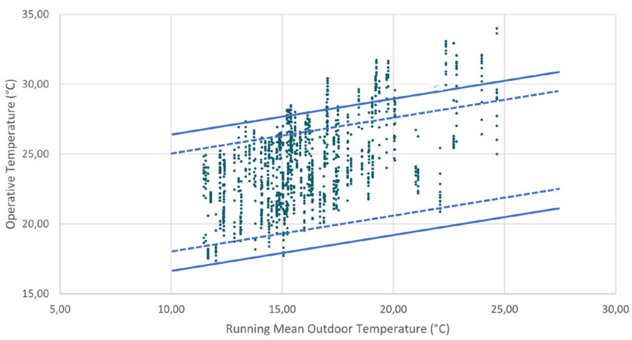

Fig.A7. Scatter plot of archetype C with occupant behaviour 1 without night ventilation

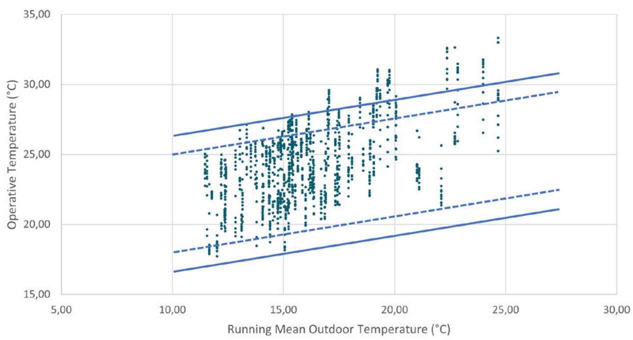

Fig.A8. Scatter plot of archetype C with occupant behaviour 2 without night ventilation

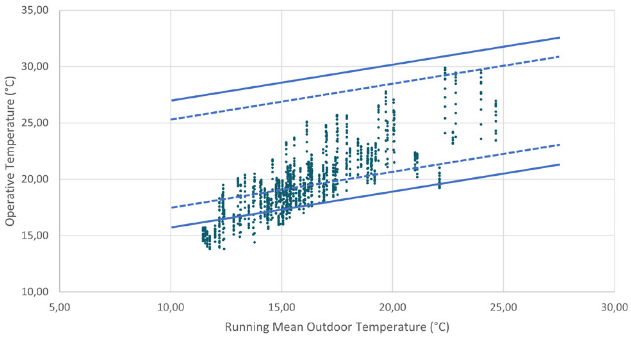

Fig.A9. Scatter plot of archetype C with occupant behaviour 1 with night ventilation

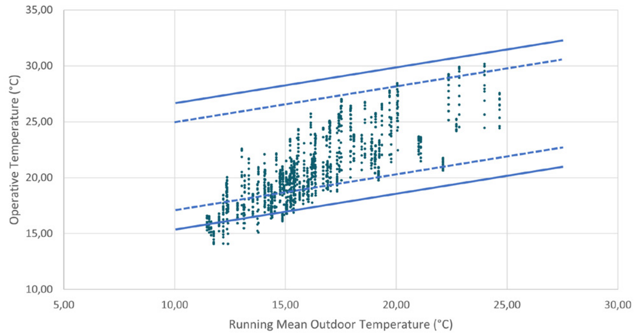

Fig.A10. Scatter plot of archetype C with occupant behaviour 2 with night ventilation

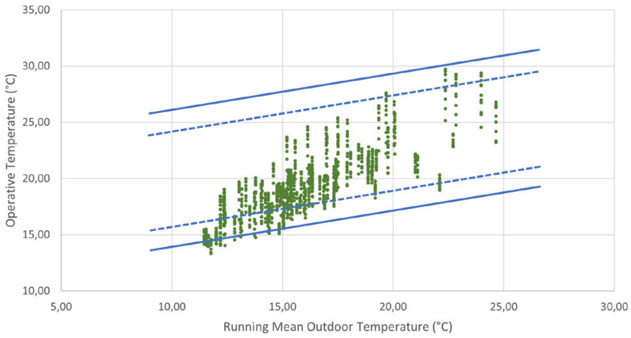

Fig.A11. Scatter plot of archetype C with windows always open

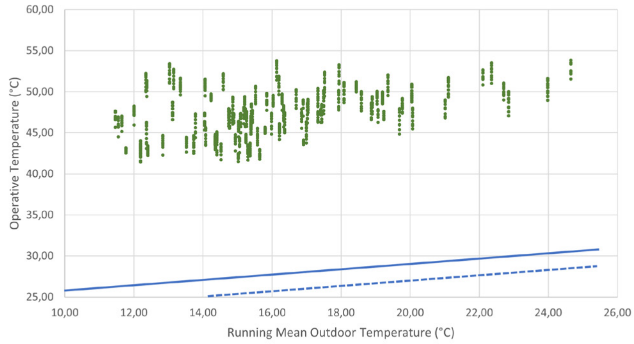

Fig.A12. Scatter plot of archetype C with windows always closed

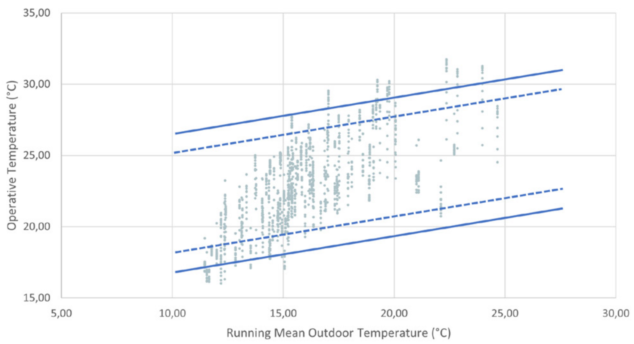

Fig.A13. Scatter plot of archetype D with occupant behaviour 1 without night ventilation

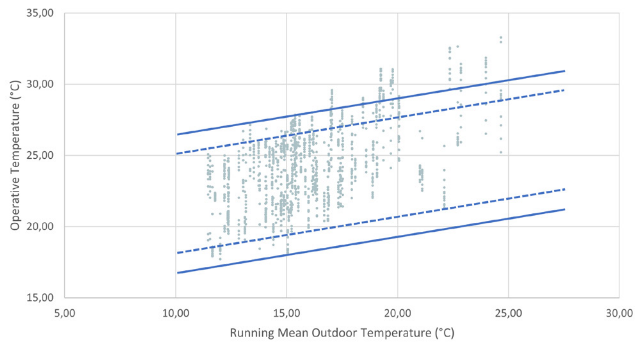

Fig.A14. Scatter plot of archetype D with occupant behaviour 2 without night ventilation

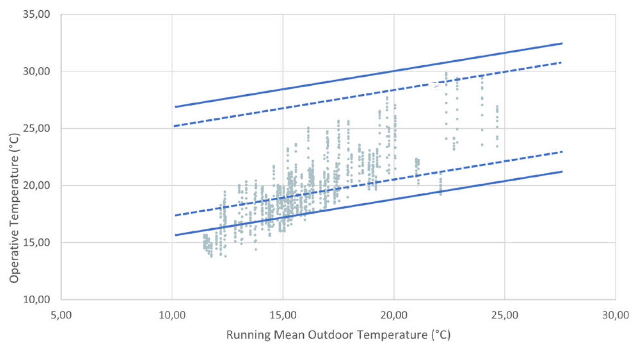

Fig.A15. Scatter plot of archetype D with occupant behaviour 1 with night ventilation

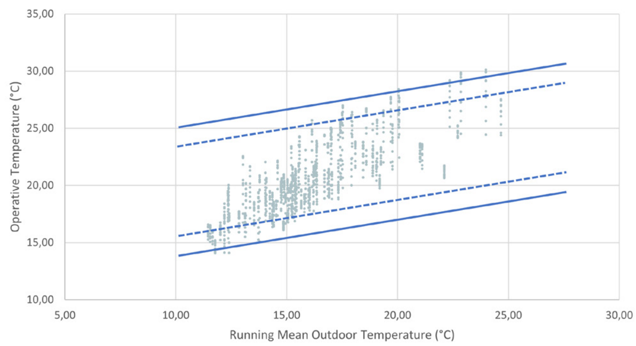

Fig.A16. Scatter plot of archetype D with occupant behaviour 2 with night ventilation

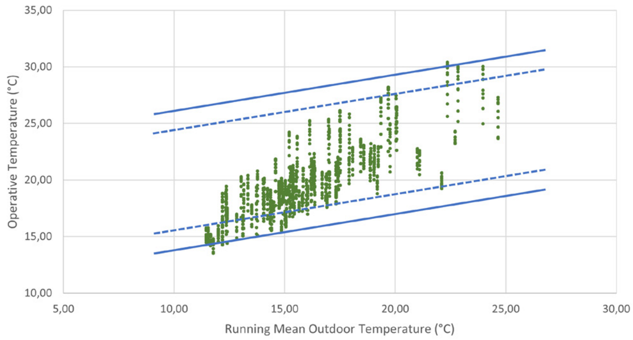

Fig.A17. Scatter plot of archetype D with windows always open

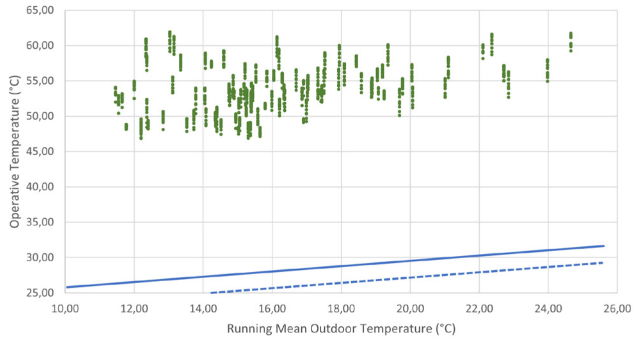

Fig.A18. Scatter plot of archetype D with windows always closed

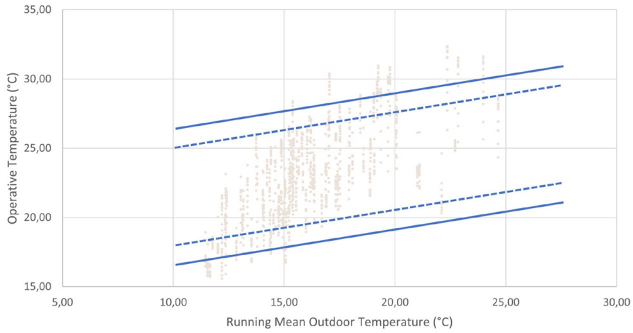

Fig.A19. Scatter plot of archetype E with occupant behaviour 1 without night ventilation

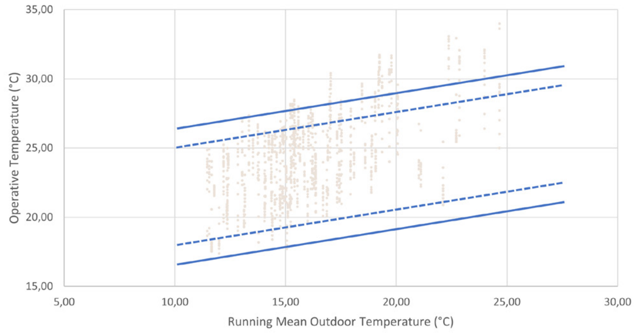

Fig.A20. Scatter plot of archetype E with occupant behaviour 2 without night ventilation

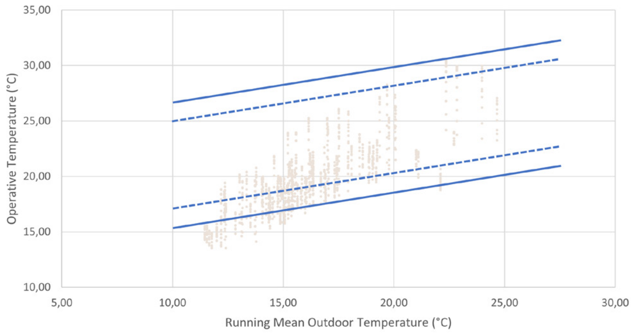

Fig.A21. Scatter plot of archetype E with occupant behaviour 1 with night ventilation

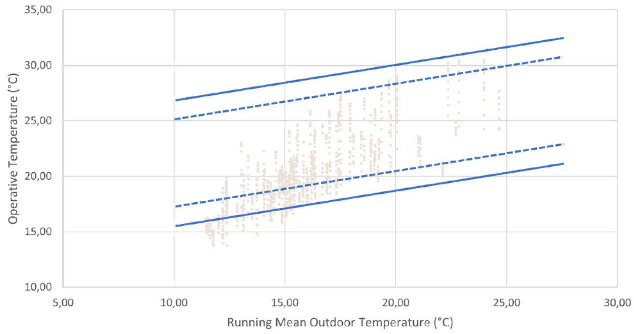

Fig.A22. Scatter plot of archetype E with occupant behaviour 2 with night ventilation

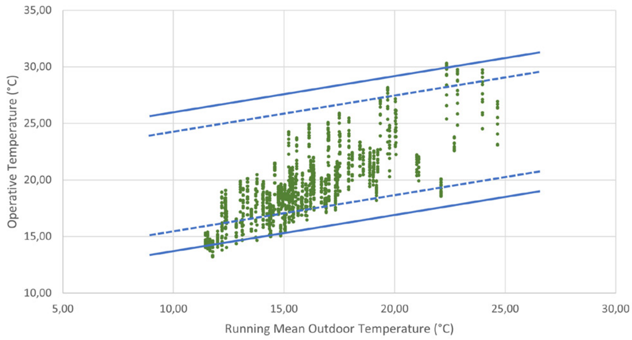

Fig.A23. Scatter plot of archetype E with windows always open

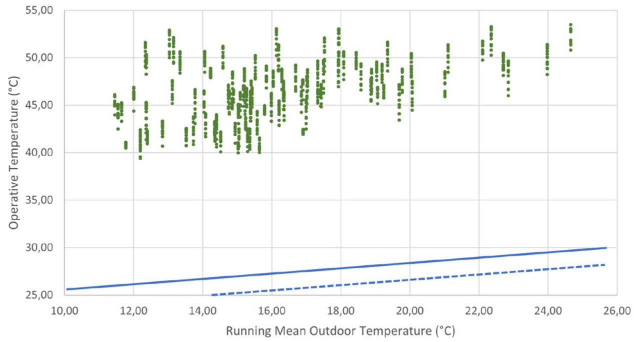

Fig.A24. Scatter plot of archetype E with windows always closed

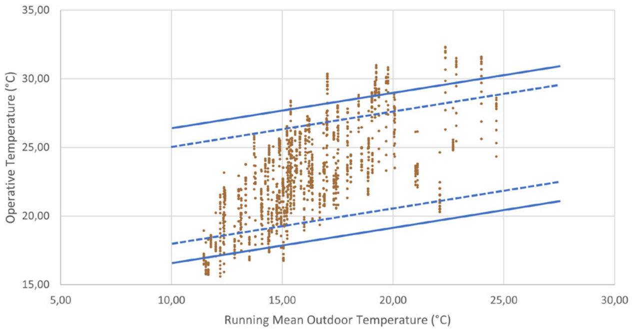

Fig.A25. Scatter plot of archetype E with occupant behaviour 1 without night ventilation

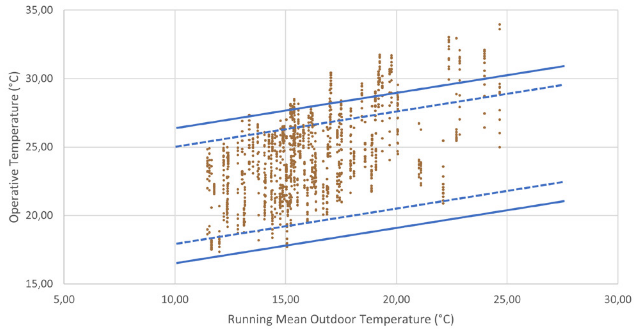

Fig.A26. Scatter plot of archetype E with occupant behaviour 2 without night ventilation

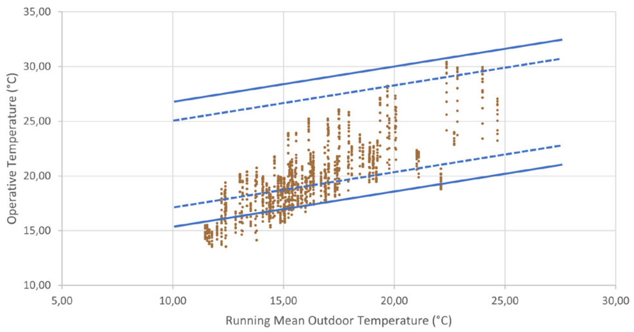

Fig.A27. Scatter plot of archetype E with occupant behaviour 1 with night ventilation

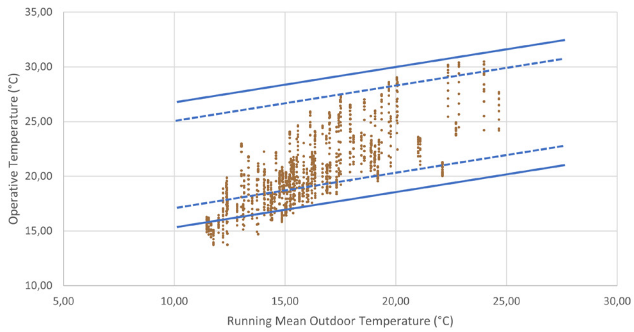

Fig.A28. Scatter plot of archetype E with occupant behaviour 2 with night ventilation

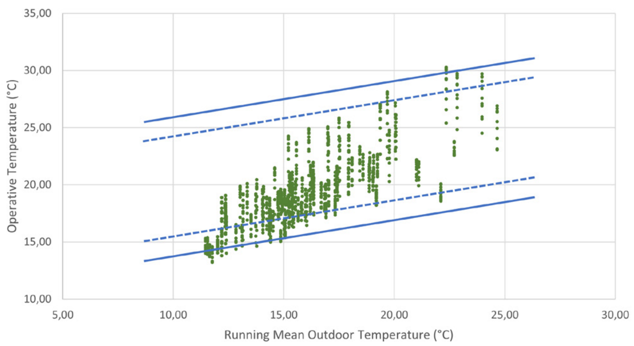

Fig.A29. Scatter plot of archetype E with windows always open

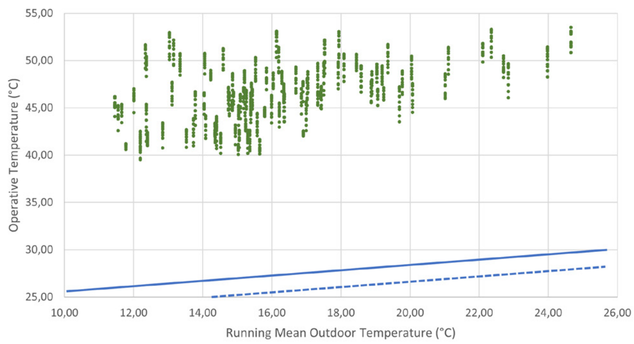

Fig.A30. Scatter plot of archetype E with windows always closed

A.2 EMS scripts for windows always open and windows always closed scenarios

```
<ForAllExternalWindows>
EnergyManagementSystem:Actuator,
   Venting_Opening_Factor_<LoopWindowVariableName>,
   <LoopWindowIDFName>,
   AirFlow Network Window/Door Opening,
   Venting Opening Factor;
<LoopNextWindow>

EnergyManagementSystem:ProgramCallingManager,
   Window_Operation,
   BeginTimestepBeforePredictor,
    WindowOperation;

EnergyManagementSystem:Program,
    WindowOperation,
   ! add program code
<ForAllExternalWindows>
         Set Venting_Opening_Factor_<LoopWindowVariableName> = 1,
<LoopNextWindow>
   ;


Output:Variable, *, AFN Surface Venting Window or Door Opening Factor, Timestep;
Output:Variable, *, AFN Surface Venting Window or Door Opening Factor, Hourly;
Output:Variable, *, AFN Surface Venting Window or Door Opening Modulation Multiplier, Timestep;
Output:Variable, *, AFN Surface Venting Window or Door Opening Modulation Multiplier, Hourly;
Output:Variable, *, Zone Operative Temperature, Timestep;
Output:Variable, *, Zone Operative Temperature, Hourly;
Output:Variable, *, Zone Outdoor Air Drybulb Temperature, Timestep;
Output:Variable, *, Zone Outdoor Air Drybulb Temperature, Hourly;
Output:Variable, *, Zone Air CO2 Concentration, hourly;
```

Fig.A31. EMS script for windows always open

```
<ForAllExternalWindows>
EnergyManagementSystem:Actuator,
   Venting_Opening_Factor_<LoopWindowVariableName>,
   <LoopWindowIDFName>,
   AirFlow Network Window/Door Opening,
   Venting Opening Factor;
<LoopNextWindow>

EnergyManagementSystem:ProgramCallingManager,
   Window_Operation,
   BeginTimestepBeforePredictor,
    WindowOperation;

EnergyManagementSystem:Program,
    WindowOperation,
   ! add program code
<ForAllExternalWindows>
         Set Venting_Opening_Factor_<LoopWindowVariableName> = 0,
<LoopNextWindow>
   ;

Output:Variable, *, AFN Surface Venting Window or Door Opening Factor, Timestep;
Output:Variable, *, AFN Surface Venting Window or Door Opening Factor, Hourly;
Output:Variable, *, AFN Surface Venting Window or Door Opening Modulation Multiplier, Timestep;
Output:Variable, *, AFN Surface Venting Window or Door Opening Modulation Multiplier, Hourly;
Output:Variable, *, Zone Operative Temperature, Timestep;
Output:Variable, *, Zone Operative Temperature, Hourly;
Output:Variable, *, Zone Outdoor Air Drybulb Temperature, Timestep;
Output:Variable, *, Zone Outdoor Air Drybulb Temperature, Hourly;
Output:Variable, *, Zone Air CO2 Concentration, hourly;
```

Fig.A32. EMS script for windows always closed

A.3 ANOVA tests

Groups	Count	Sum	Average	Variance
A_OB1_W	1224	24662	20,15	7,76
B_OB1_W	1224	24711,07	20,19	7,94
C_OB1_W	1224	24264,5	19,82	9,05
D_OB1_W	1224	24248,15	19,81	9,02
E_OB1_W	1224	24203,55	19,77	9,82
F_OB1_W	1224	24190,81	19,76	9,8

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	234,3	5	46,86	5,27	7,85E-05	2,21532
Within Groups	65302,68	7338	8,9			
Total	65536,99	7343				

Table.A1. Anova test conducted for operative temperatures of the six archetypes with occupant behaviour model 1 with night ventilation

Groups	Count	Sum	Average	Variance
A_OB2_WO	1224	30035,78	24,54	6,96
B_OB2_WO	1224	30047,49	24,55	7,01
C_OB2_WO	1224	29778,92	24,33	8,05
D_OB2_WO	1224	29769,24	24,32	8,05
E_OB2_WO	1224	29794,35	24,34	9,34
F_OB2_WO	1224	29786,56	24,34	9,37

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	73,62	5	14,72	1,81	0,10705	2,21532
Within Groups	59662,51	7338	8,13			
Total	59736,13	7343				

Table.A2. Anova test conducted for operative temperatures of the six archetypes with occupant behaviour model 2 without night ventilation

Groups	Count	Sum	Average	Variance
A_OB2_W	1224	25936,474	21,19	8,438
B_OB2_W	1224	25885,21	21,148	8,654
C_OB2_W	1224	25262,899	20,64	10,184
D_OB2_W	1224	25244,01	20,624	10,15
E_OB2_W	1224	25149,049	20,547	11,448
F_OB2_W	1224	25137,605	20,537	11,427

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	564,11	5	112,82	11,23	8,41E-11	2,21532
Within Groups	73748,89	7338	10,05			
Total	74313	7343				

Table.A3. Anova test conducted for operative temperatures of the six archetypes with occupant behaviour model 2 with night ventilation

Groups	Count	Sum	Average	Variance
A_O	1224	23940,62	19,56	8,12
B_O	1224	23963,19	19,58	8,17
C_O	1224	23731,48	19,39	9,34
D_O	1224	24238,57	19,8	9,81
E_O	1224	23762,72	19,41	10,07
F_O	1224	23749,61	19,4	10,04

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	155,31	5	31,06	3,36	0,00498	2,21532
Within Groups	67932,01	7338	9,26			
Total	68087,33	7343				

Table.A4. Anova test conducted for operative temperatures of the six archetypes with windows always open

Groups	Count	Sum	Average	Variance
A_C	1224	61741,91	50,44	4,89
B_C	1224	62787,88	51,3	4,36
C_C	1224	58035,78	47,41	7,88
D_C	1224	65746,97	53,71	11,32
E_C	1224	56699,43	46,32	9,69
F_C	1224	56808,42	46,41	9,62

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	55735,36	5	11147,07	1400,45	0	2,21532
Within Groups	58407,89	7338	7,96			
Total	114143,25	7343				

Table.A5. Anova test conducted for operative temperatures of the six archetypes with windows always closed

Groups	Count	Sum	Average	Variance
B_OB1_WO	1224	28154,43	23	10,52
B_OB2_WO	1224	30047,49	24,55	7,01
B_OB1_W	1224	24711,07	20,19	7,94
B_OB2_W	1224	25885,21	21,15	8,65
B_O	1224	23963,19	19,58	8,17
B_C	1224	62787,88	51,3	4,36

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	914627,46	5	182925,49	23525,78	0	2,21532
Within Groups	57056,87	7338	7,78			
Total	971684,33	7343				

Table.A6. Anova test conducted for operative temperatures of facade archetype B with occupant behaviour models 1 and 2 with and without night ventilation, with windows always open and closed

Groups	Count	Sum	Average	Variance
C_OB1_WO	1224	29794,35	24,34	9,34
C_OB2_WO	1224	29778,92	24,33	8,05
C_OB1_W	1224	24264,5	19,82	9,05
C_OB2_W	1224	25262,9	20,64	10,18
C_O	1224	23731,48	19,39	9,34
C_C	1224	58035,78	47,41	7,88

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	703464,9	5	140692,98	15674,9	0	2,21532
Within Groups	65863,59	7338	8,98			
Total	769328,49	7343				

Table.A7. Anova test conducted for operative temperatures of facade archetype C with occupant behaviour models 1 and 2 with and without night ventilation, with windows always open and closed

Groups	Count	Sum	Average	Variance
D_OB1_WO	1224	28147,38	23	10,52
D_OB2_WO	1224	29769,24	24,32	8,05
D_OB1_W	1224	24248,15	19,81	9,02
D_OB2_W	1224	25244,01	20,62	10,15
D_O	1224	24238,57	19,8	9,81
D_C	1224	65746,97	53,71	11,32

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1078269,41	5	215653,88	21978,51	0	2,21532
Within Groups	72000,72	7338	9,81			
Total	1150270,13	7343				

Table.A8. Anova test conducted for operative temperatures of facade archetype D with occupant behaviour models 1 and 2 with and without night ventilation, with windows always open and closed

Groups	Count	Sum	Average	Variance
E_OB1_WO	1224	28168,5	23,01	11,95
E_OB2_WO	1224	29794,35	24,34	9,34
E_OB1_W	1224	24203,55	19,77	9,82
E_OB2_W	1224	25149,05	20,55	11,45
E_O	1224	23762,72	19,41	10,07
E_C	1224	56699,43	46,32	9,69

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	655399,15	5	131079,83	12621,35	0	2,21532
Within Groups	76209,28	7338	10,39			
Total	731608,43	7343				

Table.A9. Anova test conducted for operative temperatures of facade archetype E with occupant behaviour models 1 and 2 with and without night ventilation, with windows always open and closed

Groups	Count	Sum	Average	Variance
E_OB1_WO	1224	28168,5	23,01	11,95
E_OB2_WO	1224	29794,35	24,34	9,34
E_OB1_W	1224	24203,55	19,77	9,82
E_OB2_W	1224	25149,05	20,55	11,45
E_O	1224	23762,72	19,41	10,07
E_C	1224	56699,43	46,32	9,69

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	655399,15	5	131079,83	12621,35	0	2,21532
Within Groups	76209,28	7338	10,39			
Total	731608,43	7343				

Table.A10. Anova test conducted for operative temperatures of facade archetype F with occupant behaviour models 1 and 2 with and without night ventilation, with windows always open and closed

A.4 Heatmaps for operative temperatures and window state

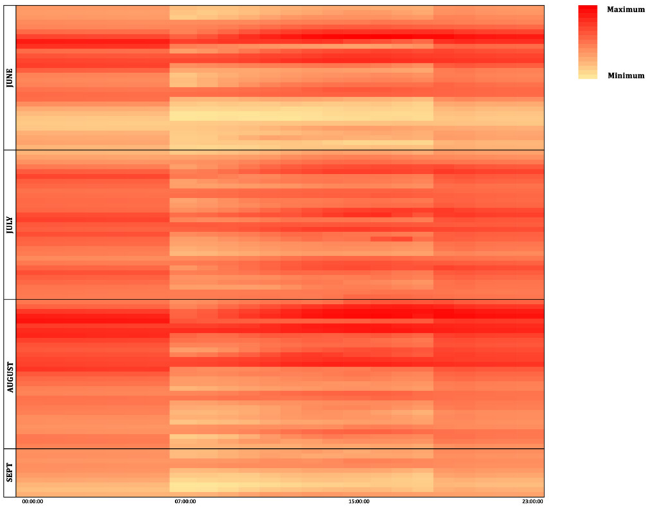

Fig.A33. Heatmap of operative temperatures for archetype B with occupant behaviour 1 without night ventilation

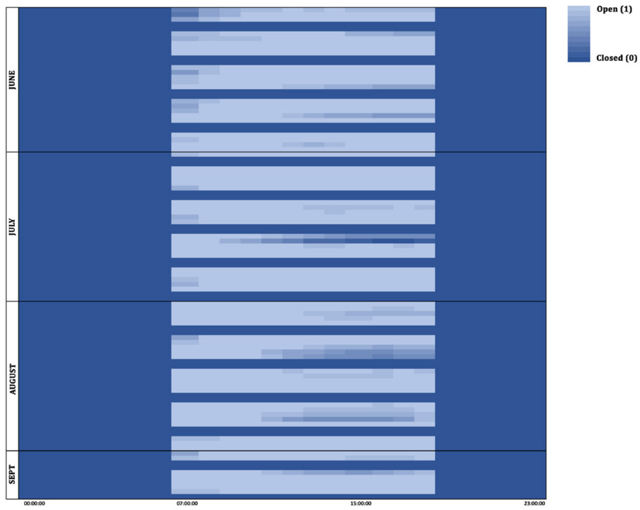

Fig.A34. Heatmap of Window state for archetype B with occupant behaviour 1 without night ventilation

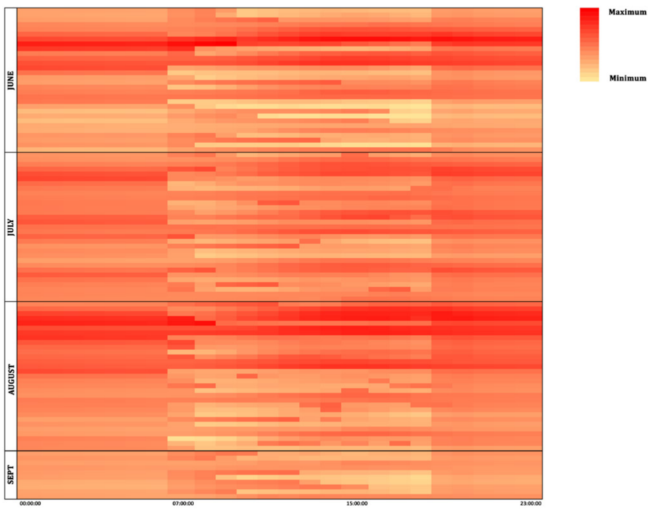

Fig.A35. Heatmap of operative temperatures for archetype C with occupant behaviour 1 without night ventilation

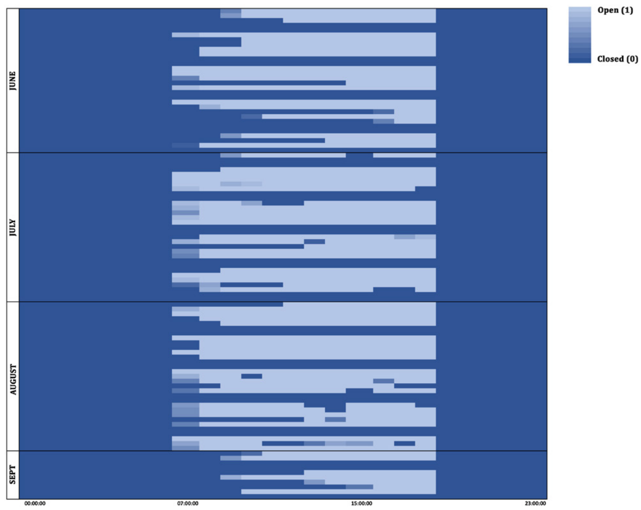

Fig.A36. Heatmap of Window state for archetype C with occupant behaviour 1 without night ventilation

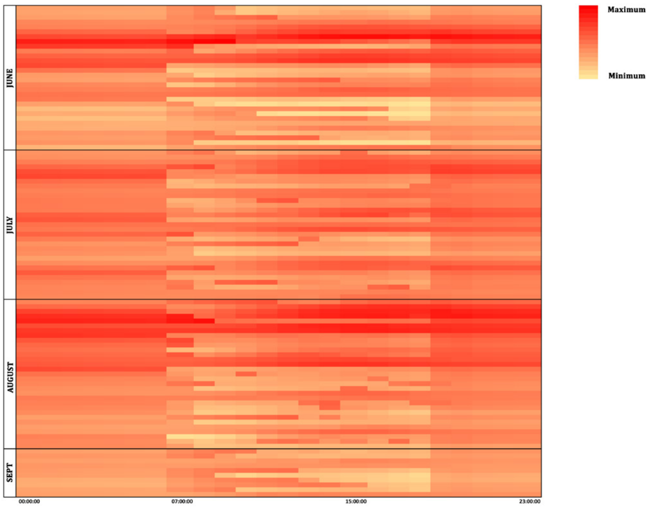

Fig.A37. Heatmap of operative temperatures for archetype D with occupant behaviour 1 without night ventilation

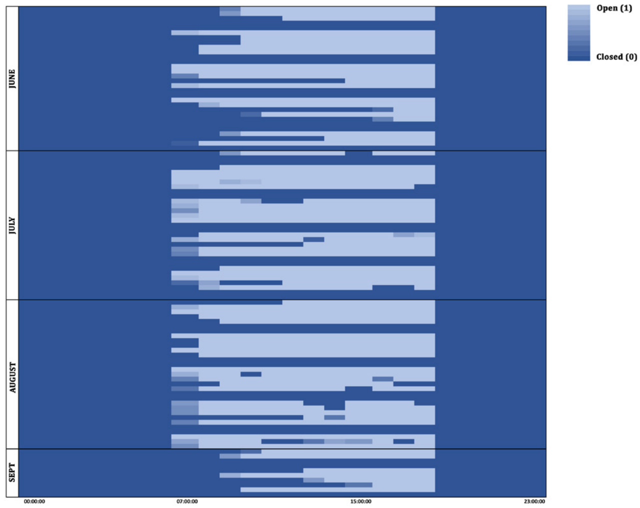

Fig.A38. Heatmap of Window state for archetype D with occupant behaviour 1 without night ventilation

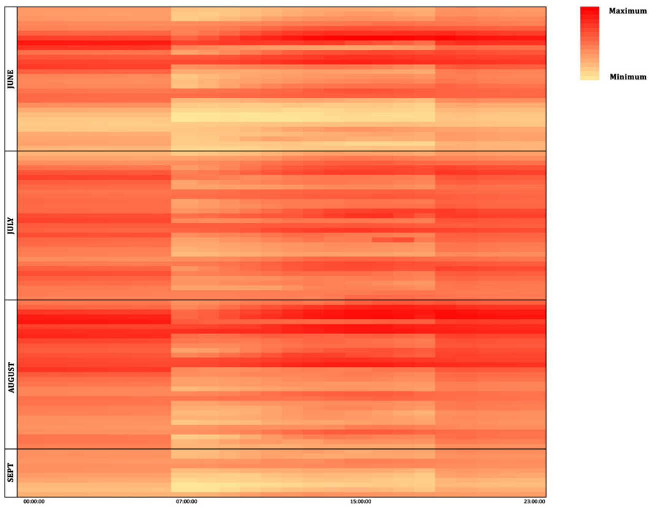

Fig.A39. Heatmap of operative temperatures for archetype E with occupant behaviour 1 without night ventilation

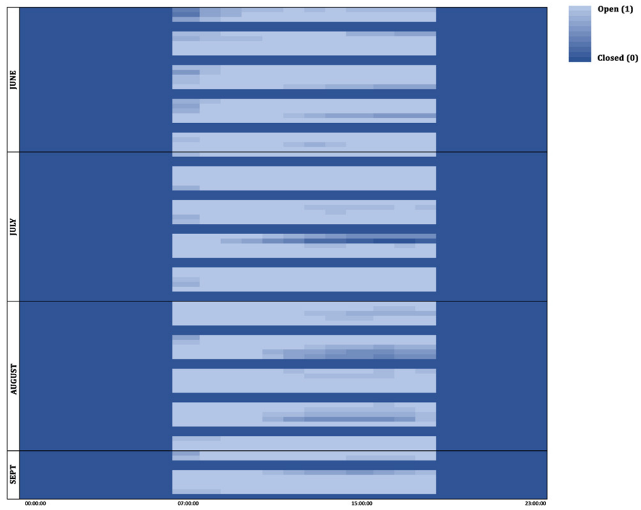

Fig.A40. Heatmap of Window state for archetype E with occupant behaviour 1 without night ventilation

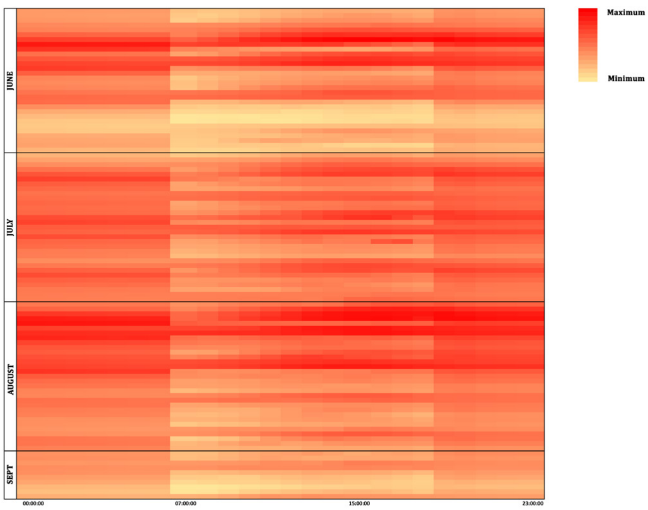

Fig.A41. Heatmap of operative temperatures for archetype F with occupant behaviour 1 without night ventilation

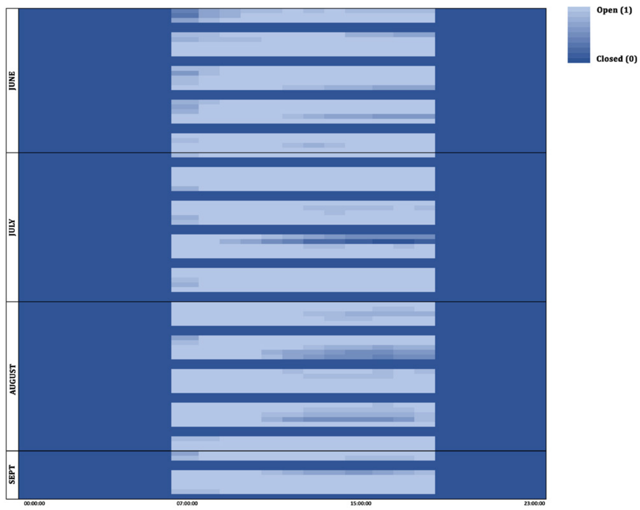

Fig.A42. Heatmap of Window state for archetype F with occupant behaviour 1 without night ventilation