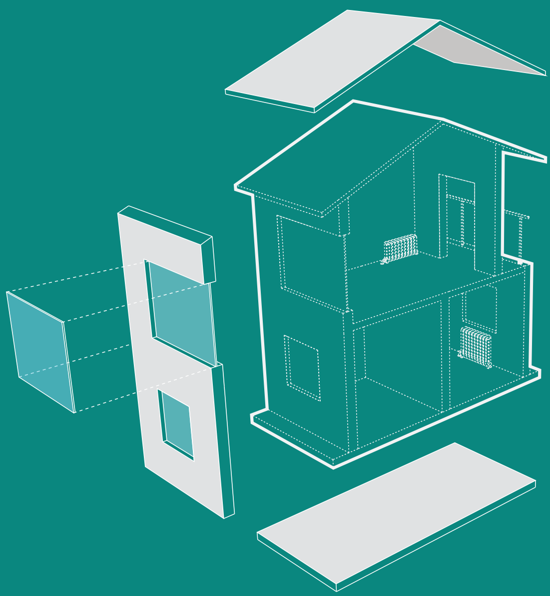
Robustness of Building Envelope

Investigating robust design solutions for energy efficient educational buildings.



Research Report

Sustainable Design Graduation Studio

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Sustainable Design Graduation Studio

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Cover Image: Passive Facade Strategy, Transsolar, Laboratory Building Agora, Lausanne, Switzerland

Abstract

Climate change has a progressive nature; thus, our buildings must be designed to be adaptive and resilient towards changing climate conditions. Passive design strategies applied to building envelope are crucial in reducing the energy demand and provide thermal comfort. However, it is essential to understand their performance in the presence of climate uncertainties. Therefore, the study investigated different passive strategies that could enhance the robustness of a building envelope to adapt and provide a comfortable indoor environment with the advent of changing climate in the future. The study focused on the educational buildings as the thermal discomfort due to overheating will certainly affect the productivity for the students. The study employed literature studies, analytical and dynamic simulations methods to develop workflows to indicate the extent of overheating risk in 2050 and 2085 climate scenario for both mechanically and naturally ventilated case studies. The workflows were also used for determining numerous passive design solution packages. The study used the statistical method of "best-case and worst-case scenario" to analyse the robustness of these solution packages. The study concluded that reducing WWR, fixed or dynamic shading, increasing albedo effect of the building envelope and mixed-mode ventilation strategy with PCM panels are the most robust passive design solutions. However, the study also found that ventilative cooling would have limited potential in reducing overheating in the latter part of the century.

Keywords: Adaptive Strategies, Passive Design Strategies, Building Envelope, Robustness Evaluations, Energy Efficient Buildings, Educational Buildings, Thermal comfort, Overheating , Future Climate Scenarios.

Contents

Preface

"We shape our buildings thereafter; they shape us" *– Winston Churchill.*

The famous quote from Winston Churchill, though used in a different setting and political agenda, often drives the designers to introspect and design space considering the adaptive nature of the users. However, this myopic approach needs to be rethought towards the context of the changing environment. Humans from many years have been deteriorating and exploiting their environment. It is only from recent years that a severe extent of saving our climate has been into action. Although, the changing climate, to some extent, is controllable but irreversible. In place of this context, the infamous quote from Churchill must be rethought, where

"We shaped the climate, therefore the climate will shape us."

The graduation topic with this background of climate change and its effects on the built environment is a part of a much broader societal context where its impact will disrupt the nature of the habitat and the way we design our buildings. There are numerous distinctive and long-term measures taken up to reduce carbon emissions, which is one of the critical reasons for this global phenomenon. Zero energy buildings or energy-efficient buildings are a response to this long-term goal. These high energy-efficient buildings aim at reducing carbon emissions by becoming independent from the use of fossil fuels and use a clean source of energy.

The highly energy-efficient buildings in temperate climate entail highly insulated and airtight building envelope to reduce heating energy in winters, but in summers, it causes the building to overheat. One of the significant indicators of climate change is the increasing outdoor mean temperature, which can cause indoor thermal comfort problems. With current climate projections, the future climate will become hotter, which will increase the overheating problems in energy-efficient buildings in the future. The buildings we design now will stand for the next 50 years and will undoubtedly face the climate change phenomenon. Therefore, it is imperative to investigate the design solutions which are robust for future climate change.

Acknowledgment

“We’ve always been defined by the ability to overcome the impossible. And we count these moments. These are the moments when we dare to aim higher, to break barriers, to reach for the stars to make the unknown known. We count these moments as our proudest achievements.”

- Cooper, Interstellar, 2014

The journey for this study has made me indebted to many people for guiding and helping me with the serious situations that I could not handle at some point in time and for boosting my morale high.

I want to express the deepest appreciation to my mentors Ir. Eric van den Ham and Dr. ing. Marcel Bilow for their immense help and prudent advice which always set up high goals for me. Without their supervision, excellent guidance, patience, and constant help, this thesis would not have been possible.

I owe my profound gratitude to Roy Beekman from Wolf Dikken Adviseurs for his help in infusing new thoughts and ideas in me. I would also like to thank Gilbert de Nijs, Anne Madema and Danny Pronk from CHP Plant TU delft, for helping me understand the details and monitoring of Pulse building.

Without support, No person is an island……, Especially when there is a pandemic.

When the tasks seem impossible, turn to your friends and family, they will remind you of your goals. I extend my thanks to my friends at Bout and building technology for their precious time and making the process interesting and ideas tangible to achieve. Also my lovely friends Anagha Yoganand, Ivneet Singh Bhatia, Divyae Mittal and Hamidreza Shahriari, for their cumbersome exercise of understanding the complexity of my topic and helping me out with it.

My thesis is incomplete without the tiresome efforts of my parents, who helped me understand that the time of lockdown and disappointment is a challenge and its worth fighting for.

A good thesis might not be a complete one, but a good thesis surely is a satisfactory one, for me, for my mentor and my family.

“May the odds be ever in your favor”

– President Snow, The hunger games, Suzanne Collins

Part 1

Research Design

1. Introduction

1.1 Context

Climate Change is one of the biggest threats which has detrimental impacts on natural and built environments. The climate change and global warming data published by NASA ("NASA: Climate Change and Global Warming," n.d.) states that the global temperature has increased by 0.9˚C since late 19th century and estimated to rise to 4.0˚C by the end of this century (Stocker et al., 2013, p. 1031). The constant rise in global temperature (fig 1.1) due to global greenhouse gas emissions (GHG) is the critical factor for this change in climate, and the building sector has a significant contribution to these emissions.

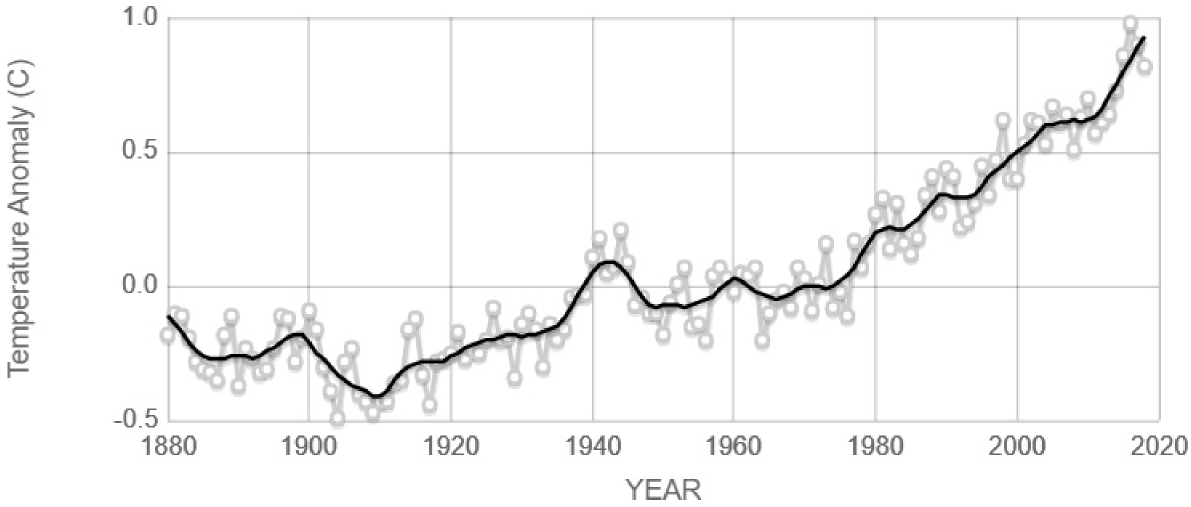


Figure 1.1 Change in Global surface temperature taking 1951-1980 average temperatures. The latest temperature anomaly recorded in 2016 as .8ºC . Source: climae.nasa.gov

In European Union, the building sector accounts for 40% of the primary energy consumption and 36% of the CO2 emissions, making them one of the biggest energy consumers as compared to transport, industry, and agriculture in EU ("Energy performance of buildings directive | Energy," n.d.; Tichaona Dande, 2018). To mitigate climate change, the European Commission has taken initiatives for the reduction of this energy consumption by introducing the Energy Performance of Building Directive (EPBD). The EPBD directive of 2010 focuses on reducing carbon emissions by 90% and restoring energy efficiency in building stock by encouraging the members to focus on zero energy buildings from 2020 onwards.

According to the EPBD, a zero-energy building is defined as a very high energy performance building that requires zero or low amount of energy, and this energy should be generated from renewable resources on-site or nearby. Throughout, every member state of the EU must comply with its definition and plan for the implementation of zero energy buildings.

1.2 Thermal Comfort Problems in Energy Efficient Buildings

To meet the targets laid by the European Union, the new construction and renovations in the Netherlands are following a national target of achieving 45-80% of energy saving in the built environment and nearly zero energy performance coefficient (EPC). The EPC includes energy performance of HVAC, DHW and lighting installations and building envelope insulations. (Hermelink et al., 2013, p. 100). To achieve an EPC close to zero, the primary design strategy is to reduce the energy consumption for space heating as low as possible. The energy is reduced by minimizing the heat loss due to transmission and ventilation and maximizing the solar gain resulting in highly insulated and airtight building envelopes (fig 1.2a).

Highly insulated building envelopes:
Reduce heat loss due to transmission

Increase Airtightness:
Reduce heat loss due to ventilation

Glazing Surface:
Maximum Solar gain for Passive Heating

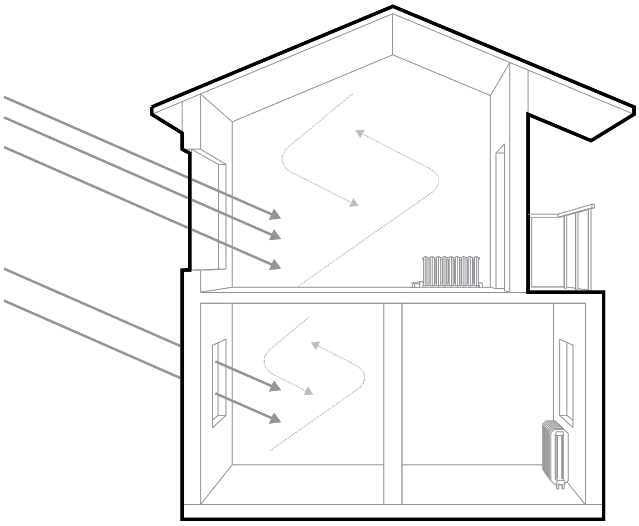


Figure 1.2a Primary Design Strategies in Temperate climate. The figure illustrates the design strategies used to reducing heating loads in winters.

Risk of Overheating

In summers , due to high insulations and airtightness of the building envelope , the heat gained during the day is unable to escape .

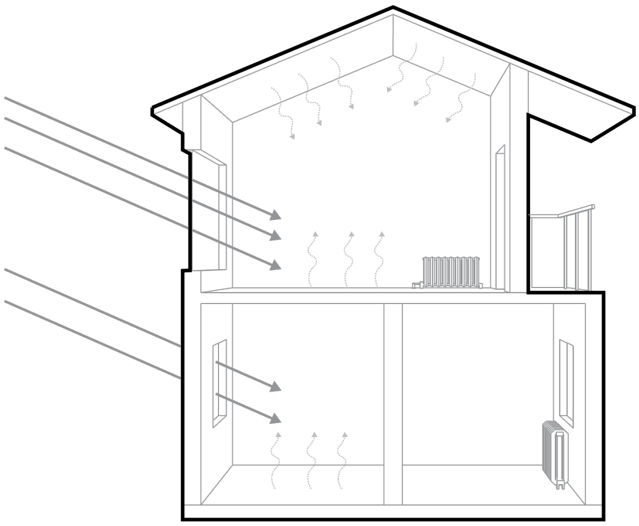


Figure 1.2b Risk of overheating in summer due to highly insulated and airtight building envelope.

However, these measures should not comprise the indoor thermal environment for its occupants. (Athienitis & O'Brien, 2015). Researches and case studies (Attia, 2018b; Barbosa, Barták, Hensen, & Loomans, 2015; Kazanci & Olesen, 2016) show that these energy-efficient buildings tend to develop indoor environmental quality issues like overheating of spaces (fig 1.2b).

Overheating is regarded as one of the essential causes of thermal discomfort and dissatisfaction among the occupants. In the worst-case scenario, it may also even lead to illness or death (Hamdy, Carlucci, Hoes, & Hensen, 2017). In the Netherlands, where the maximum temperature reached 40 ˚C in July 2019, it caused 2,964 deaths, which are 400 more than an average summer week, as mentioned by the Dutch National Statistics Agency(CBS, n.d.). A similar study by CBS(Garssen, Harmsen, & de Beer, 2005) shows a correlation between elevated temperatures and increased death rates. With the projected rise in temperature due to climate change, the thermal comfort problem of overheating in the future may become severe in these energy efficient buildings.

1.3 Thermal Comfort in Educational Buildings

90% of the occupants spend their time indoors, and for students, it is even more (Heracleous & Michael, 2018). The Netherlands accounts for almost 3.2 million students in primary and secondary schools in 2017, while 290,000 university students in 2018 (CBS, n.d.). Educational buildings are one of the essential building stocks which ought to undergo energy efficient designs and renovations. The EPC requirements are, however, rigorous from 0 to 0.7. Therefore, educational buildings require a significant amount of energy reduction as per the Dutch regulations for zero energy buildings (Golshan, Thoen, & Zeiler, 2018).

However, energy-neutral educational buildings exhibit the problems of poor indoor quality (Shadmanfar et al., 2019). Through literature research, it was found that there is a high correlation between the thermal comfort and performance of the students (Heracleous & Michael, 2018; Jenkins et al., 2009). With the increasing risk of climate change and its effects on indoor thermal comfort, it is imperative to study the risk of overheating in an educational energy neutral building.

1.4 Robustness of Energy Efficient Buildings

Overheating in energy efficient buildings is caused due to the heat trapped in the highly insulated building envelopes majorly during the summer period. The risk of overheating is expected to increase with the rise of outdoor temperature due to climate change. (Attia, 2018c; R Kotireddy, 2018). Therefore, it is imperative to consider the effects of changing climate on our built environment and how to design for such future climate scenarios.

In current design practice, there are numerous assumptions made concerning energy performance and indoor comfort to determine building performance in its lifespan. However, in practice, the buildings do not perform as expected, resulting in a performance gap (S. Juricic, 2011; Rajesh Kotireddy, Hoes, & Hensen, 2017b). The performance gap can be understood as the difference in the assumed performance and performance in the operation of a low energy building (Attia, 2018b).

According to Moazami (2019), one of the primary reasons for the performance gap of energy-efficient design is the exclusion of the uncertainties of the future climate. To ensure the performance of the building regarding energy efficiency and thermal comfort, the buildings should be designed to have a high tolerance towards the uncertainties of climate change. Buildings with these characteristics and profiles which can withstand the uncertainties of its operation are said to be robust (S. Juricic, 2011; Rajesh Kotireddy et al., 2017b; van den Ham, Leyten, & Kurvers, 2007)

1.5 Climate Adaptive Strategies

While a robust energy-efficient building design is insensitive to the variations due to external climatic conditions and indoor comfort requirements, it is essential to think about the strategies which can contribute towards a robust building. The building characteristics and strategies which can adapt to the effects of climate change while maintaining the energy balance of the energy-efficient buildings can make designs tolerant and adaptive for future climates. Therefore, it is essential to research such solutions that could be incorporated into the early design stage for promoting robust designs in low energy consumption buildings.

2. Research Framework

2.1 Problem Statement

To fulfil the targets set by the European Union, the Netherlands aims at achieving 45-80 % of energy reduction in their built environment with an 80% reduction in the heating consumption by 2050. To achieve these stringent goals, the focus is on the deep renovation of existing buildings and the new buildings to be nearly zero-energy or highly energy efficient from 2020 onwards. For reducing the heating energy consumption, the building design focuses on accentuating the passive solar gain and minimising the heat loss through the building envelope. Though these strategies can significantly reduce the heat consumption in winter, it creates thermal comfort problems in summer by increasing the risk of overheating.

However, according to the trends of climate change, there will be an increase in the global outdoor temperature which will increase the risk of overheating and affect the performance of the building. Thus, the future warm climate will result in an increase in the cooling demand, negating the energy efficiency of the building.

Educational buildings are one of the essential building stocks which will undergo energy renovations and energy efficient building design. Through literature research, it was found that there is a high correlation between the thermal comfort and performance of the students (Heracleous & Michael, 2018; Jenkins, Peacock, & Banfill, 2009). With the increasing risk of climate change and its effects on indoor thermal comfort, it is imperative to study the risk of overheating in an educational energy efficient building.

Climate change has a progressive nature; thus, our buildings must be designed to be adaptive and resilient towards changing climate conditions. Passive design strategies applied to building envelope are crucial in reducing the energy demand and provide thermal comfort. However, it is essential to understand their performance in the presence of climate uncertainties. Therefore, it is imperative to analyse different passive strategies that could enhance the robustness of a building envelope to adapt and provide a comfortable indoor environment with the advent of changing climate in the future.

2.2 Research Questions

For the study, the main research question was formulated as the main driver for the research process. The primary research question was then subdivided into sub research questions to answer the main question cohesively. Furthermore, few key questions were also formulated among the sub research questions as means to compartmentalise the research process. The hierarchy of research questions from main research questions to key questions was instrumental in enhancing the research process as well to track the progress in parallel with time planning and organisation.

According to the problem statement stated in section 2.1 to investigate the different passive strategies that could enhance the robustness of a building envelope, the main research question was formulated as:

*What are the **adaptive strategies** in a temperate climate, applicable to **building envelope** facilitating **robustness** of **energy efficient educational buildings** by reducing the risk of **overheating** in **future climate** change scenario?*

To answer the primary research question, a few sub-questions are devised. These sub-questions were further divided into key questions which helped explore different aspects of the research thesis:

1. What are the influential parameters corresponding to building envelope design?
    1.1. What is the role of building envelope in maintaining thermal comfort and energy efficiency?
    1.2. What are the energy-efficient guidelines for building envelope in the context of the Netherlands?
2. What are the factors that contribute to the overheating of space?
    2.1. What is overheating
    2.2. What are the sources of overheating?
3. What are the potential spaces which may overheat in case study buildings?
    3.1. What are the thermal comfort guidelines for educational buildings in the Netherlands?
    3.2. What are the overheating thresholds in the Netherlands?
    3.3. What are the precedence studies for the overheating problem in educational buildings?
    3.4. How to identify the spaces which may overheating in the case study buildings?
4. What is the potential risk of overheating in educational buildings in the present and future climate scenarios?
    4.1. What are the future scenarios to be considered for evaluation?
    4.2. How to identify the risk of overheating using analytical calculations?
    4.3. How to validate the analytical tool for identifying and measuring the overheating in educational buildings?
    4.4. How to use a dynamic simulation tool to identify the risk of overheating?
5. What are the adaptive design strategies in temperate climate available for building envelope?
    5.1. What are the different passive design strategies in temperate climate available, which could reduce the risk of overheating?
    5.2. Which among the passive strategies found in key question 5.2 is applicable for building envelope?
    5.3. When in the building lifespan, these strategies should be incorporated?

6. How to evaluate the robustness of different design solutions in mitigating overheating problems in the present and future climate scenarios?

    6.1. What is robustness in the context of energy efficient buildings?

    6.2. What are the assessment methods available in the literature to evaluate the robustness of a design?

    6.3. What are the different parameters needed to evaluate the robustness of a design?

7. How robust are different passive design building envelope solutions?

8. How to incorporate robustness in the design process for architects and designers ?

2.3 Research Objectives

Energy-efficient buildings tend to develop the risk of overheating in summer. The risk is likely to increase with the increasing outdoor temperature. Reducing overheating of space would require either active or passive measures to cool the building. The active measures can account for extensive cooling loads; therefore, it is imperative to use passive design measures.

As climate change is a moving target, it accounts for the passive design strategies that are adaptive or climate-responsive. The passive design strategies apply to various levels of design like the site, building, spatial or component level. However, the building envelope acts as a barrier between the exterior and interior will play a significant role in reducing or accentuating the risk of overheating. Therefore, the study will focus on passive design measures, which can be incorporated well into the building envelope.

Henceforth, the primary objective of the study is to investigate the passive design strategies applicable to the building envelope, which can increase the robustness of energy efficient buildings in providing thermal comfort in future climate scenarios. Furthermore, the study will also provide robust solution packages for building envelope as initial design development, post-occupancy, or renovation strategies.

The research also aims at using building energy modelling as a dynamic tool over the case study of educational buildings to evaluate the robustness of the passive strategies on building envelope to assess the risk of overheating in the present and future.

2.4 Expected End Products

The study aims at providing a descriptive comparative analysis of different passive design strategies for building envelope, which are robust for future climate change. Furthermore, the study will also provide robust solution packages for building envelope as initial design development, post-occupancy, or renovation strategies.

Through the means of this study, the work flow designed to evaluate robustness can act as an indirect end product that can be utilised for further research into this field.

Finally, the research aims at proposing an excel based tool for architects and designers to help them understand the impact of design decisions on summer comfort and provide insight towards robust design solutions for future climate.

2.5 Boundary Conditions

For narrowing the scope of the research, certain boundary conditions were set. These boundary conditions were instrumental in focusing the direction of the study.

1. The study only focuses on the thermal comfort aspects of energy efficient buildings.
2. There are numerous indicators of climate change, like temperature rise, water, soil, and so forth. For this study, temperature as an indicator of climate change is considered.
3. The passive design strategies are narrowed to applicable for temperate climate only.
4. For the study, the context of only educational buildings is considered.

2.6 Research Design

The research followed a design by research and followed by research by design methodology. To be able to answer the research questions, the research is designed into five different stages. These stages are divided to overlap with deliverables of respective presentations from P1 to P5. The organization of these stages and interconnection is illustrated in figure 1.3

P1: Background Studies

In this stage, initial background and contextual studies were done to understand in-depth knowledge of the problem. Initially, keywords that are general to the topic, such as climate change, zero energy buildings, thermal comfort problems, overheating, and robust design, were used to find articles, blogs, videos, research, and journal papers. The studies helped to understand the bigger picture and to understand the context of the problem. The context studies further helped to structure literature studies.

P2: Problem Definition and Literature Studies.

The contextual studies helped to narrow down the topic into the specific problem statement. The problem statement was further developed into specific research objectives and goals. To structure the research in a more comprehensive and evaluative way, the main research questions, sub-questions, and key questions were developed.

To answer the research questions, literature research was conducted. Specific keywords such as Robustness assessment, Energy-efficient buildings, Building envelope guidelines, Thermal Comfort guidelines, Overheating Thresholds, Overheating Assessment, Adaptive Strategies, and Passive strategies in Temperate climate were used to search scientific papers, research thesis, journal papers, and Ph.D. thesis. Databases like Web of Science, Google Scholar, Science Direct, Scopus, Tu Library were used as a credible source of information. The papers were assessed based on the journals they were published in and the credentials of the authors. The quality of the papers was assessed based on the objectivity of the research presented by the author.

The results from the literature studies were used to further develop a workflow for the assessment and evaluation of case study buildings.

P3: Data Collection and Case Study analysis

The results of the literature study were then used to formulate a detailed workflow to model, assess, simulate, and evaluate the case studies.

Two case studies of the educational building were selected. The two case studies represent a broad spectrum of educational buildings where one is a university building while the other is a secondary school building. To analyze the case studies with the designed workflow, data was collected based on input parameters needed for simulation and assessment of overheating.

After data collection, spaces were analysed using both empirical studies and analytical calculations to identify the spaces which have the potential of overheating.

P4: Robust Design Selection

After identification of spaces that may overheat, building simulation models were created and calibrated. These spaces were simulated in the present, 2050, and 2085 climate scenarios to determine the extent of the overheating problem. The simulations will also further help to support the literature studies if the problem is due to building envelope or any other reasons.

After the identification of the problem, passive adaptive strategies were selected based on the context of case studies. These strategies were simulated again individually in different climate scenarios to observe their impact on overheating. Along with that, these were also evaluated for robustness. Based on their robustness, design solution packages were made, and robustness was rechecked to analyse the combined effect of these strategies on overheating.

P5: Designer's Tool and Conclusions

The final set of guidelines to develop a future-ready solution were developed. The final set of conclusions will also be drawn, and suggestions for further research were made. The guidelines will be used as a base to develop a tool for designers to include robustness in their design process.

2.7 Planning and Organization

To achieve the research results in designated time, an overview of weekly objectives with the amount of weeks allocated to each task is illustrated in figure 1.4

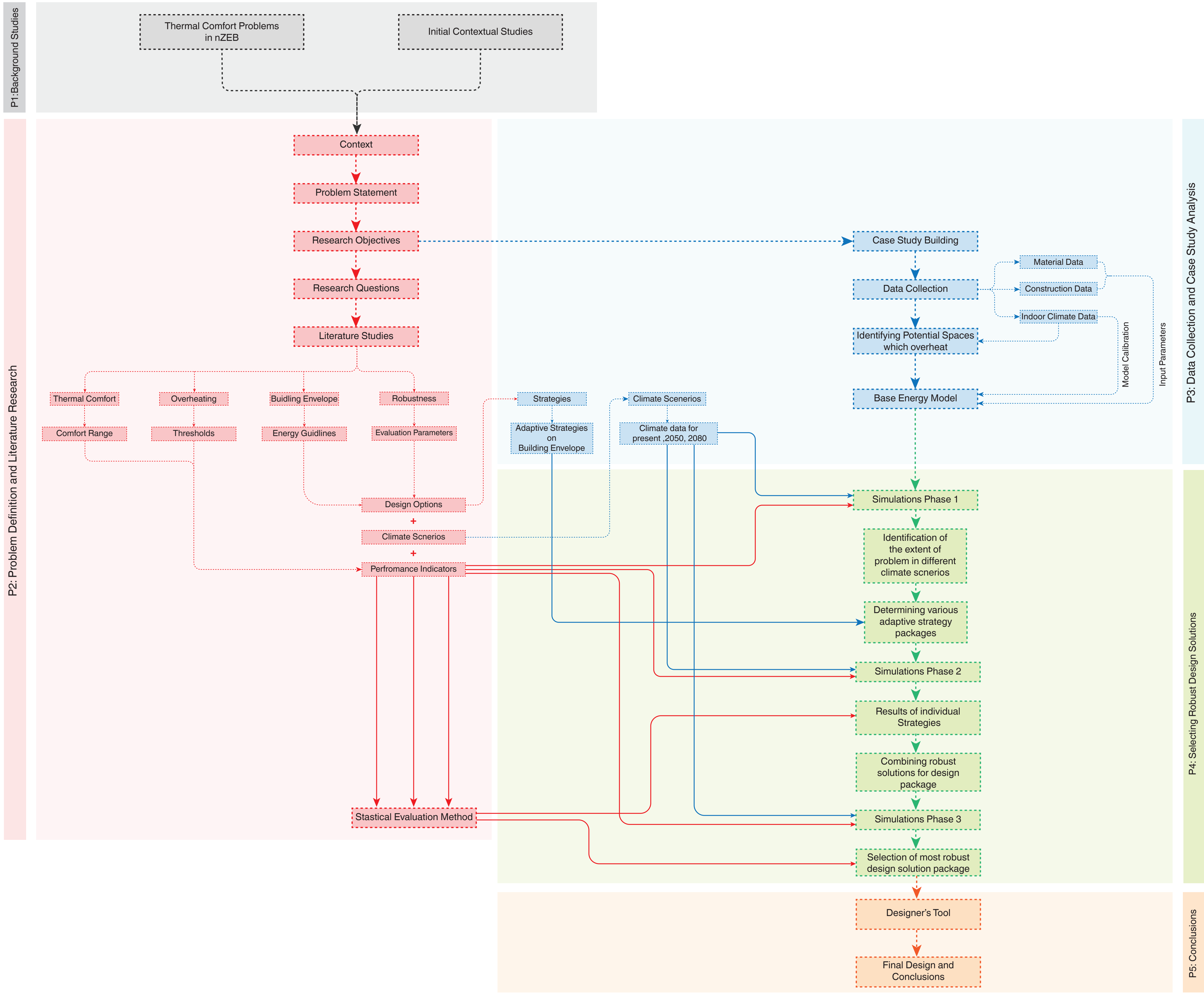


Figure 1.3 Research Design Methodology.

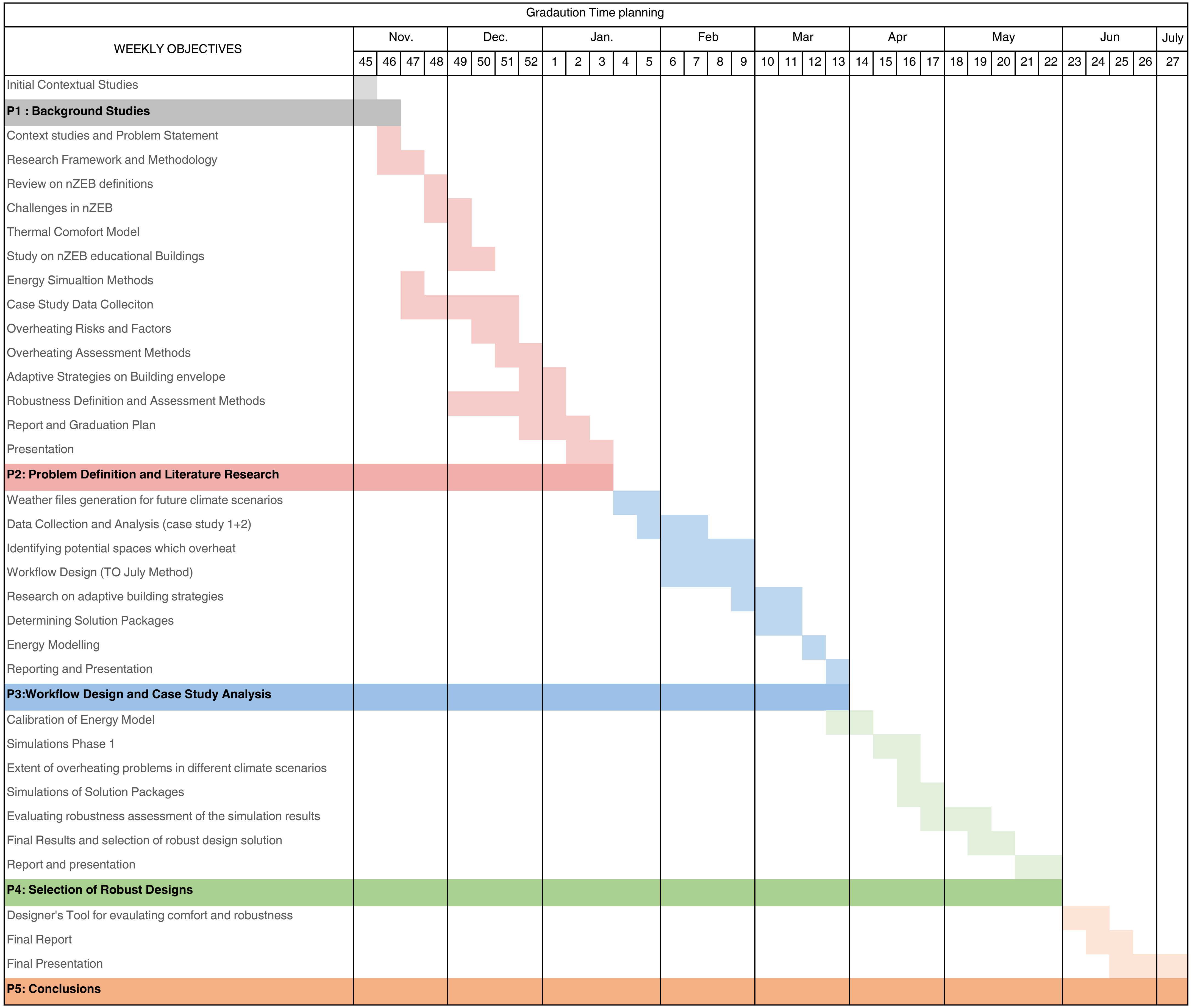


Figure 1.4 Weekly Time Planning and organisation of Research.

Part 2

Literature Review

3. Role of Building Envelope

The building envelope is essentially analogous to the human skin but for our built environment. Comparable to the human skin, the building envelope behaves as a protection layer between the indoor environment and external conditions. In building design, building envelope plays a crucial role in providing comfort while maintaining energy efficiency. According to the Technological Roadmap for Energy-Efficient Building Envelopes by International Energy Agency (2013), efficient envelope design can reduce as much as 60% of the heating and cooling demands depending on the context. Therefore, to understand further, this chapter will explore different components of a building envelope and its impact on energy efficiency and thermal comfort. Furthermore, Dutch guidelines for these components will also be discussed.

3.1 Building Envelope Components

The building envelope can be defined as the physical barrier or interface between the conditioned interior space and the external environment. The inherent characteristics of the building envelope to provide indoor comfort by regulating environmental factors like solar radiation, air temperature, precipitation, wind speed, and humidity passively plays a dual role in maintaining occupant comfort and energy savings. A building envelope is a group of building elements (fig 3.1) such as external walls, roofs, floors, foundations, windows, and doors (International Energy Agency (IEA), 2013). Based on the function of the component to limit the outdoor environment into the inside, the components can be divide as opaque or transparent components. The opaque components like the roof, external wall, floor, and foundation contribute towards regulating the heat gain or loss through transmission and infiltration while the transparent components constitute the windows, doors, skylights which regulate the heat gain or loss via sun or ventilation (Al-saadi, 2006).

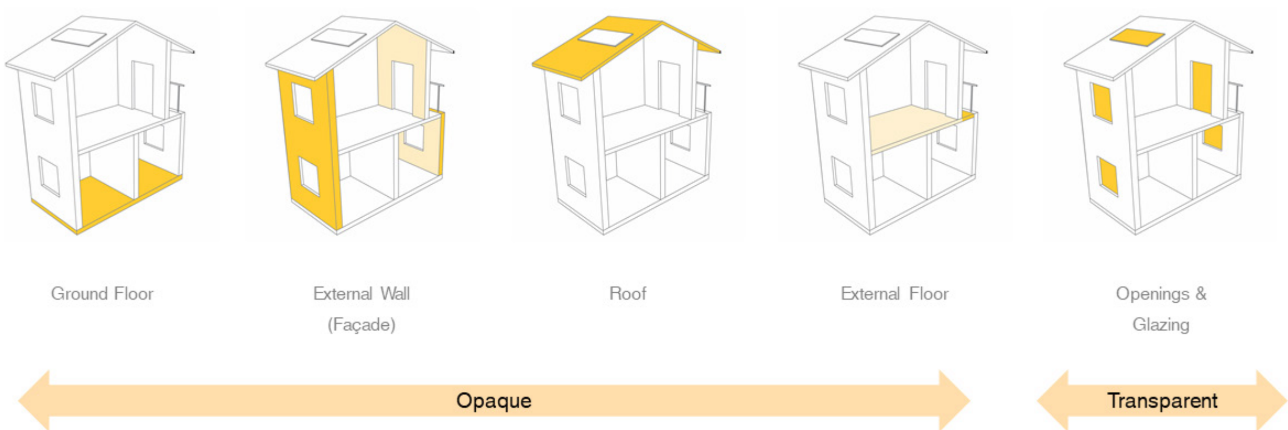


Figure 3.1. Building Envelope Components, opaque and transparent elements.

3.2 Functional Requirements

3.2.1 Thermal Insulation

The envelope being in direct contact with the external environment undergoes various heat exchanges via conduction, convection, and radiation. The heat gain or loss by the building fabric through heat transmission, heat storage, ventilation, infiltration and solar loads have a significant impact on the comfort and energy consumption (Al-saadi, 2006; Knaack, Klein, Bilow, & Auer, 2014). The role of thermal insulation in the fabric is thus essential to regulate the heat losses or gains depending on the context. For instance, a poorly insulated envelope in a heating-dominated climate will result in higher heat loss increasing the heating loads. Similarly, in cooling dominated climate, the heat gain through building envelope can cause an increase in indoor temperature resulting in extensive cooling loads. Therefore, thermal insulation is an important requirement for the building envelope.

The thermal resistance of the building envelope is represented as the conductive heat flow between a material of 1m thickness and surface area of 1 m^2 till achieving a temperature difference of 1 K (1°C) (Chinazzo, 2015). This thermal resistance is represented as R-Value which is calculated according to equation 2.1(Dobbelsteen, Ham, Blom, & Leemeijer, 2019)

$$R = \frac{d}{\lambda} \left[\frac{m^2K}{W}\right] \qquad (2.1)$$

Where :

R	Thermal Resistance	m^2K / W
d	Thickness of the material	m
λ	Thermal Conductivity of the material	W/m.K

From equation 2.1, it can be observed that the insulation value is dependent on the thickness of the material. Thus, it corresponds to the fact that building fabric comprises of many layers with different insulation values to achieve the desired thickness. The insulation values for various components like roof, floor, external wall are specified in the Dutch standards, which will be discussed further in the chapter.

3.2.2 Transparent Elements (Glazing)

Transparent elements of the envelope account for the openings in the external wall or the façade of the building. It comprises of the elements for solar entry such as windows, skylights, external doors. The transparent openings also account for heat gain or loss through transmission and infiltration. One of the significant factors associated with heat control is the thermal bridges.

Thermal bridges are spots of low thermal insulation developed due to the connection between different envelope components (Dobbelsteen et al., 2019).

The windows for the building envelope must be determined based on four essential factors namely U-Value of the frame, U-value of glass, Solar heat gain coefficient of glass (SHGC), Visual Light Transmittance of glass (VLT)(Dobbelsteen et al., 2019; International Energy Agency (IEA), 2013).

U-Value of Frame and Glass

As mentioned earlier, the R-value is described as the thermal resistance of the material as a measure for the insulations in the opaque part of the envelope. On the contrary, the insulation of the window frame and glass are measured as the amount of heat transfer through conduction and radiation represented as U-value (Bokel, 2017). The U-value is calculated as the inverse of the R-value mentioned in eq 2.1. When determining the U-value of the window, it is essential to consider the combined effect of window and frame (Dobbelsteen et al., 2019).

Solar Heat Gain Coefficient

The Solar heat gain coefficient (SHGC) value indicates the amount of solar heat gain through transmission from the glazing. It is also expressed as g-value and represents a value between 0 and 1, where 1 represents 100% of solar heat transmission of the incident solar radiation (Bokel, 2017).

Visible Light Transmittance

The visible light transmittance value (VLT) represents the amount of visible light that can enter the building through the glazing. The VLT value is essential to control optimum daylighting inside the building. Lower VLT may result in increased lighting loads, while higher VLT may cause glare (Bokel, 2017).

3.2.3 Infiltration

The heat loss or gain due to infiltration occurs due to the air leakages within the building envelope. Poor construction practices, testing, and lack of standards can result in air leakages in the building fabric(Al-saadi, 2006). The building envelope must be airtight to reduce any energy loss as well to reduce the risk of local discomfort. However, if the fabric is entirely airtight, it will result in Indoor Air quality problems. Therefore, a certain amount of infiltration should be allowed; however, as low as possible(International Energy Agency (IEA), 2013).

3.2.4 Ventilation

Ventilation is an essential functional requirement for the building envelope to maintain the Indoor Air quality to maintain the CO^2 levels generated by the occupants (Knaack et al., 2014). Ventilation is also essential in maintaining indoor thermal comfort by introducing fresh air and providing a medium for heating and cooling of the space. The heat loss due to ventilation is another aspect that governs the energy loads of the building. The ventilation method generally adapted is based on air supply and air extract, which is done either naturally through windows and openings or mechanically (Dobbelsteen et al., 2019; Knaack et al., 2014).

3.2.5 Thermal Mass

The thermal mass of light or heavyweight construction also affects the thermal comfort of a space. Where the lighter construction can heat and cool quickly, a heavyweight construction provides a time lag of storing and releasing the energy (Dobbelsteen et al., 2019). Therefore, the appropriate selection of construction is needed, along with other factors like insulation, ventilation, openings, and infiltration.

3.3 Building Envelope Guidelines in the Netherlands

The Dutch Building Decree or Bouwbesluit provides regulations and guidelines concerning the construction, demolition, and usage of the buildings in the Netherlands (Rijksoverheid.nl, n.d.). The building decree under chapter 3 provides technical guidelines concerning the minimum ventilation required in a space, while Chapter 5 illustrates technical requirements for the insulation levels of building envelope concerning promoting energy efficiency. These regulations are provided for both residential and non-residential buildings like offices, educational spaces. However, for the study, we will only consider the regulations for educational spaces.

According to Building Decree (2012), the insulation R-values for the roof, external wall, and external floors must be used as 6 m^2.K/W, 4.5 m^2.K/W and 3.5 m^2.K/W respectively. The U-value of external windows, including frame and glass, must not be more than 1.65 W/ m^2.K. The building decree also states the minimum ventilation rate of 8.5L/s per person for educational buildings for designing ventilation systems (Rijksoverheid.nl, n.d.).

Although the regulations stated in the decree represent the current practices, these regulations will be tightened from January 2021 with the inclusion of a Technical agreement document called NTA 8800. The NTA 8800 was drafted to enable the construction of nearly zero-energy buildings from 2021 onwards. According to NTA 8800, minimum thermal insulation values for the roof, external wall, and the external floor have been suggested as 6.3 m^2.K/W, 4.7 m^2.K/W, and 3.7 m^2.K/W respectively (NEN, 2019).

3.4 Conclusions

The building envelope is the physical barrier between the outdoor and indoor environments. The key components of the envelope can be classified as opaque and transparent elements, where the opaque parts correspond to building roof, external wall, and floors while the transparent part relates to the glazing and openings.

The building envelope primarily regulates the heat transfer between inside and outside conditions. The heat gain or loss from the building envelope, dictates both comfort and energy usage of the building. Therefore, the building envelope must have the functional requirements of appropriate insulation levels to control heat gain and loss through transmission, storage, ventilation, and infiltration. According to the Dutch regulations NTA 8800, the minimum insulation R-values for the roof, external wall, and the external floor is specified as 6.3 $m^2.K/W$, 4.7 $m^2.K/W$ and 3.7 $m^2.K/W$ respectively, whereas the heat transfer from the windows must be limited to the maximum U-Value of 1.65 $W/m^2.K$ including glazing and frame.

Ventilation is another aspect of the building envelope in providing optimum indoor air quality by regulating the CO2 generated by the occupants. Similarly, it also controls the indoor climate by providing a medium for heating and cooling. The ventilation strategy can be incorporated in the building envelope either by natural means or mechanical means. According to W2012, for an education building, a minimum of 8.5 l/s per person must be used in designing ventilation openings or mechanical systems.

4. Thermal Comfort

The energy use for providing indoor comfort (heating, cooling, ventilation) consumes more than 50% of total primary energy and acquires a significant part in the energy balance of the building for both residential and commercial buildings (Pérez-Lombard, Ortiz, & Pout, 2008). Therefore, for energy efficient buildings, the primary focus is on reducing the energy demands for space conditioning. However, while doing so, it should not comprise the quality of indoor comfort. Therefore, the objectives of thermal comfort must be explicitly defined in the process of designing a low energy building (Athienitis & O'Brien, 2015).

According to ASHRAE-55 (2010, p. 4), thermal comfort regards to the satisfaction of the state of mind corresponding to the thermal environment of a person who dwells in it. The thermal comfort, however, has been defined based on three approaches, namely: Physiological, Psychological, and a static or rational approach (Athienitis & O'Brien, 2015). To predict thermal comfort, there are many models and metrics developed in due course of time. Although these models can be grouped into two major categories to determine the human thermal response in an environment, these are Rational or Static model and Adaptive Model (Athienitis & O'Brien, 2015).

In this section, we will review these models of thermal comfort, followed by thermal comfort guidelines for educational buildings in the Netherlands.

4.1 Static Model

The static model uses heat balance equations to determine the thermal comfort conditions of the occupants. Various thermal comfort indices were developed out of which Fanger's predicted Mean Vote (PMV) and Predicted People Dissatisfied (PPD) model is widely used. In 1970 Fanger proposed the model by studying the heat exchanges between occupants and its environment through laboratory studies (Pouniou et al., 2019). The model analyses six parameters that have an influence on thermal sensation, such as air temperature, mean radiant temperature, air velocity, relative humidity, activity level, and clothing value under steady-state conditions (Hoof, Mazej, & Hensen, 2010).

To determine the deviation from the comfort level, Fanger proposed two indices The Predicted mean vote (PMV) and the Predicted Percentage of dissatisfied (PPD) (Hoof et al., 2010). The PMV is an index that predicts the thermal sensation of occupants derived from the thermal comfort equation. PMV helps in estimating the average values of thermal sensations vote, which can also be expressed using ASHRAE's seven-point scale (Table 4.1) (Athienitis & O'Brien, 2015). PPD is used to express the percentage of unsatisfied people who are expected to feel either warm or cold in an environment. The PPD can be plotted as a function of PMV (fig 4.1), this model is also known as PMV/PPD model (Athienitis & O'Brien, 2015; Hoof et al., 2010)

The PMV/PPD model was developed for the mechanically controlled building and is also included in international standards like ISO 7730, ASHRAE 55, CEN 16798 (Attia, 2018c).

Question	How do you feel at this time?						
Descriptor	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
Value	−3	−2	−1	0	+1	+2	+3

Table 4.1 ASHRAE Seven-point Scale of Thermal Sensation. Source: Athienitis & O'Brien, 2015.

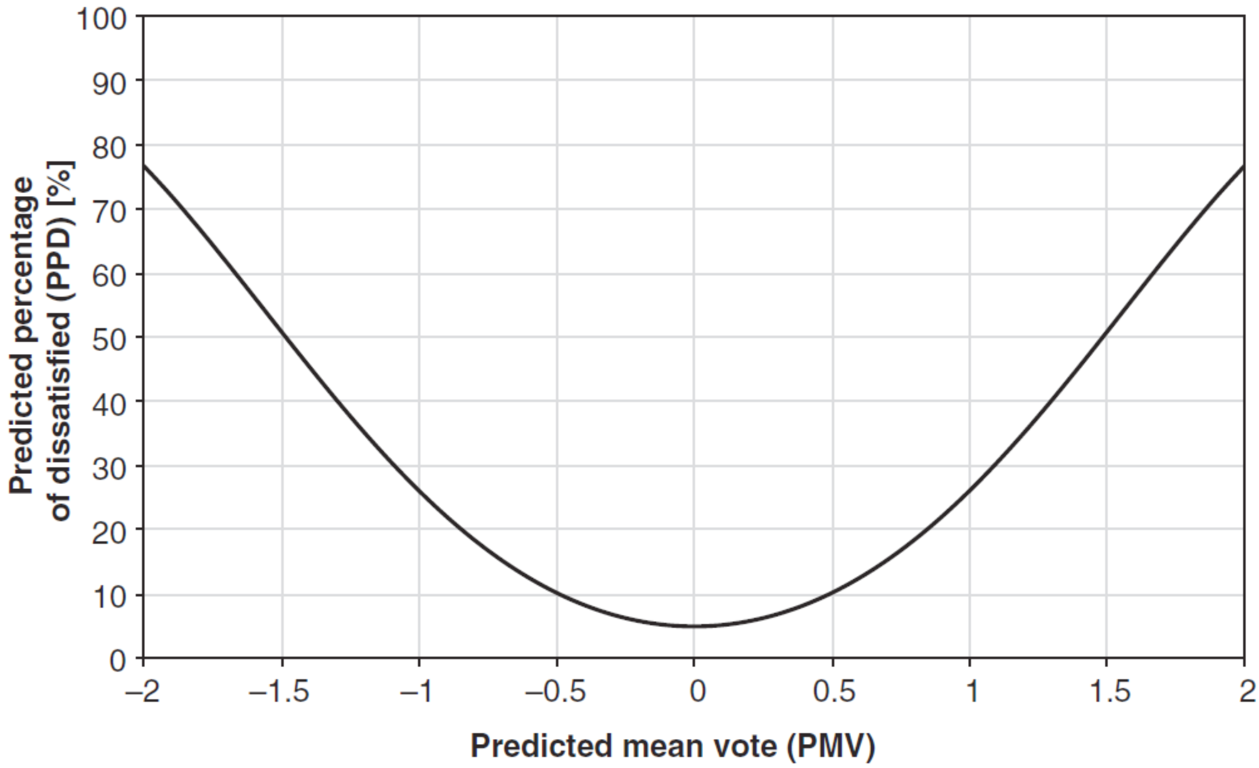


Figure 4.1. PPD as a function of PMV Source: Athienitis & O'Brien, 2015.

4.2 Adaptive Model

The static model considers a steady-state heat balance equation to determine the thermal comfort setpoint for a mechanically ventilated space. However, various researchers believed that this method could not be applied for naturally ventilated buildings since the occupants in a naturally ventilated building can adapt to a much wider range of temperatures (Athienitis & O'Brien, 2015). Therefore, an adaptive model was developed, which instead of a single setpoint temperature provides a comfort range.

The adaptive comfort model provides flexibility to the occupants to control their environment, which has a strong influence on occupant's health and energy consumption of the building (Athienitis & O'Brien, 2015; Attia, 2018c; Hoof et al., 2010). The adaptive comfort model has already been incorporated in standards such as ASHRAE-55 and CEN-15251 (Attia, 2018c).

4.3 Thermal Comfort Guidelines in the Netherlands

The Netherlands, in the mid-70s, developed its guidelines and strategies to achieve thermal comfort in buildings. These guidelines were based on the ISO-EN 7730, which used the steady-state model, which is the PMV/PPD model (Leitão & Graça, 2017). The Netherlands has further developed the thermal comfort guidelines and used three methods to assess thermal comfort for a design (Leitão & Graça, 2017; Witkamp et al., 2019). These methods are Temperature Overrun (TO), Predicted Mean Vote (PMV), Adaptive Temperature Limits (ATG). These are explained briefly in table 4.2.

Temperature Overrun (TO)	**Predicted Mean Vote (PMV)** (NEN-EN-ISO 7730)	**Adaptive Temperature Limit Value (ATG)** (ISSO 74/NEN EN 15251)
The number of hours in a year that a room exceeds a specific fixed temperature. *For example, the home may be a maximum of 300 hours per year above 25.5 degrees Celsius.*	Percentage of people who are dissatisfied with the temperature in a room. A target bandwidth is then specified. *For example, the PMV may fall below 0.5 or above 0.5 for a maximum of 300 hours in a year.*	The number of hours in a year that the temperature in a room rises above the outside temperature. *For example, the home may exceed 30 hours per year above class C following the ATG as described in ISSO 74*

Table 4.2. Different thermal comfort assessment methods. Source: Witkamp et al., 2019

The temperature Overrun (TO) method was developed in 1979 by the Dutch government, which stated a limit to the number of temperature exceedance hours above 25 °C and 28 °C in an entire year. However, this method does not give information about how long the overheating must last (Leitão & Graça, 2017). Therefore, the TO in 1989 was evolved into Weighted Overheating Hours (GTO), which was based on the PMV/PPD model. However, this method was suited for mechanically ventilated buildings, and it was not sufficient for the naturally ventilated buildings (Leitão & Graça, 2017; Witkamp et al., 2019).

Later in 2004, a new assessment method was developed in which the buildings were categorized into free-running (naturally ventilated) or mechanically cooled buildings as alpha or beta buildings, respectively. This method which is called as Adaptive Temperature Limits (ATG) method, is described in detail in ISSO 74 (Witkamp et al., 2019). The ATG method for thermal comfort assessment is preferred due to its clear distinction of building types concerning the nature of space conditioning. The ATG method also considers the difference in the comfort perceived by the occupants, building design, external and interior temperatures, and occupant's behavior (Leitão & Graça, 2017; Witkamp et al., 2019).

The ATG method was further developed, and a more detailed version was released in 2014, which makes the current guidelines for adaptive thermal comfort in the Netherlands. The revised

ATG method was developed in line with the international comfort standards NEN-EN 15251 and NEN-EN-ISO 7730. In the new guidelines, the Operative temperature is used to check limits, and the buildings were to be examined initially based on the alpha or beta type and the classification level (Class A/B, C, D) (Boerstra, Van Hoof, & Van Weele, 2015; Leitão & Graça, 2017).Table 4.3 illustrates the adaptive thermal comfort limit for each class, while figure 4.2 illustrates the relation between the comfort class limits and outdoor running meaning temperature for both alpha and beta buildings.

Class (bandwidth)	Explanation	PPD	PMV analogy (bandwidth)
A	High level of expectation. Select this category as a reference when designing spaces for people with limited load capacity (for instance, sensitive people or persons who are diseased) or when there is a higher demand for comfort	Max. 5%	–
B	Normal level of expectation. Select this category as a reference when designing or measuring new buildings or in the case of substantial renovations	Max. 10%	$-0.5 < PMV < +0.5$
C	Moderate level of expectation. Select this category as a reference in the case of limited renovations or when measuring older existing buildings	Max. 15%	$-0.7 < PMV < +0.7$
D	Limited level of expectation. Select this category as a reference in the case of temporary buildings or limited use (for instance, one to two hours of occupation per day)	Max. 25%	$-1.0 < PMV < +1.0$

Table 4.3. Description of class A/B, C, D. Source: Boerstra, Van Hoof, & Van Weele, 2015

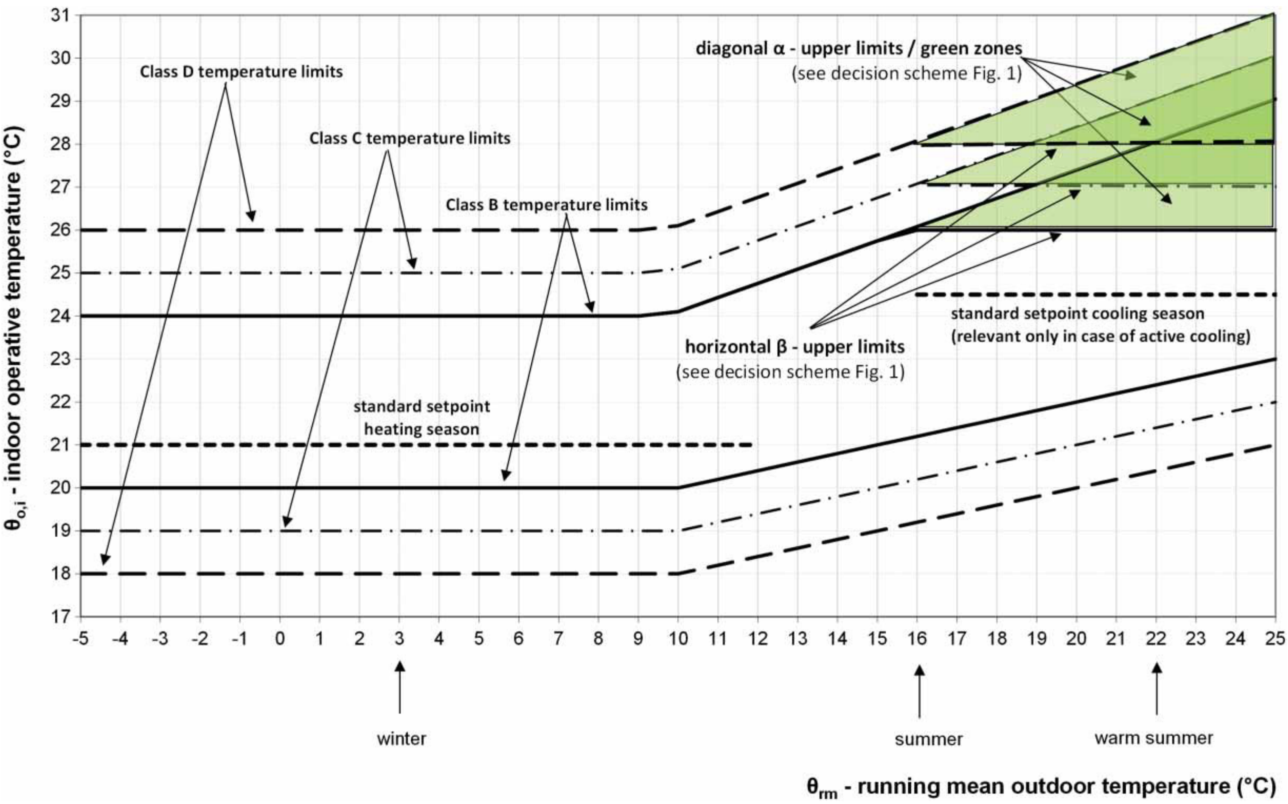


Figure 4.2. Relation of comfort limits of different class and outdoor running mean temperature for Alpha and Beta Buildings. Source: ISSO 74 , 2014 ; Boerstra, Van Hoof, & Van Weele, 2015

4.4 Conclusions

Thermal comfort is regarded as the satisfaction of the state of mind concerning the thermal environment around the occupant. There are various researches, comfort models and metrics developed to determine the thermal comfort. These metrics, however, can be classified broadly into steady-state models and adaptive models. The chapter researched both the steady-state models, which are based on the static heat balance equation, to determine a set point temperature for a mechanically ventilated space, whereas the adaptive comfort model considers the adaptive nature of the occupant. The adaptive model gives freedom and flexibility to the users to interact with its environments, which can help improve the health and well being as well as the energy consumption of the space.

The Netherlands also has various assessment measures, namely TO, GTO, and ATG, where the ATG method is widely accepted and most used. The ATG method first determines the typology of buildings based on the presence of active cooling or not. Secondly, depending on the requirement of the space comfort limits are classified as A, B, C, D. Therefore, further, in the research, we would follow an ATG method to assess the comfort of a space.

5. Overheating

Overheating can be defined as the accumulation of heat inside a building to such an extent that it creates thermal distress among the occupants. Most of the occupants start to feel warm at 25 °C while hot at 28 °C, although indoor temperature exceeding 35 °C may cause thermal distress (Gupta & Gregg, 2018; NHBC Foundation, 2012). The highly energy-efficient buildings aim at reducing the energy consumption of the design by minimising transmission and ventilation heat losses by high insulation and increased airtightness. However, studies show (Attia, 2018a; Barbosa et al., 2015; Gupta & Gregg, 2018; Kazanci & Olesen, 2016); these design measures are the primary cause for overheating in summers. In the following chapter, we will discuss in detail the sources and factors contributing to the overheating of a space. The chapter would also include various overheating assessment methods in the context of Europe and the Netherlands.

5.1 Overheating Sources

Overheating is a problem associated with high energy-efficient buildings. The primary reasons which cause the overheating problems are excessive heat gains from the building envelope, poor prediction of internal heat gains, and ineffective ventilation strategies (Attia, 2018c; Gupta & Gregg, 2018; NHBC Foundation, 2012). Some of the sources of heat gain are explained further. (Zero Carbon Hub, 2012).

5.1.1 External Heat Gains

Overheating is caused due to external heat gains from solar radiation falling on the building fabric and high external temperatures (K. Lomas & Porritt, 2017). The short-wave solar radiation enters the building through window openings, which are absorbed and re-radiated into long-wave infrared radiation.

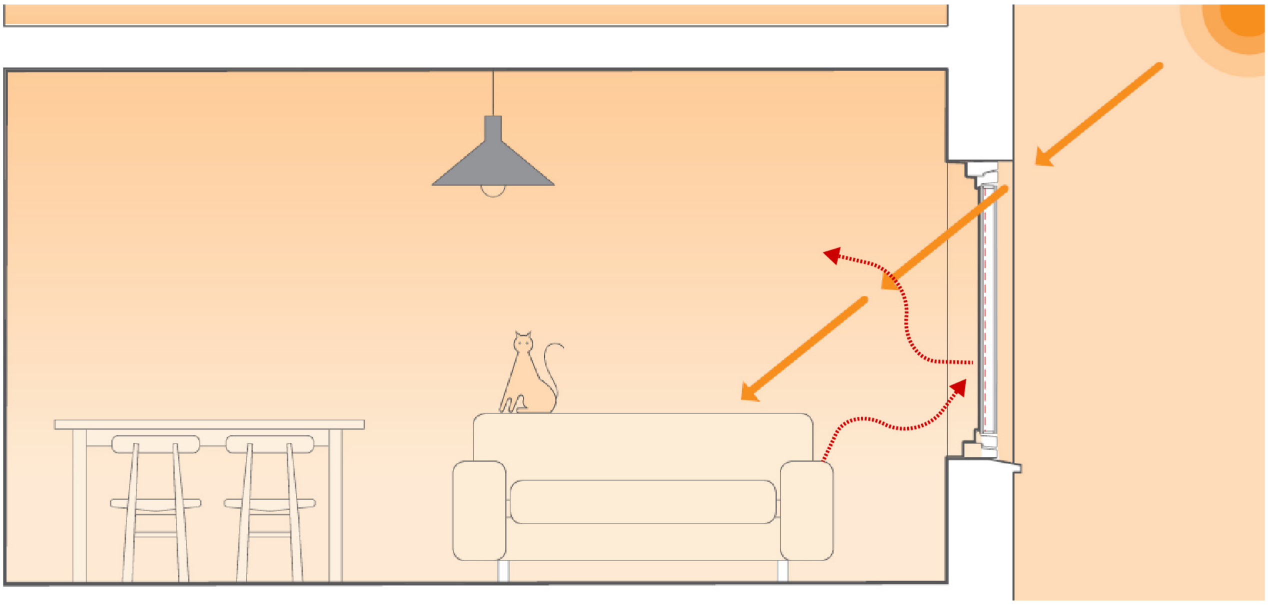


Figure 5.1 External heat gain. The long wave radiations are re-emitted and trapped by glazing. Source: Zero Carbon Hub, 2012

The long wave radiations are trapped by the double or tripled glazing units with relatively low U-values, thus retaining the heat inside the space during winters. However, in summers, this may prevent the heat from escaping, thereby causing overheating (NHBC Foundation, 2012). This principle is illustrated through fig 5.1.

5.1.2 Internal Heat Gains

The internal heat gains can be beneficial for winter since it can behave as a supplement to the heating system (fig 5.2). This strategy helps lower heating energy demand. However, in summers, it could cause excessive temperature rise, causing overheating of spaces (K. Lomas & Porritt, 2017). The sources of internal heat gains are:

1. **Occupants**

   The occupants dissipate heat based upon their activity level, thus giving rise to internal heat gains.

2. **Lighting**

   The lighting fixtures can contribute significantly to internal heat gain if the fixtures are high in number. However, LED fixtures are a suitable replacement of high energy-consuming light bulbs (NHBC Foundation, 2012).

3. **Appliances**

   Appliances like microwaves, refrigerators, laptops, and so on generate heat as well (NHBC Foundation, 2012).

4. **Building Services:**

   Building services like mechanical ventilation systems and hot water storage systems can also contribute highly to internal heat gains (NHBC Foundation, 2012).

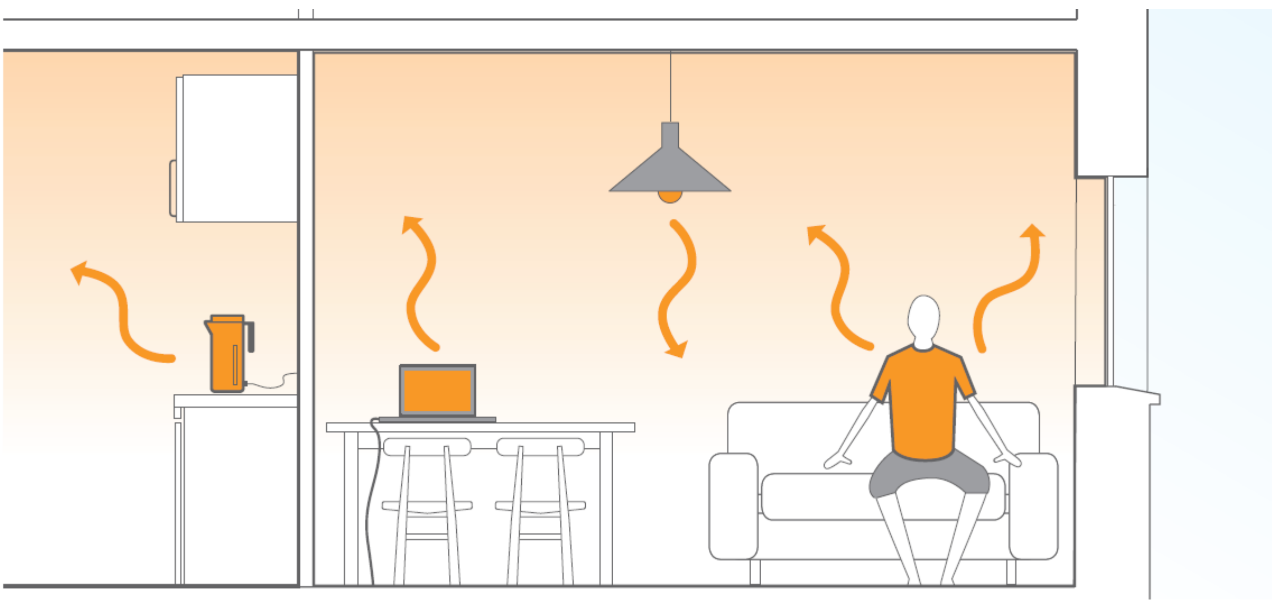


Figure 5.2 Sources of internal heat gain. Source: Zero Carbon Hub, 2012

5.1.3 Inadequate ventilation

Ventilation plays a crucial role in mitigating the effects of excess heat gains. A higher air exchange rate is generally desirable to replace the warm air with fresh air from outside, which can be done by providing an adequate opening area. Nigh time ventilation is also one of the passive solutions for removing excess heat from the building. However, in the urban areas giving a bigger opening into the façade creates a problem of noise, pollution, and theft (NHBC Foundation, 2012). For energy-efficient buildings, the risk of overheating increases due to the airtightness of building fabric to reduce heat loss through infiltration (Gupta & Gregg, 2018).

Another problem with ventilation is the high temperature of the outside air due to combined effect of the urban heat island effect and climate change (Dengel & Swainson, 2012). Therefore, opening windows for ventilation may, in such cases, contribute further for overheating of spaces(NHBC Foundation, 2012).

5.2 Factors Affecting Overheating

The risk of overheating is dependent on various factors such as the location of the building, microclimate, building shape, and form. The risk of overheating will further increase due to the cumulative effects. Some of the risks associated are illustrated below:

1. **Site Context**

The location and surroundings of the building can have a significant effect on the overheating of the building, such as proximity to heavy traffic zone, railways, factories, mechanical services, and so on (fig 5.3). The proximity of the building from the sources of noise, pollution may affect the potential of opening windows for adequate ventilation, thus reducing the loss of accumulated heat during summers (NHBC Foundation, 2012).

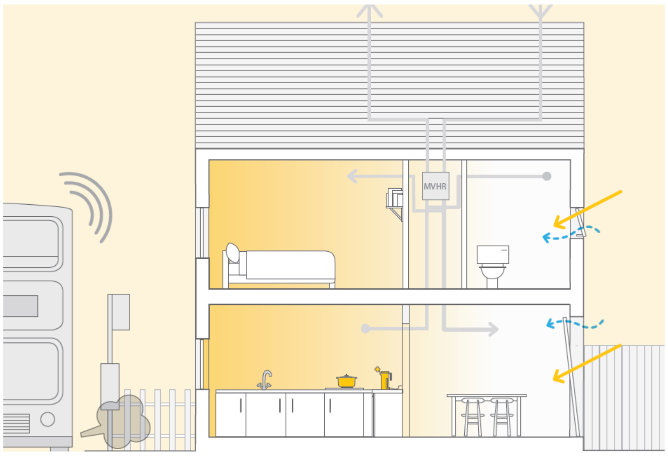


Figure 5.3 Nearby Context can affect overheating risks. Source: NHBC,2012

2. **Urban Heat Island**

Urban Heat Island (UHI) accounts for temperature variation of urban city centers from its nearby rural surroundings (fig 5.4) due to the absence of vegetation, surface with low albedo like concrete, brick (Attia, 2018c). These surfaces reflect less and absorb more heat during the day and release the heat at night, which causes an increase in the temperatures of the urban centers (NHBC Foundation, 2012). The UHI effect couples with increasing global outdoor temperature will further intensify the risk of overheating.

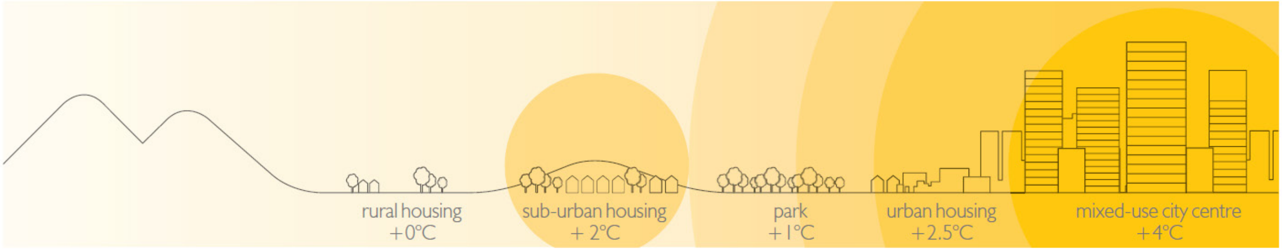


Figure 5.4 Temperature rise in Urban Centers. Source: NHBC,2012

3. Orientation

The orientation of the spaces is an important parameter to facilitate solar heat gain in winters and protect the interior spaces from overheating in summers (NHBC Foundation, 2012). However, the effect of orientation on solar heat gain must be considered carefully in building design. For example, a building, when oriented westward with its main windows, will behave differently than it faces south. At a westward elevation, one may experience more unwanted solar gain from the lower level sun in the evening (fig 5.5). While at the south-west elevation, there will be direct sunlight in the afternoon with high ambient outdoor temperature, thus overheating the spaces (NHBC Foundation, 2012).

Figure 5.5 Westward orientation of the building with large glazing will cause the solar gain late in the evening with high outdoor temperatures. Source: NHBC,2012

4. Building Design

To achieve a low energy building, an approach of trias energetica (three steeped strategy) is adopted, focusing on reducing energy consumption via building envelope, reducing primary energy consumption, and finally producing renewable energies on-site. As discussed earlier, the energy efficient buildings are designed with high insulation and airtightness along with numerous passive solar strategies such as orientation, natural ventilation, thermal mass to reduce heating loads during winters. However, these measures can cause overheating in summers (NHBC Foundation, 2012). Therefore, facilities like solar shading, night ventilation, overhangs can be useful to reduce overheating in summers. Although, in the urban context, there many factors like site restriction, limited natural ventilation, air pollution cause the design restriction, which multiplies the factors of overheating (NHBC Foundation, 2012).

5. Thermal Mass

Thermal mass refers to the properties of the building material, which reduces the temperature fluctuation by storing and emitting heat concerning the temperature of the surroundings. Although, in modern construction, to reduce the transportation cost, decreasing construction time, using materials with low carbon embodied energy, lightweight construction of the building envelope is preferred. This leads to a highly insulated building envelope that has low thermal mass as compared to heavy bricks and concrete construction (Fraser, 2009; K. Lomas & Porritt, 2017). The lower thermal mass results in heat gain during the summers which can cause overheating.

Since the buildings are made with high insulation, the thermal mass can absorb heat in the summer day time, but during the night when the outside temperature decreases, the thermal mass will emit the heat inside. Therefore in the absence of night time ventilation, the spaces could get overheat (NHBC Foundation, 2012).

6. Service Design

The mechanical systems and pipes used to carry hot water throughout the building, if not insulated well, can also lead to overheating (fig 5.6) (K. Lomas & Porritt, 2017; NHBC Foundation, 2012)

Figure 5.6 (right) Damaged insulation from the pipes carry hot water can lead to overheating of spaces.

5.3 Overheating assessment

The definition and metric for assessing overheating differ from place to place and specified by various standards. The definitions, however, are primarily based on the thermal comfort indicators or health-related indicators (Gupta, Barnfield, & Gregg, 2017), although the research will focus on the definitions based on thermal comfort indicators.

The assessment methods for overheating comprises of both the static and adaptive models, where the static approach uses simple and fixed calculation methods while the adaptive methods consider the adaptive nature of the occupants (Gupta et al., 2017; Selincourt, 2016). Some of the overheating metrics used in Europe are illustrated in table 5.1.

As discussed in chapter 2, in the Netherlands, the GTO and ATG methods are used to determine the thermal comfort, and they are also used for the assessment of overheating in the buildings. With the advent of BENG (nearly zero energy) regulations, another criterion of TOJuly is used to assess the risk of overheating of a space. However, the new indicator of TOJuly is only useful for indicating the chance of overheating for residential projects (Nieuwbouw, 2019). For a residential or non-residential building, the construction permit will only be given if the temperature exceeding hours are limited under 450 GTO hours (Lente Akkord, 2019; Nieuwbouw, 2019). The more detailed and precise calculations for GTO is mentioned in ISSO 32 (Nieuwbouw, 2019). The GTO method is, however, used for mechanically controlled climate; for naturally ventilated buildings, it is advisable to use the CIBSE TM52 method (Kurvers & Leijten, 2019, p. 76).

On the contrary, the new ATG method, which is in line with the international standards, has hybrid use for both naturally ventilated and mechanically controlled space (Boerstra et al., 2015). Another important aspect is the ease of communication of the results. Therefore, for the purpose of the study, the ATG method will be used to assess the risk of overheating in the case study buildings.

Standard	Type	Definition
CIBSE Guide A 2006	Static	*Limit 1% of occupied hours more than 28 °C indoor Operative Temperature (offices/living room)* *Limit 1% of occupied hours more than 26 °C indoor Operative Temperature (Bedrooms)*
Passiv Haus Standard 2007 / Passive House Planning Package (PHPP)	Static	*Limit 10% of occupied hours more than 25 °C of indoor temperature*
BS EN 15251:2007	Adaptive	*The indoor comfort will be dependent on "running mean outdoor temperature." and three different comfort category. The operative temperature should remain in comfort category II.*
SAP Appendix P 2012	Static	*Significant risk if monthly mean indoor temperatures are more than 23.5 °C as modeled.*
CIBSE TM 52 2013/ CIBSE guide B 2015 (based on BS EN 15251:2007)	Adaptive	*For free-running buildings, two out of three criteria must be met to indicate that the buildings will not suffer from overheating.* • *The difference between indoor OT and adaptive thermal comfort limits must not exceed by 4 oC.* • *Hours of exceedance is not more than 3% of occupied hours.* • *The weight temperature must be less than or equal to 6 hours in any one day*

Table 5.1: Different overheating Assessment guidelines. Source: Gupta et al., 2017; Selincourt, 2016

5.4 Conclusion

The chapter discussed external and internal heat gains and insufficient ventilation strategies as the primary reasons for overheating. These heat gains, when coupled with other factors like urban heat island effect, insufficient thermal mass, airtightness, increases the risk of overheating in any space. However, that building envelope being the primary concern; the strategies must focus on improving and proposing building envelopes for future scenarios.

The chapter also discussed various assessment methods of overheating. The methods are both static and adaptive in nature. In the context of the Netherlands, the ATG method combines the study of thermal comfort in mechanically and naturally ventilated buildings. Another advantage of the ATG method as compared to the GTO method is the communication of the results. Therefore, the ATG methods will be used further in this study to identify the risk of overheating in current and future climate scenarios.

6. Future Climate Scenario

Warming greater than the global average has already been experienced in many regions and seasons, with higher average warming over land than over the ocean (high confidence). IPCC, 2018, p. 51

The human interventions have excessively resulted in the change in natural variation of the globe. This phenomenon often described as "climate change" is much severe then excepted. Even if we control this phenomenon, the changes in the climate system are irreversible (Gething & Puckett, 2012). The building industry is accounted for utilisation of a considerable amount of fossil fuels to provide comfort, which in turn results in the emission of greenhouse gases, which are the primary culprit for the Climate change. Hence comes the initiative of EPBD directive of promoting energy efficient buildings.

The energy-efficient designs are simulated and verified for current climate systems; however, the future climate scenario must also be taken into account to forecast the possible change in energy use and indoor comfort. Therefore, this chapter will discuss future weather scenarios in the context of the Netherlands. Furthermore, the chapter would also discuss the methodology to use future weather data into the design process.

6.1 Future Climate Scenarios for the Netherlands

The Dutch Meteorological Institute (KNMI) is the national governing body that monitors the weather forecasting, weather variables, and seismic activities. KNMI has developed future climate scenarios that are currently used for water management, monitoring of urban environments, agriculture predictions (KNMI, 2015).

The KNMI has prepared four future climate change scenarios for the Netherlands based on the findings of IPCC 2013. These climate scenarios are based on the changes in air circulation pattern and global temperature rise (Fig 6.1).

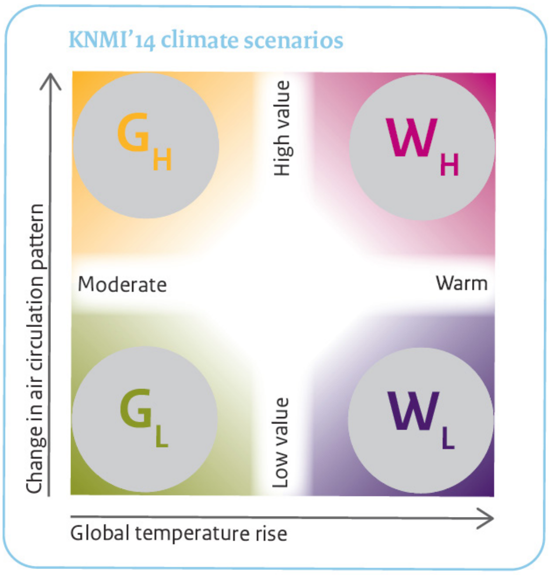


Fig 6.1: Four Climate Change Scenarios based on change in air circulation and global temperature rise. Source: KNMI,2015

Where G_H and G_L represent average temperature with high and low changes in circulation patterns, while W_H and W_L represent warm temperatures with high and low changes in circulation patterns (KNMI, 2015). These four climate change scenarios are further developed for two time horizons 2050 and 2085, taking the climate data of 1981-2010 as the reference period.

The climate change scenarios provide data for climate variables such as temperature, wind, precipitation, humidity. For the study, we will consider the worst-case scenario that is W_H with only outdoor temperature as the indicator of climate change.

6.2 Using Future Climate Scenarios

The climate change scenarios provided by the KNMI provides the annual change in the future climate of 2050 and 2085 concerning the reference period of 1981-2010. However, for predicting the behaviour of the building for energy or comfort assessment in future scenarios, detailed weather files are required. Weather files are consolidated hourly data for variables such as temperature, wind direction, wind speed, sky cover, precipitation, solar radiation for a specific location. In building energy and comfort assessment, these weather files are used in energy model simulation software like Energy Plus, Design Builder, IES VE, Open Studio, and so forth. For the study, Design-Builder will be used to actively simulate the case study buildings for thermal comfort and overheating assessment.

For analysing the thermal comfort and cooling load calculation, specific weather data is suggested by the Dutch Standards. The NEN 5060 (2018) provides climate reference files for both energy calculations and comfort assessment. The reference files for comfort assessment are a cumulation of different months in different years in the past 30 years to prepare a Test Reference Year (TRY). These different months are also suggested based on the 5% and 1% probability of temperature exceedance or undershooting then the data suggested. For this study, a TRY with 1% chance of exceedance will be used to simulate the worst-case scenario.

6.3 Test reference year for baseline, 2050 and 2085

For generating the TRY for future weather the KNMI (2015) has suggested few methods :

1. Considering the regions which have a similar climate to the predicted future change. For example, the climate of Amsterdam in 2050 would resemble the current winters of Nantes, France (KNMI, 2015). This is a quick method; however, it is not correct due to the differences in the geographical locations.
2. Another method is to reshuffle the calendar months of a year. For example, the January and February months of the W_H scenario in 2050 will resemble close to the current March or April (KNMI, 2015). This method is useful for estimating the average hourly temperature variation, but the conditions of solar angle and variations remain the same, thus not making it precise.
3. The last method is to use a highly detailed model with precise resolutions and transformation of climate data.

The preparation of TRY for baseline, 2050, and 2085 weather files was done in collaboration with Hamidreza Shahriari. The methodology for preparing files was adapted from the works of Ham and Spoel (2012). For the transformation of the climate files KNMI *Klimaatscenerio* transformation program was used, which transforms the recorded weather data at the De Bilt weather station. The TRY for thermal comfort with 1% exceedance probability, the NEN 5060:2018, contains months beyond 2010, and the transformation tool cannot support years beyond 2010 for preparing future TRY. Therefore, the study uses 1% exceedance files from NEN 5060:2008. Table 6.1 illustrates the 1% and 5% TRY from standard 5060:2008. The online tool by KNMI provides transformed data for temperature, radiation, and precipitation. For the study, only the temperature data was transformed.

Month	Selected months for Test Reference Year	
	5% Exceedance	1% Exceedance
January	2003	1987
February	1994	1986
March	1989	1991
April	1991	2003
May	1988	1992
June	1989	2005
July	2003	1995
August	1995	2004
September	2004	1991
October	2001	1995
November	2005	1996
December	1989	1996

Table 6.1: Test Reference Year for 5% and 1% probability of Temperature Exceedance. Source: NEN 5060:2008

The steps taken to prepare the Test Reference Year for baseline 2008 1% exceedance, 2050 1% exceedance and 2085 1% exceedance are the following:

1. In the KNMI'14 Klimaatscenario transformation program, first the daily average temperature of the reference period 1981-2010 was downloaded. Then the files were converted to a spreadsheet, and the data for code 260, which represents "De Blit" weather station, was selected and recorded on a separate spreadsheet.

2. The 'W_H' scenario, which is the worst-case scenario for climate change, was chosen, and the data for 2050 and 2085 time series were downloaded. The transformation program translates each day between 1981-2010 to future climate predictions. For the 2050 time horizon case, it translates each year to 55 years later, so it contains years between 2036 and 2065, and for 2085 case, the time series is between 2071 and 2100. The data were then separated for 'De Blit' station, similar to the previous step.

3. To find the increase in average daily temperature, the difference between two future time series and the reference file is taken.

4. The temperature difference then is chosen and separated for the months between 1981 and 2010, according to NEN-5060:2008 on a spreadsheet. The selected time series for a 1% percent exceedance chance can be seen in table 6.1.

5. The hourly weather data for the same months and years was taken from NEN-5060:2008. Then for each hourly temperature value in a day, the relevant daily temperature increases were added to obtain the temperature increases according to the future climate scenario.

6. To make the data file used by the simulation software design builder's weather data converter was used. First, the weather data file for Amsterdam was transferred to .csv format. Then the temperature values obtained in the previous step and the wind speed and direction, vertical, horizontal, and diffuse solar radiation, and humidity obtained from KNMI hourly weather data according to NEN-5060:2008 were copied to the .csv file.
7. In the last step, the transformed weather file was converted to the energy plus weather data file (.epw) using the Design Builders weather data converter.

After the weather files were converted into epw format, a demo simulation for the whole year with daily and hourly data was done on design-builder to check any simulation errors. Appendix A illustrates the comparison of daily temperature for annual simulation between baseline 2008 1% TRY, 2050 1% TRY, and 2085 1% TRY.

6.4 Conclusions

The Dutch meteorological institute provides four climate change scenarios based on the change in air circulation and average global temperature. For the study, the worst-case scenario of W_H, which represents the warm temperature with the high change in air circulation, was taken. The climate change scenarios are also provided for two specific future time horizon that is 2050 and 2085.

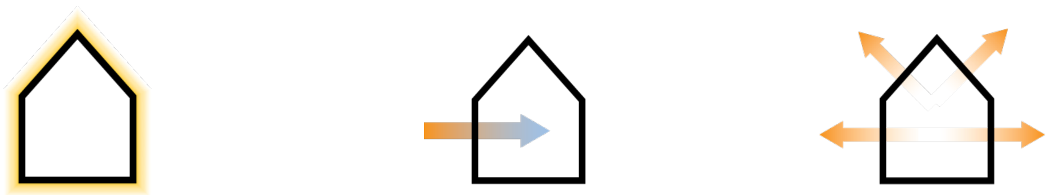
To incorporate future weather into the assessment of overheating and thermal comfort, the hourly weather files are prepared based on the test reference years mentioned by NEN 5060:2008. The online transformation tool from KNMI was used to prepare three weather files, namely baseline 2008 1%, 5060 1%, and 2085 1%, where 1% is the probability of actual temperature overshoot then specified in the reference months. These three weather files will be used further for the analysis of overheating in the case study buildings.

7. Strategies for Reducing Overheating

The risk of overheating is expected due to the cumulative effects of the factors discussed in Chapter 5. These risks range from the urban level to the building level. Therefore, to mitigate overheating, the strategies must be incorporated on all levels of design, context, and even users. The following chapter will discuss the numerous adaptive strategies essential to reduce overheating.

7.1 Controlling overheating

The energy-efficient building design in a temperate climate in winter makes use of passive solar heating strategies involving external and internal heat gain. However, as discussed in chapter 5, these heat gains must be controlled in summer for reducing the risk of overheating. The high insulation and airtightness in winters reduce the heat loss, but in summers, the heat accumulated inside due to high insulation must be removed via ventilation. Thus, to reduce overheating, the strategies must focus on heat protection, heat control, and heat removal (table 7.1).



Heat Protection	Heat Control	Heat Removal
The main objective here is to avoid excessive heat gains from both external and internal loads.	*To reduce the risk of overheating it is imperative to control the heat gain from the building envelope or hot outside air in future climate*	*The main objective here is to remove the excessive heat gains primarily through ventilation.*

Table 7.1: Passive cooling objective of reducing overheating by heat avoidance, control and removal. Source: CIBSE, 2005; Looman, 2017; Prieto et al., 2018

7.2 Adaptive Strategies

Adaptive strategies can be understood as the strategies which interact with the external environment and adapt to provide indoor comfort by utilising the full potential of natural conditions(Knaack et al., 2014). Studies conducted on overheating (Elsharkawy, Zahiri, & Ozarisoy, 2018; Jenkins et al., 2009; Pathan, Mavrogianni, Summerfield, Oreszczyn, & Davies, 2017; Shadmanfar et al., 2019) in office, residential, and school buildings do suggest the risk of overheating with the current climate and will eventually increase in future climate scenario. Therefore, it is vital to consider the strategies which are adaptive to the climate to reduce the risk of overheating.

Adaptive strategies can also be further classified as autonomous or planned strategies (Mastrandrea & Schneider, 2010, p. 65), where autonomous adaptation refers to the immediate adaptive reaction, for example, tolerance of occupants in a warmer climate for high indoor temperature. On the other hand, Planned strategies refer to the anticipatory steps planned on various levels of design (Mastrandrea & Schneider, 2010).

To design for climate change, it is essential to understand that the effects of climate change are not a static objective; instead, it is a moving target (Gething & Puckett, 2012). With the constant increase in the global outdoor temperature, it can be assumed that the general tolerance of occupants to higher indoor temperature would increase; however, this autonomous adaptation would have its limits. Therefore, it is imperative to focus on planned adaptive strategies on various aspects of a building design to curb the risk of overheating as one of the primary indicators of the effects of climate change on our built environment.

7.3 Passive Design Strategies

In response to the summer comfort, the general conscience is to provide cooling. However, the increasing outdoor temperature will increase the cooling demands, which can be counter-productive for energy-efficient buildings. Therefore, as an initial strategy to reduce the cooling demands, passive design and cooling principles which are climate responsive must be employed (Looman, 2017; Prieto, Knaack, Auer, & Klein, 2018).

The passive design strategies for cooling are generally referred to as the use of natural climate and systems for providing indoor comfort. These strategies avoid any active systems; however, to increase the effectiveness of these strategies, ancillary mechanical equipment like fans or pumps are also considered passive systems (Knaack et al., 2014; Looman, 2017; Prieto et al., 2018).

According to the extensive studies conducted on climate responsive design by Looman (2017) and the integration of passive cooling concepts into façade by Prieto (2018), it can be concluded that the passive design strategies which are climate responsive require a complete integration onto the building design as an initial step. According to Heiselberg (2006, p. 8), passive design strategies should be integrated by first designing the building itself. In this pre-design stage, the building should also investigate the effect of site, context to inform the building form, orientation, solar shading. In this stage, the functional requirement of the building should also be thought for adequate space planning to achieve daylight and natural ventilation (Engel & Roaf, 2019). Designing a smart bioclimatic architecture as a passive design strategy would be instrumental in reducing the overheating risks (Liu et al., 2017; Looman, 2017; Prieto Hoces, 2018). By designing according to the local context, incorporating landscaping and buffer areas, the design would also help reduce the temperature gain due to UHI.

After the basic design, the next stage is to look for the climate design of the buildings. In this stage, the buildings integrate passive cooling, heating strategies like building envelope, thermal mass, window to wall ratio, and window locations to inform the design further (Looman, 2017). The above two stages would be instrumental in reducing the cooling demands; therefore, the final step is the system design stage. Where the low energy systems like radiant heating, cooling, geothermal, evaporative cooling, wind towers must be designed and integrated into the building design (Heiselberg, 2002; Prieto et al., 2018).

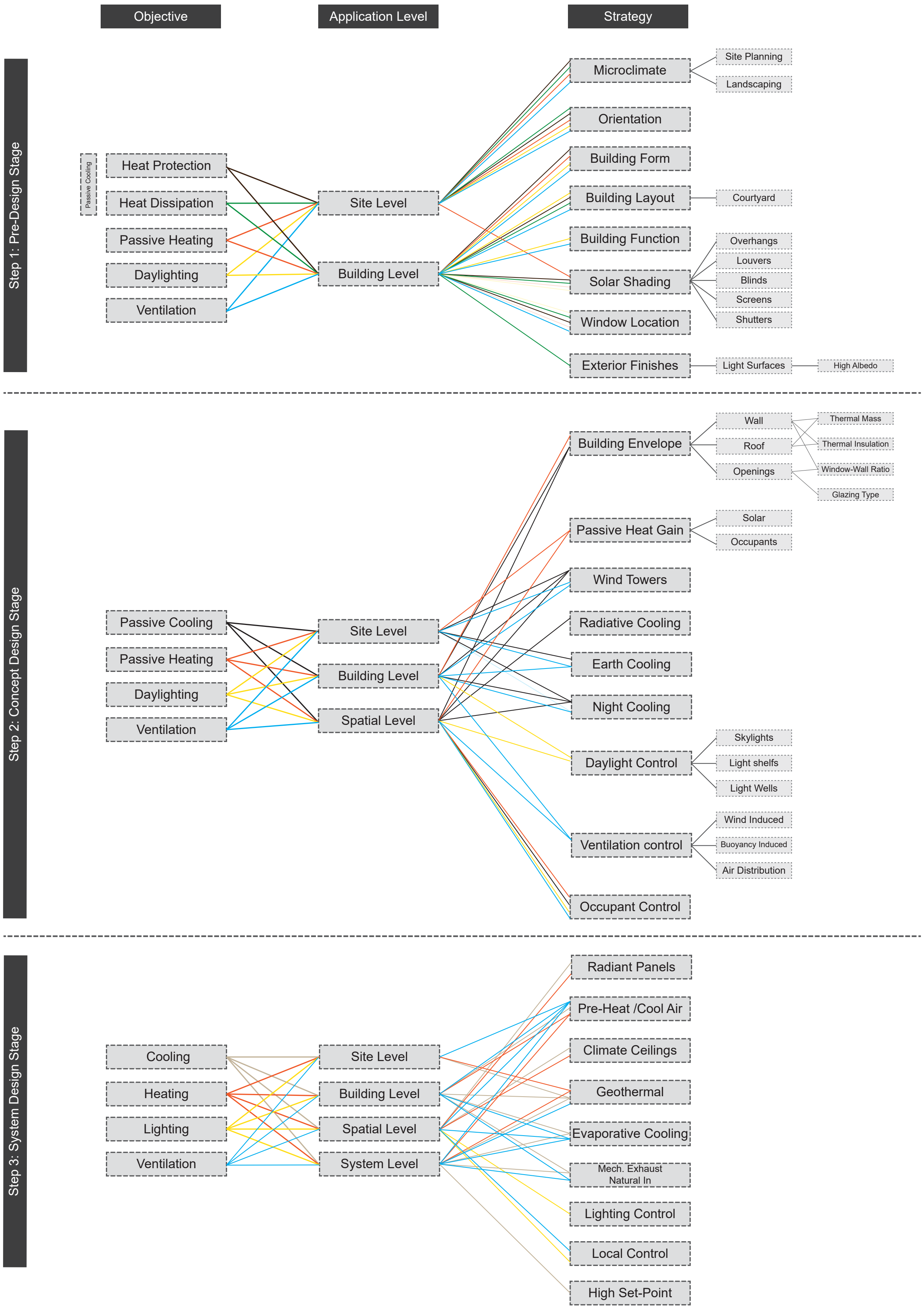


Figure 7.1 Overview of design strategies: The image illustrates the design strategies for three stages of design. The strategies are distributed based on the objective and the level of building design. Source: Engel & Roaf, 2019; Freewan, 2016; Heiselberg, 2006; Looman, 2017; Prieto et al., 2018

Although these stages look deeply into the integration of the passive strategies in the building design, the designers must also investigate the performance and operation of these strategies correspondingly for selecting the best suitable strategies.

Fig 7.1 provides a non-exhaustive overview of different passive design strategies at three stages of design, namely pre-design, concept design, and system design. In each design stage, the strategies are arranged on the objective of the passive design strategy that is passive cooling, ventilation, heating, and daylighting. While selecting the appropriate passive measures, it is also essential to consider the level of application like the site, building, spatial, and component to facilitate the utmost integration of strategies.

7.4 Trends for Passive Strategies in Future Climate

From the transformed weather files for 2050 and 2085 in chapter 6, it was concluded that the future weathers would account for elevated temperature in summer (Appendix A). Currently, in the temperate climate of the Netherlands, the passive design strategies for heating is much need as compared to cooling. However, this might likely to change in the future climate. To analyse the effect of climate change on passive design strategies, psychrometric charts were plotted from May till September (Appendix B). The charts were used to compare the difference in the comfort ranges and changes in passive design strategies. Fig 7.2 shows a comparison of the number of hours different strategies can provide comfort in baseline 2008, 2050, and 2085.

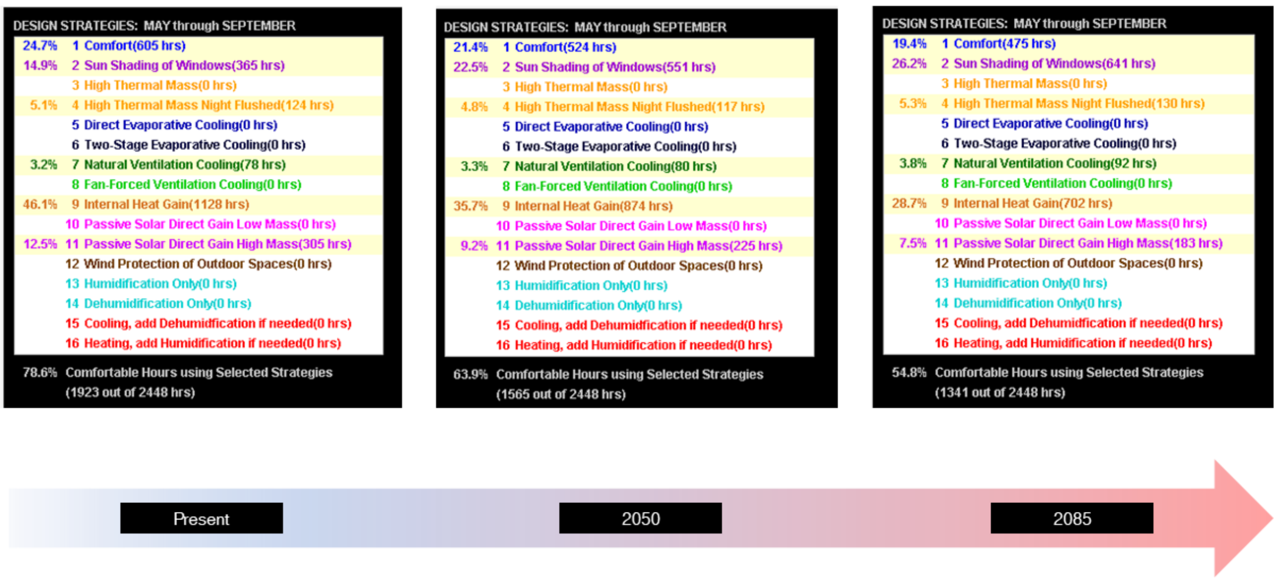


Figure 7.2 Trends in passive design strategies for summer comfort from climate consultant.

By comparing the strategies to provide comfort by only passive means, it was observed that in the future, the strategies related to providing passive cooling would be accentuated. The most striking difference was that the natural comfort hours would be reduced from 24.7% in

2008 baseline to 21.4% and 19.4 % in 2050 and 2085, respectively. This indicates that the opportunities to achieve comfort from the climate alone will be reduced, thus increasing the reliance on other strategies. It can also be observed in figure 7.2 that sun shading strategies would provide more comfort hours in the latter part of the century. The opportunities for thermal mass with night ventilation would also be useful in providing comfort in the future. However, in 2050 and 2085, internal heat gain must be reduced, and passive heat gain opportunities would be lower since the climate in general would become hotter. Therefore, the strategies related to heat protection and heat control must include the application of solar shading strategies and reducing internal heat gains, respectively.

The effect of natural ventilation on summer comfort can also be observed to increase in future climate. It could be explained as an increase in the outdoor temperature from lower temperature air to comfortable air temperature, which can be used for ventilation.

The significance of passive strategies with regards to changing climate scenarios is also discussed in detail in numerous literature. Research on future schools with a low carbon footprint in the UK (Jenkins et al., 2009) highlights overheating problems in the current meteorological year as well as in year 2030. The research suggests the importance of external shading and increased ventilation, coupled with passive cooling measures (ground-based heat exchangers), would be vital in curbing overheating in the future. Another research focusing on benchmarking of nearly zero-energy schools in Belgium (Shadmanfar et al., 2019) studied 20 models of nearly zero energy schools. Out of these 20 schools, 85% of the nearly zero schools have overheating more than 10% of occupied hours, while 57% of the sample size has overheating more than 20% of occupied hours (Shadmanfar et al., 2019). However, according to the research, increasing thermal mass, night time cooling has combined effects in reducing overheating and energy loads.

Lomas, Giridharan, and Short (2012) suggested renovation design options with a combination of insulations, shading and natural ventilation (table 7.2) for reducing the risk of overheating in a hospital ward in the UK. Option 1 and option 2 were proved beneficial in reducing overheating by 2080. However, a combination of option 3 with radiant cooling was suggested to remove overheating from the wards altogether.

Description	Wall 'U' value (W/m²K)	Roof 'U' value (W/m²K)	Volume (m³)	Window opening and shading	Upper level trickle vent	Space conditioning strategy	Set point temperature (°C)
Existing	1.0	0.3	958	Middle pane opened but no shading	NA	Perimeter heating only	Winter: 23 Summer: 22
Opt-1	0.2	0.1	958	All three window panes are opened and shading above the two pane	NA	Perimeter heating only	Winter: 23 Summer: 22
Opt-2	0.2	0.1	958	All three window panes are opened and shading above the two pane	NA	Perimeter heating and ceiling fan	Winter: 23 Summer: 22
Opt-3	0.2	0.1	868	All windows are fixed and shading above the two pane	25 no. 100mm diameter louvre units	Heating and cooling through radiant ceiling	Heating Winter: 26 Summer: 21; Cooling Summer: 16

Table 7.2: Existing and Proposed renovation options for hospital wards. Source: Lomas et al, 2012

Gupta and Gregg (2012) also presented an overview of the adaptive strategies for UK residential stock to mitigate overheating risk in changing climate. These adaptive strategies included increasing insulation levels in interior and exteriors, using cavity wall insulation, increase the albedo of exterior surfaces, exposed thermal mass, and shading strategies. The study concluded that for effective reduction in overheating hours, a combination of these measures must be adopted. In the context of the Netherlands, similar research on residences and overheating risk (Hamdy et al., 2017) emphasised on the use of ventilative cooling and solar protection as the most effective adaptive measure to combat climate change. Similarly, a study on office buildings (C Jimenez, 2019) also suggests the use of thermal mass and ventilation strategies to curb overheating. Table 7.3 summarises the different passive design strategies found in the literature to curb overheating in future climates.

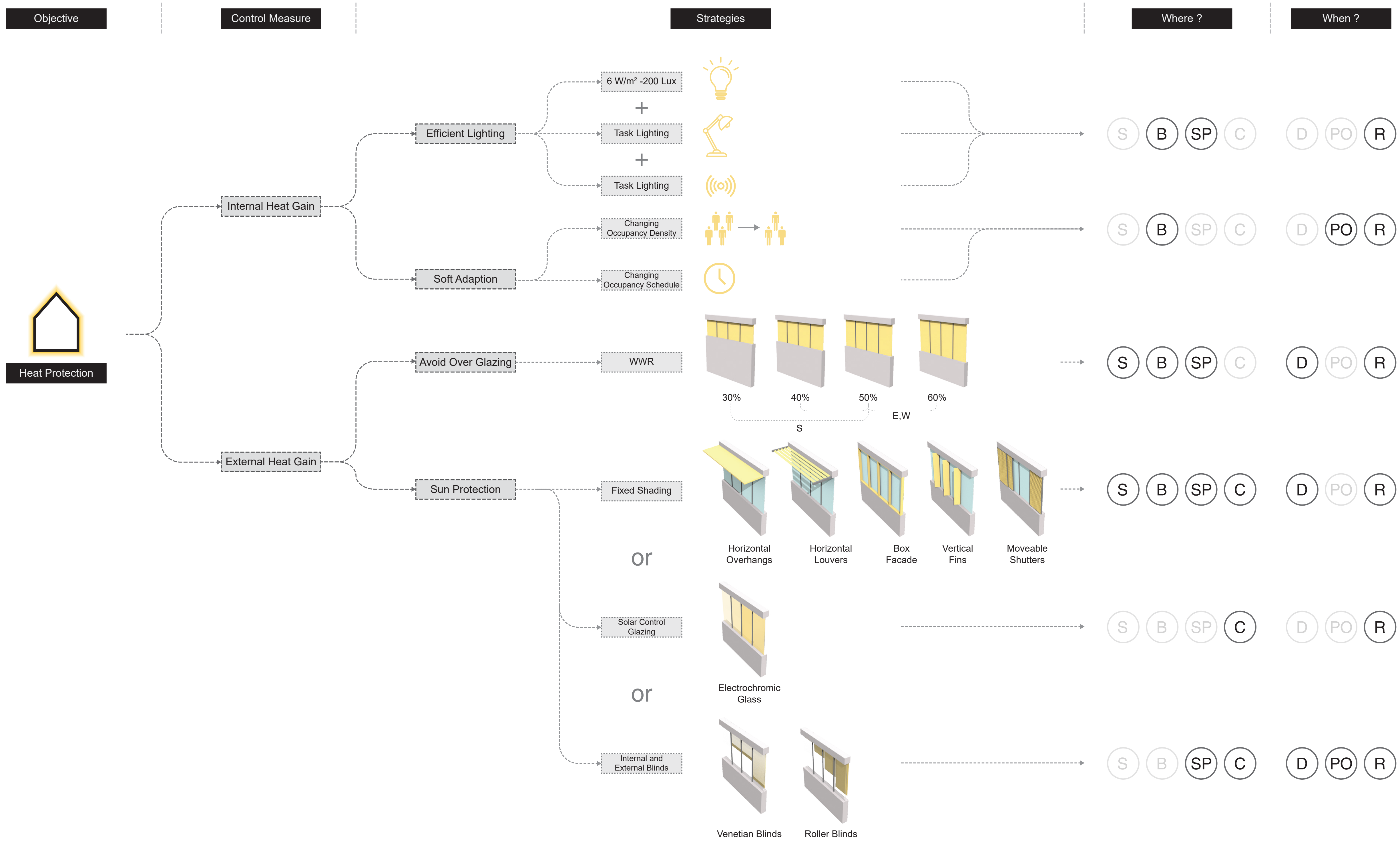
Author	Year	Building Type	Adaptive Strategies
Jenkins et al.	2009	*Schools*	• *External Shading* • *Passive Cooling* • *Ventilation Strategies*
Lomas et al.	2012	*Hospitals*	• *Insulations* • *Shading Strategies* • *Natural Ventilation Strategies*
Gupta and Gregg	2012	*Residences*	• *Increased external and internal insulations* • *Cavity wall insulations* • *High Albedo exterior surfaces* • *Exposed Thermal Mass* • *Shading Strategies*
Keefe and McHugh	2012	*Residences*	• *Solar Shading* • *Cross Ventilation* • *Night Ventilation* • *Managing micro climate by green walls* • *Evaporative Cooling*
AECOM	2013	*University Housing*	• *Solar control glass and shutters on west facade.* • *Increased ventilation* • *Increased thermal mass* • *Managing internal gains*

Author	Year	Building Type	Adaptive Strategies
Humphries et al.	2013	*School*	• *Green Roofs* • *Mixed Mode Ventilation* • *Reduced Glazing Ratios* • *Reduced SHGC Values for Glazing* • *Brise soleil and shading device*
Gupta and Hu Du	2014	*School*	• *External Shutters* • *Window Films* • *Albedo Effect* • *Night Ventilation* • *Triple Glazing*
Hamdy et al.	2017	*Residences*	• *Ventilative cooling* • *Solar protection*
Shadmanfar et al.	2019	*Schools*	• *Increasing thermal mass* • *Nigh time cooling*
C Jimenez	2019	*Offices*	• *Thermal Mass* • *Ventilation Strategies*

Table 7.3: Comparison of adaptive strategies used in different literature studies to reduce overheating. Source: Authors.

7.5 Adaptive Strategies for Building Envelope

From the analysis of the utilisation of passive design strategies in the future climate and literature studies done in section 7.4, appropriate strategies when applied to building envelope may reduce the risk of overheating. Figure 7.5-7.7 illustrates the passive design strategies which can be applied to the building envelope. The figures presented are a cumulation of various literature research and analysis. The strategies are again arranged as the objective of the passive cooling strategy that is heat avoidance, control, and removal. Further, the strategies were arranged based on the control parameter and "where" in the design stage it can be integrated. As mentioned earlier, climate change is a moving target; therefore, a progressive approach to upgrade the building envelope can benefit in reducing the risk of overheating in future scenarios (CIBSE, 2005). Therefore, another dimension of "when" to apply these strategies was also added to the illustrations.



S Site Level

B Building Level

SP Spatial Level

C Component Level

D Design Phase

PO Post - Occupation

R Renovation

Fig 7.5: Building Envelope solution set for heat protection.

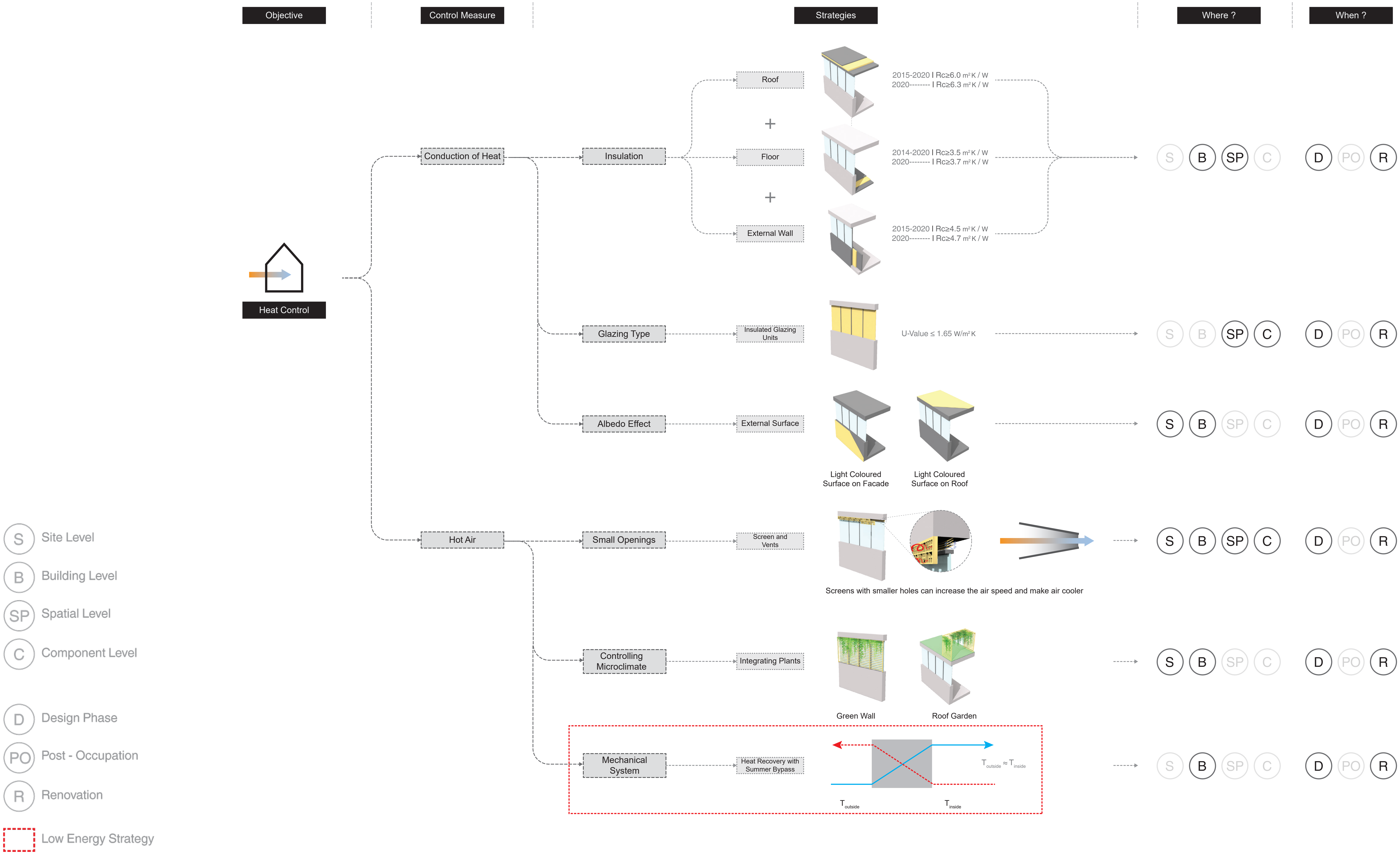


Fig 7.6: Building Envelope solution set for heat control.

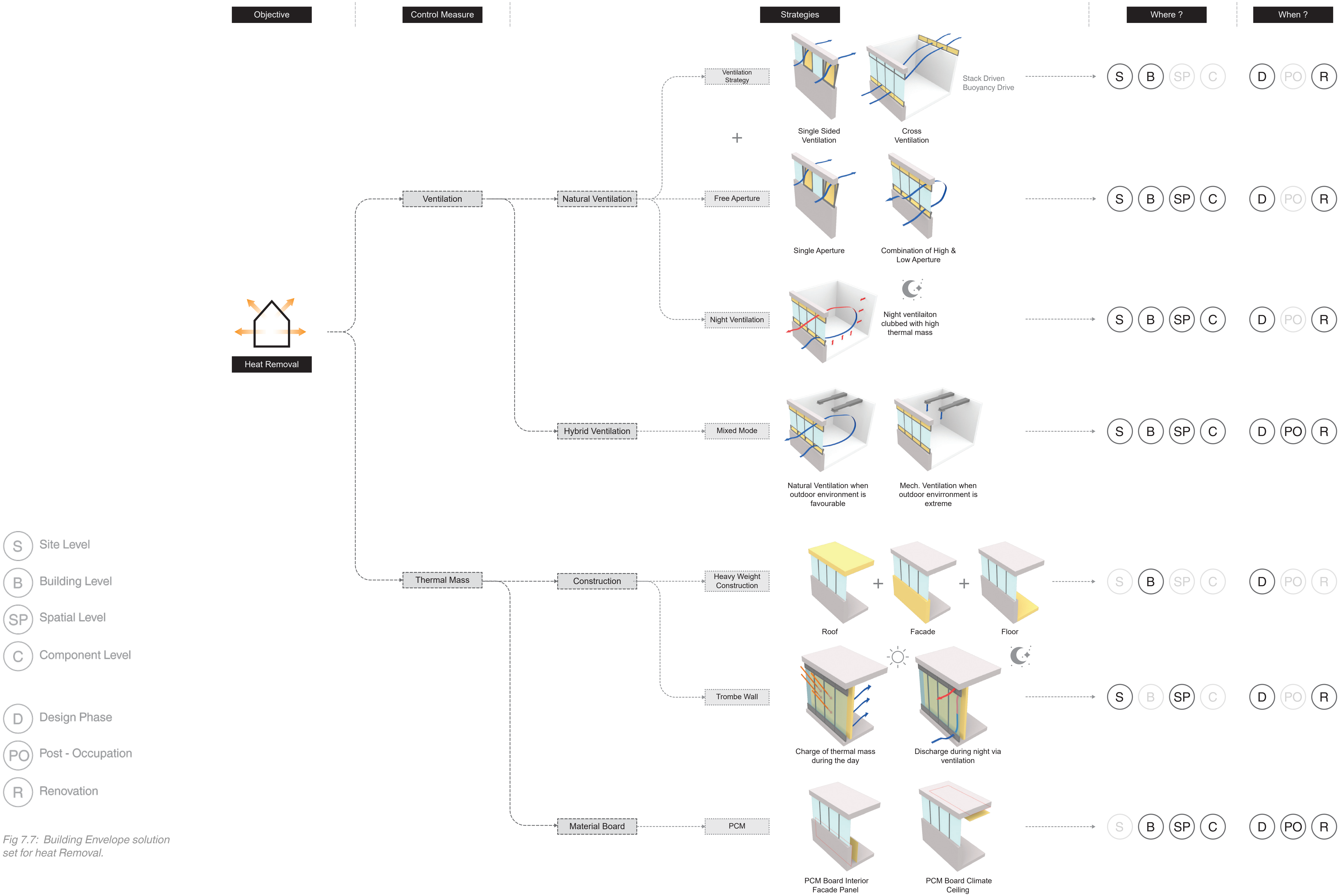


Fig 7.7: Building Envelope solution set for heat Removal.

8. Robustness

The concept of robust design was first coined by Dr. Genichi Taguchi, who implied that a design could be made robust by reducing the variations in the products without eliminating the leading cause of the variations. In other words, a robust design is a design that is insensitive to the variations ("What is robust product design," n.d.). In terms of building design, the buildings should be insensitive to the external and internal variations to perform as expected. Therefore, this section will discuss robustness in the context of building performance and its impact on energy efficiency and comfort.

8.1 What is Robustness?

Although the concept was developed from a product design point of view, the concept of robust design is thoroughly discussed in the literature for the built environment as well.

For example, Juricic, Kurvers, Leyten, and Van den Ham (2011; 2012; 2007) in their studies have defined robustness in the context of comfort, health, and energy consumption as:

"the degree to which the building meets the design objectives concerning the quality of the indoor environment and energy consumption when being used by its occupants in every day (and varying) conditions."

(Palme, Isalgue, Coch, & Serra, 2006) defines robustness as the ability of the building to mitigate the unintended variations by occupants or external factors, whereas Attia(2018a) in his book on zero energy design, emphasized the importance of a robust design which eliminates performance gap or sick building syndrome by connecting building components, elements, and systems in a robust manner which does not result in variations due to climate change or other unintended loads.

8.2 Incorporating uncertainties due to climate variations in Design Process

To achieve highly energy-efficient buildings, it is essential to predict the operation of the buildings in different scenarios. With the advent of sophisticated Building Performance simulation (BPS) tools, it has become more comfortable for the designers, architects, and engineers to simulate the performance of the building. However, in the current design practice to predict the building's performance, some assumptions are made for the building's operation. These assumptions are generally based on a typical scenario like historical weather data or generic occupant's profile. Although the buildings should also be designed for atypical or extreme situations. For example, the heat waves that struck Europe in 2003 lead to an increase in energy consumption due to air-conditioners, since the buildings were not designed for such extreme situations (Bulletins, 2003). In the worst-case scenario, the energy systems failure may lead thousands of occupants devoid of any energy for cooling, leaving them in overheated buildings.

The impact of the uncertainties due to climate change is high for energy efficient buildings, which are rarely considered in the design process, resulting in a building sensitive to such variations (Rajesh Kotireddy et al., 2017b). Therefore, these uncertainties should be considered in the design of low energy buildings to reduce such performance gaps and provide comfort and achieve energy efficiency even in the worst-case scenario.

To achieve a robust energy efficient design, a performative design approach can be used where the goal is to minimize the energy demand without compromising indoor comfort by taking the variations due to climate into consideration. A performative design can embed adaptability in a robust design by making decisions based on the performance of the design concerning performance indicators and thresholds (Attia, 2018a).

8.3 Use of Scenarios to evaluate robustness

To evaluate robustness, the assessment approach in the literature is categorized as a probabilistic approach where the probabilities of uncertainties are assumed and non-probabilistic where the probabilities of the uncertainties are unknown (Rajesh Kotireddy, Hoes, & Hensen, 2017a; Van Gelder, Janseen, Roels, Verbeeck, & Staepels, 2013). According to Kotireddy (2019), the probabilistic approach requires information regarding the probability of an occurrence of an uncertain situation. This is explained by the example of generic households where it is difficult for a designer to know the occupancy behaviour and climate variations in a residence over its lifespan. On the other hand, the use of a non-probabilistic approach can be understood by taking "scenarios" into consideration. Scenarios can be formulated as the range of possible events or alternative situations over which different design solutions can be assessed to quantify the risk into a best case or worst case scenario (Rajesh Kotireddy, Hoes, & Hensen, 2018).

The use of different climate scenarios is carried out in various field researches in dwellings, offices and educational buildings (Carbon & Group, 2014; Hamdy et al., 2017; Heracleous & Michael, 2018; Salem, Bahadori-Jahromi, & Mylona, 2019; Shadmanfar et al., 2019), where the scenarios were used to assess the impacts of climate change. Therefore, for this research, different climate scenarios will be considered to assess the robustness of energy efficient educational building design.

8.4 Assessment of Robustness

Genichi Taguchi first developed the assessment of robustness in 1950, also known as the Taguchi Method. This method used a signal to noise ratio as a measure to reduce the variations in the product (signal) due to uncertainties (noise) using a statistical approach of mean and variance to assess the robustness of a product (Moazami et al., 2019). However, this method cannot be used for scenario-based analysis since it takes an average of the performance of design across all scenarios, thus causing the scenarios to be redundant. It is essential to check the designs' performance in different alternative situations and scenarios to assess the robustness of the design (Rajesh Kotireddy et al., 2019; Moazami et al., 2019)

In the context of building performance, a thorough analysis of different assessment methods based on scenario analysis is done by Kotireddy (2018, 2019). These methods include the max-min method, the best-case and worst-case scenario, and the minimax regret method. These methods are used to select a robust design from various design options, which are considered in different scenarios and performance indicators. The choice for using one of the methods depends upon the decision-maker's approach for taking risks in design decisions. A comparative analysis of these methods is illustrated in table 8.1

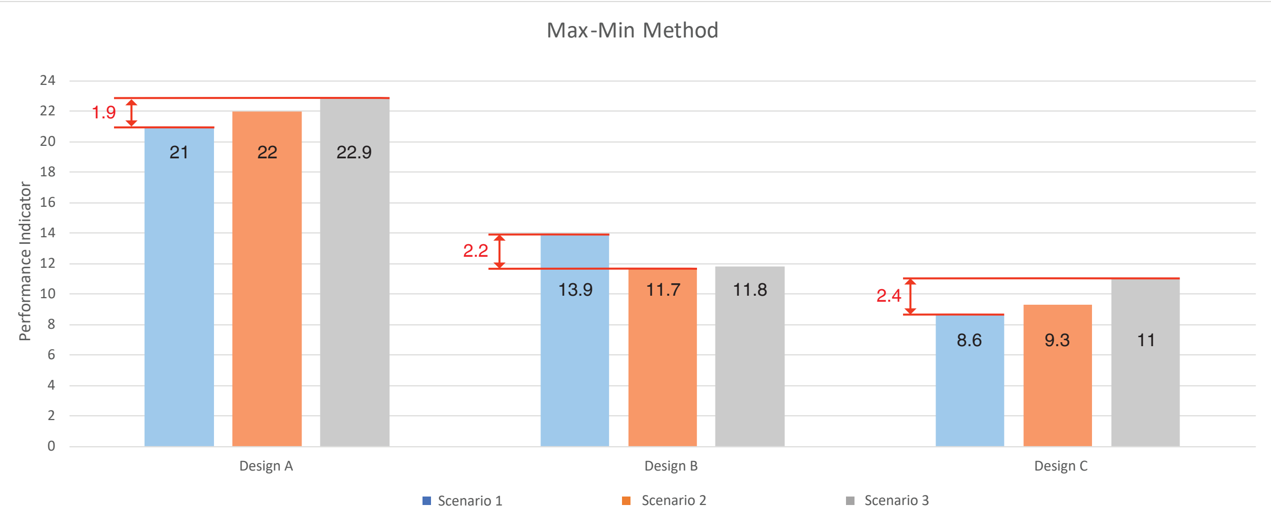
Parameter	Max-Min Method	Best-Case and Worst-Case Method	Adaptive Strategies Minimax Regret Method
Robustness Assessment Indicator	Performance Spread	Performance Deviation	Maximum Performance Regret
Calculation Method	Difference between maximum and minimum performance of a design across considered scenarios	Difference between the best performance of the entire design space and the worst performance of a design across considered scenarios	Difference between the performance of a design and the best performing design for that scenario and the maximum difference across all scenarios.
Robustness Test Scenario Selection	Only extreme Scenarios	All Scenarios	All Scenarios
Robust Design Selection	Design with minimum or ideally zero performance spread	Design with minimum or ideally zero performance deviation	Designs with minimum or ideally zero maximum performance regret
Application	Designing for data centres	Designing for hospitals	Designing for residential buildings

Table 8.1: Comparison of robustness assessment methods for scenario analysis. Source: R Kotireddy, 2018

The Max-Min Method

The max-min method uses the difference between maximum performance and minimum performance across all designs. In this method, design with the least performance spread will be considered as the most robust design. The performance spread is calculated as the difference between the maximum and minimum performance of the design. However, this method does not compare the designs within each other or with different scenarios. (Rajesh Kotireddy et al., 2018). The method is further explained using a random sample of data.

In this example, the performance of design A, B, C, is plotted in different scenarios. According to graph 8.1, Design A will be considered as the most robust option, since its performance spread is the lowest. However, it is important to notice that Design B and Design C though their performance spread is higher then Design A, does well in terms of actual performance in the first place. Therefore this method does not compare design options across all scenarios and options.

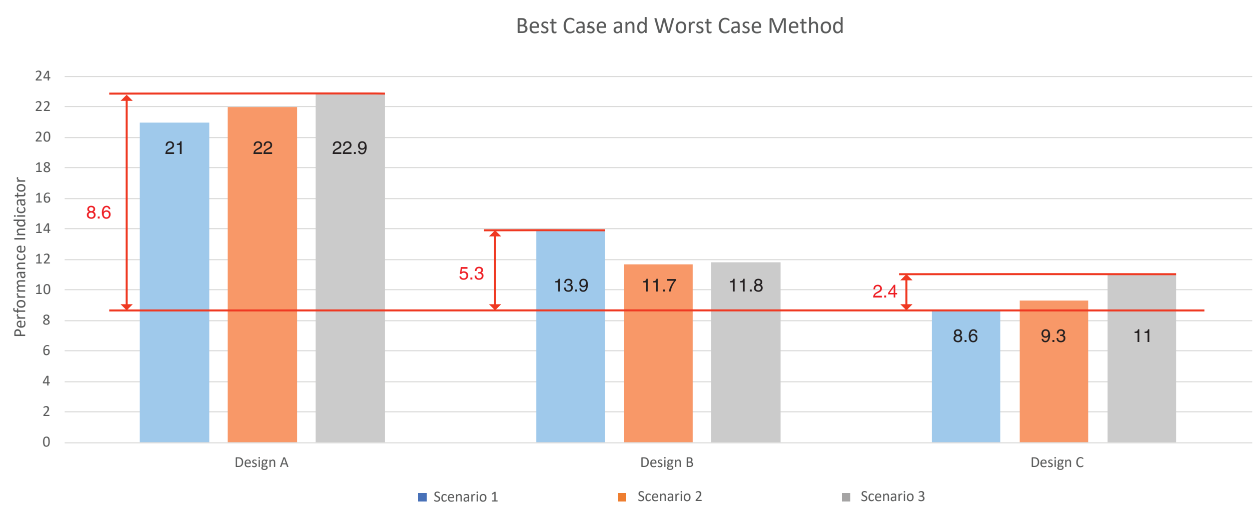


Graph 8.1: The Max-Min Method.

The Best-Case and Worst-Case Method

The Best-Case and Worst-Case method use the performance difference between the worst performing design and best performing across all the scenarios and design options. This method is useful for finding the most robust design, which is performing well, even in the worst-case scenario (Rajesh Kotireddy et al., 2017a).

Graph 8.2 illustrates the method on the same data set. We can observe that Design C performs much better in comparison to all the design options and also in all the three scenarios.

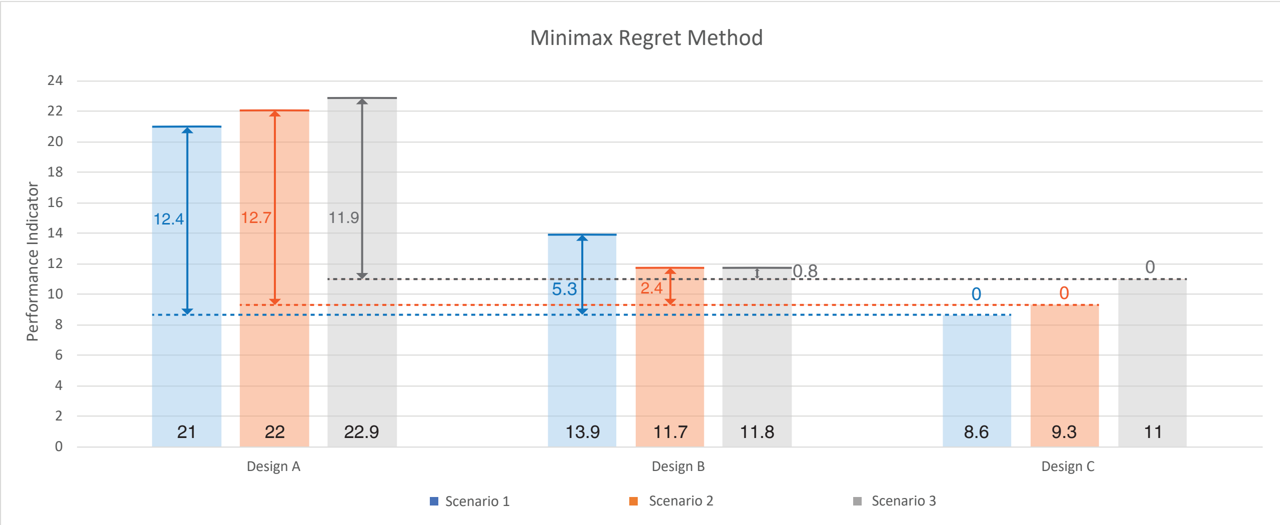


Graph 6.2: The Best Case and Worst Case Method.

The Minimax Regret Method

The Minimax Regret method uses the maximum performance regret among all the scenarios for assessing robustness. The performance regret is explained as the performance difference between the designs and the best performing design in that scenario (Rajesh Kotireddy et al., 2019).

Graph 8.3 illustrates that Design C has minimum performance regret among all design options in all the scenarios. Therefore, Design C is considered the most robust option. However, Design B can also be robust because of its less performance regret and can be improved further to become a robust design option.



Graph 8.3: The Minimax Regret Method .

From the literature studies, it is observed that the methods explained for assessing robustness the Best-Case and Worst-Case and the Minimax Regret methods compare the designs across all scenarios. The Best-Case and Worst-Case method will provide us the best solution performing in the worst-case scenario while the Minimax Regret would return the set of optimal solutions where the decisions can be taken based on trade-offs.

The minimax regret method suggested proportionality between robustness and predicted performance; therefore, this method will be preferable in real-life situations (Rajesh Kotireddy et al., 2019). Whereas the best-case and worst-case scenario are preferable when the design selected has to perform in the worst-case scenario. For the study, no trade-offs are considered, and the objective is to find the most robust design solutions in the worst-case climate change scenario. Therefore, the study will use the Best-Case and the Worst-Case method to evaluate robustness.

8.5 Conclusion

From the literature, it can be concluded that the concept of robustness is applied from product design to building design, where the primary focus is to reduce the performance gaps or variability of the design in the presence of uncertainties. The impact due to the uncertainties of climate change is high on the performance of energy-efficient design. Therefore, a performative design approach can be used where the robustness is assessed on the performance of design concerning specific performance indicators in different situations, in this case, reducing overheating hours in future climate.

Building performance tools help simulate the performance of low energy design, although the assumptions taken for the simulation do not consider the uncertainties which cause the performance gap and thus, in fact, create thermal comfort problems like overheating. Therefore, it is essential to include uncertainties in the design process at an early stage.

To consider the uncertainties in the simulation process, a non-probabilistic method must be adopted using scenario-based analysis where the robustness of the design can be tested on the different alternative situations. Therefore, it will be imperative to take the climate scenarios as the situations where the robustness of the design can be assessed.

The assessment of the robustness, according to literature, can be done using max-min, worst-case and best-case and minimax regret methods. However, in the research "best-case and worst-case" method will be used.

For the research, we can now define robust design as

"A design with minimum performance variability under the presence of uncertainties."

Where the performance indicators will be overheating assessment while the uncertainties related to climate change will be considered. To assess the robustness, we need to define the overheating parameters as performance indicators, scenarios for climate change, and adaptive strategies, which could provide us various design options whose robustness we could assess.

Part 3

Case Study

9. Case Study: Educational Buildings

Thermal comfort in educational buildings is of paramount interest as it has a direct correlation with the performance of the students (Heracleous & Michael, 2018; Jenkins et al., 2009; Shadmanfar et al., 2019). With the projected rise in the global temperature, it is most likely that the indoor comfort conditions in educational buildings will progressively become worse. Educational buildings are also of further importance in terms of the hybrid activity levels between an office or a residence, where the students spend more than 90% of their time indoors (Heracleous & Michael, 2018). Therefore, it is essential to analyse the impact of the changing climate on the educational realm.

Educational buildings are a vast typology of building stock; therefore, to cover more ground, two different cases of educational buildings were selected. A university building in TU Delft campus and a secondary school in Rotterdam was chosen for the studies. The case studies set up under the bigger umbrella of educational buildings; however, they are quite different in terms of occupancy and activities. Hence, applying the strategies on these buildings would further help the development of design guides which can be scaled for any type of educational buildings. In the following chapter, both the case studies will be discussed in terms of architecture, building envelope, climate control strategies, occupancy pattern, and lighting.

9.1 Pulse, TU Delft Campus

The Pulse building (fig 9.1) is the first energy-neutral building of the TU Delft campus designed by Ector Hoogstad Architects. The building with a gross floor area of 4700m^2 has multiple functions such as educational spaces, seminar rooms, self-study spaces, multi-cuisine cafeteria with a capacity of 200 people. The building also comprises 490 solar panels on the roof, which can generate up to 1,50,000 kWh of clean energy("Pulse - Campus Development - TU Delft," n.d.).

Fig 9.1: Pulse Building, TU Delft Campus . Source: qbiqwallsystems.com

9.1.1 Architectural Layout

The pulse building has four floors, including a split floor between the ground and the first floor (fig 9.3). The building's internal layout exhibits conscious decisions in placing the learning spaces to maximise daylight and reduce overheating in the first place. The lecture halls were placed on the northeast side of the building, which is comparatively less susceptible to overheating as compared to the south orientation. Spaces such as self-study workstations and corridors were planned on the south (fig 9.2). Utility spaces were kept in the middle for reducing the long transportation of services. Vertically, the ground floor house most of the public functions like cafeteria or seminar rooms. Upper floors have the lecture rooms, thus separating the public and private spaces.

Fig 9.2: Internal Layout of the second floor, Pulse, TU Delft. Adapted from the drawings provided by Campus & Real Estate(CRE) Dpt. , TU Delft. Source: CRE,TU Delft

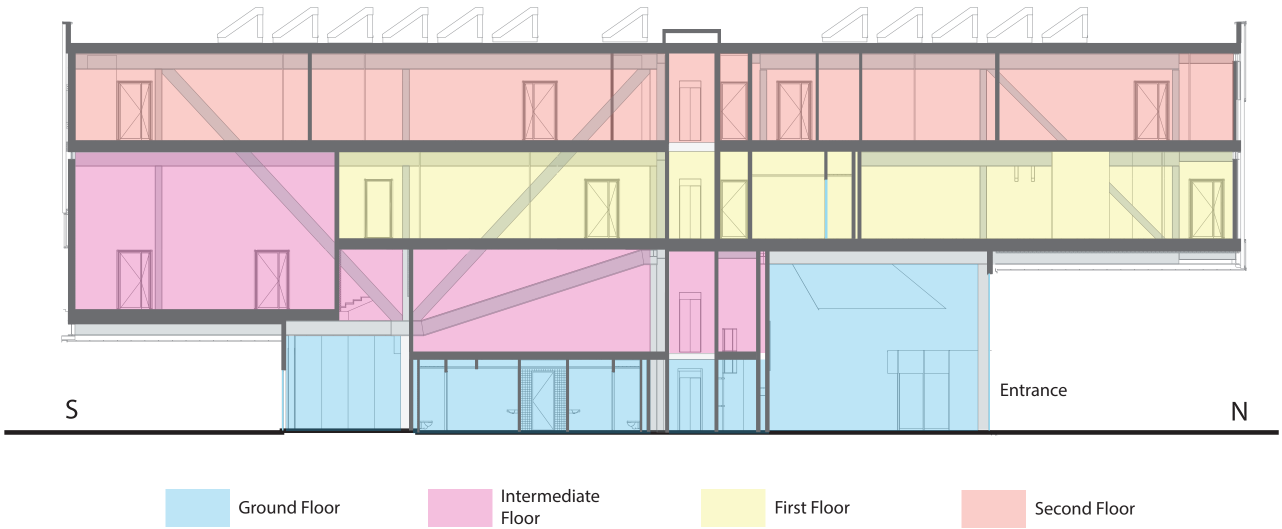


Fig 9.3: Longitudinal Section, Pulse, TU Delft. Adapted from the drawings provided by Campus & Real Estate(CRE) Dpt. , TU Delft. Source: CRE,TU Delft

9.1.2 Building Envelope

External Walls, Roof, External Floors

The insulation values applied for the building envelope were determined, keeping energy efficiency in mind. DGMR, as the building physics consultant, proposed insulation values considering the passive-house regulations. The opaque part in the façade and the roof thus has an R-value of 7m^2.K/W. The ground floor and the external floors have an R-Value of 5 m^2.K/W.

As compared to the Dutch Building Decree, these values are on a higher side, thus making the building envelope super insulated. Along with the building envelope, DGMR also proposed to have an R-Value of 3 m^2.K/W for internal partition walls separating the conditioned spaces like lecture halls and less conditioned spaces like corridors, staircase.

Glazing, Infiltration, Solar Shading

Pulse building majorly has glazing on the south-west and north-east façade with a window to wall ratio of .75. A triple glazing unit with a U-Value of .8 W/m^2.K (Uglass+UFrame),g-value of 0.40, and VLT greater than 0.70 is used throughout the building.

The pulse building is highly airtight with the infiltration value of .15 dm^3/s /m^2 calculated at the difference of 10 Pa.

For controlling the solar gains from the southwest façade, shading panels were installed. Initially, a 3D-printed optimised shading panels were proposed (fig 9.4), however, the quality of the 3D-printed panels could not be guaranteed, therefore, the façade now has textile shading panels (fig 9.5). These panels are made up of PVC-Styrofoam Fabric, which is lightweight and instrumental in blocking the harsh sun in summers. The lecture halls in the north-east façade are equipped with internal blinds that function autonomously as well as can be controlled by the users.

Fig 9.4: 3D printed Facade on the South West Facade. Source: schooldomein.nl

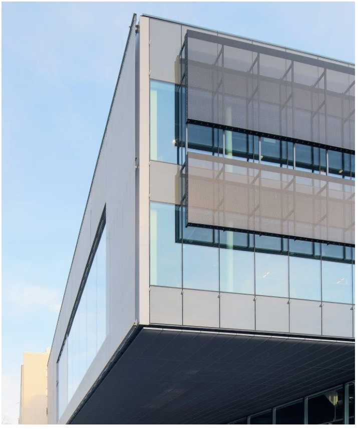


Fig 9.5: Textile Facade on the South West Facade. Source: ods-geveltechniek.nl

9.1.3 Climate Control

Heating and Cooling

The pulse building uses Aquifer Thermal Energy Storage (ATES), which uses boreholes to store or use heat and cold from the ground to provide heating and cooling into the building. Currently, it is considered to be one of the most sustainable ways of meeting the building demands as it can reduce the heating or cooling energy by 45-80% (Rozemeijer, 2014). In Pulse building, the ATES system comprises of two separate wells for storing heat or cold. In winters, the groundwater at 15°C is extracted from the hot well through heat pumps and raised to 35 °C via a heat exchanger, which is then delivered to the heating systems. The returned cooled water at 27 °C then go through the heat exchanger, where the temperature is brought down to 8 °C and stored in the cold well.

In Summers, the cooled groundwater at 11 °C is pumped back into the building cooling system. The returned groundwater of 19 °C is then stored in the hot well for use in winters. In the case of high cooling loads, dry coolers are used to cool the return groundwater at 19 °C to 14 °C. During maintenance of the ATES system or when the ATES system is unable to provide cooling, heat pumps are used in combination with dry coolers, which is an active cooling measure.

The ATES system in the pulse building has a COP of 4.5 for heating operation while cooling the COP is as high as 30. However, the active cooling system has a COP of 3.5. Hence, the ATES system is instrumental in reducing the energy consumption of the building.

The heating and cooling provided by the ATES system are then further used by various climate control installations. The lecture halls and study spaces are equipped with climate ceilings to provide radiative heating and cooling, while the corridor spaces use underfloor heating and cooling. The radiative system is, however, a slow system; therefore, mechanical ventilation is also used to cool the building.

Ventilation

The Pulse building uses mechanical supply and discharge for ventilating the spaces. The system controls the amount of ventilation based on the CO_2 sensors. The system is designed according to the “fresh school” Class B guidelines of providing at least 8.5L/s per person. The system is also designed to limit the CO_2 levels of 950ppm for class B according to “fresh schools” guidelines (RVO, 2015). The ventilation system is also equipped with heat recovery with a summer bypass. The pulse building also has openable windows in the north-east façade for promoting natural ventilation and night ventilation. However, it is not being used in the present scenario.

9.1.4 Occupancy, Lighting

Pulse building provides around 1,020 learning spaces, thus making it a conducive space to work after university hours. The building operates from 8:00 till midnight and throughout the week. The building has peak occupancy during the university hours that is from 8:00 till 17:00, after that it is used for self-studying or group works.

To reduce energy consumption due to lighting, the Pulse uses occupancy-controlled lighting with a power density of 9 W/m^2. The lighting system is also developed to use the energy directly from the PV panels to eradicate any energy loss due to conversion from DC to AC.

9.2 Melanchthon Kralingen, Rotterdam

The Melanchthon Kralingen school (fig 9.6) is a secondary school providing pre-vocational training to almost 345 students. In 2018, the school moved into the building, which was a big leap in terms of design, energy efficiency, comfort from the old building of the 1970s. The new building has a gross floor area of 4230 m^2 and was designed by KAW Architects.

Fig 9.6: Melanchthon School, Rotterdam. Source: KAW architects.

9.2.1 Building Layout

Due to the limited plot size and construction area, the building has compacted many functions into just two floors. The ground floor comprised of practice rooms, a library, sports hall, and multi purpose central area, whereas the first floor has all the classrooms. The classrooms are arranged along the building façade in all orientations (fig 9.7) to maximise the use of daylight and passive solar heat gain in winters.

Fig 9.7: First floor plan indicating different activities. Source: KAW Architects

9.2.2 Building Envelope

External Walls, Roof, External Floors

The thermal insulation of the school building was proposed in consultancy with Wolf+Dikken advisors. The insulation levels of the opaque part of the façade were proposed in line with the Dutch Building Decree (Bouwblsuit), 2012. The external façade was proposed to have an R-value higher than 4.5 m^2.K/W, whereas the roof and the external floors have an R-value higher than 6 m^2.K/W. The ground floor was proposed to have an R-Value higher than 3.5 m^2.K/W.

Glazing, Infiltration, Solar shading

The school building has a uniform window to wall ratio of .60 throughout in all the orientations except the east façade. The glazing units proposed are double glazing units with Uframe less than 1.6 W/m^2.K and HR++ glass with a Uglass less then 1.1 W/m^2.K. The glazing unit also has a g-value of .35. All external doors were also proposed to have a U-value of less than 1.65 W/ m^2.K, as mentioned in Bouwblsuit,2012.

The infiltration values in the School buildings were limited .42 dm3/s / m^2 at a pressure difference of 10Pa.

To avoid heat gain through windows, the school building uses fixed overhangs and side fins as a building design strategy (fig 9.8). The windows are also equipped with external roller blinds.

Fig 9.8: Deep set windows with side-fins and overhang as design strategy. Source: KAW Architects

9.2.3 Climate Control

Heating and Cooling

The school building utilises district heating network from ENCO Rotterdam for heating and hot water. The district heating system provides a supply temperature of 50 °C, which is supplied to the underfloor heating and climate ceilings for heating. However, the school building does not have any active cooling and relies on natural ventilation for cooling.

Ventilation

The Melanchthon school uses balanced ventilation with heat recovery system with a possibility of natural ventilation by opening windows. The heat recovery system is capable of using summer bypass to provide free cooling when the outdoor temperature is comfortable. The system is designed to provide a minimum of 8.5l/s per person, according to Class B of "fresh school" guidelines. Like the Pulse building, the ventilation is controlled by CO_2 sensors to limit CO_2 levels of 950 ppm, according to "Fresh School" Class B.

9.2.4 Occupancy and Lighting

Unlike the pulse building, the school is operated only for 7 hours between 9:00 and 16:00 for five days a week. The building is equipped with lighting control with presence detection with a maximum power density of 8 W/m^2 for classrooms while 10W/m^2 for sports function.

Part 4

Identification of Overheated Spaces

10. Overheating Risk in Case Study Buildings

As mentioned in previous sections, climate change will have an impact on the educational building. To incorporate climate change, it is first essential to test the buildings in the present scenario. Therefore this chapter will discuss a methodology designed to identify the spaces which may overheat. Further, the chapter will also discuss analytical methods prescribed by the Dutch standards to check the risk of overheating in the present scenario.

10.1 Work flow Design

To evaluate the case studies for the risk of overheating in the different climate scenarios, it is essential to follow a pragmatic approach concerning existing studies, available methods, and validation of the results. Figure 10.1 illustrates the methodology designed and each steps are discussed sequentially.

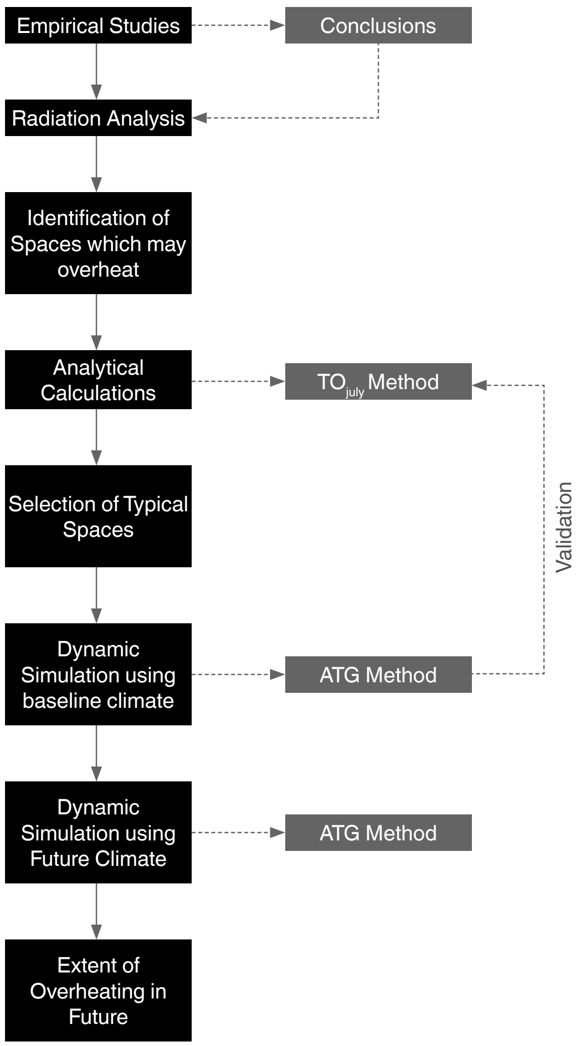


Fig 10.1: Workflow design for identify the risk of overheating in different climate scenarios.

10.2 Empirical Studies

To identify the spaces which may overheat, literature studies were conducted through scientific papers and journals found in databases such as Scopus, Science Direct, TU library, and Elsevier. To narrow down the studies and observe the trends of overheating studies, the search was limited to the past 20 years. Furthermore, essential keywords such as educational buildings, school buildings, university buildings, overheating, temperate climate were used to limit the research. From the research, 8-10 papers were then analysed, and the results were tabulated in table 10.1. The table illustrates the author, publishing year, spaces analysed, overheating criteria, and the results.

Author/s	Year	Assumed Spaces	Overheating Criteria	Spaces evaluated/resulted in overheating
Jenkins et al.	2009	• Teaching spaces with office type areas which may need air conditioning if necessary. • Larger communal areas not being used in same frequency.	Percentage of occupied hours in the teaching areas that exceed 28 degree.	• Teaching spaces in all directions
Coley et al.	2010	• Classrooms	CIBSE TM36	• Classroom with south façade, heavy construction and no infiltration.
Teli et al.	2011	• Classrooms	Survey and Aerial Photo analysis	• Classrooms with NE and SE orientation with outdoor tarmac surface, bitumen roof, light weight construction, single glazing and lack of wind exposure.
Kamensky et al.	2014	• Classrooms	Percentage of occupied hours in the teaching areas that exceed 28 degree.	• Classrooms located at South – East Façade direction.
Gupta et al.	2014	• Office Space • Teaching Room	Percentage above 1% of annual occupied hours over Operative Temperature of 28 degree	• Office facing south west façade – Second Floor • Teaching Room facing south west façade- ground floor.
Zinzi et al.	2017	• Classrooms	Percentage above 28 degree	• Classrooms at the upper floor. • South Facade
Irulegi et al	2017	• University Classroom	Percentage above 25 degree	• Seminar room facing north west façade on the second floor.
Lykartsis et al.	2017	• Classrooms	Building Bulletin 101	• Classroom in South direction
Heracleous & Michael	2018	• Classrooms	CIBSE	• Classroom in all directions direction

Table 10.1: Literature studies on overheated spaces in educational buildings.

From the empirical studies, it was observed that the teaching spaces like classrooms, seminar rooms are most likely to be overheated because of large occupant loads. With regards to the location of the spaces, it was observed that the spaces which are on the south, south-east, north-east, and north-west are susceptible to overheating. Furthermore, the spaces which are on the top floors are under the risk of overheating, considering the external heat gain through the façade and roof both.

10.3 Solar Radiation Analysis

From empirical studies, it was observed that spaces on the top floors in South, South-West, North-East, and North-West are susceptible to overheating. However, these results are depended on the context of the building. Therefore, based on this assumption, solar radiation analysis was done on the case study buildings to analyse the spaces with the highest solar radiation considering the nearby context.

The radiation analysis was done using Rhino and Ladybug plugin for grasshopper. The analysis was performed for summer months that are May-September as specified in ISSO 74. For the analysis, the baseline 2008 1% climate file was used.

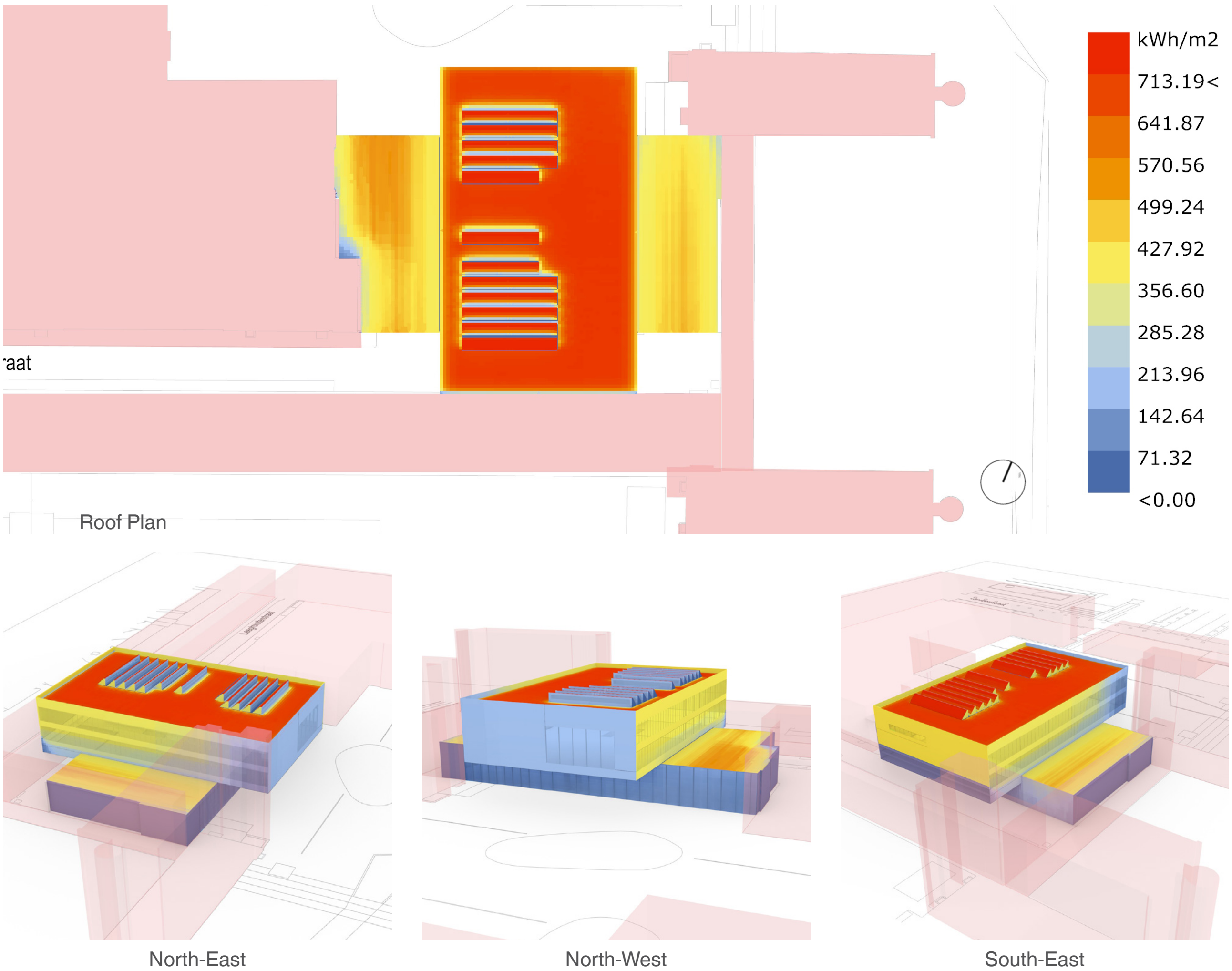
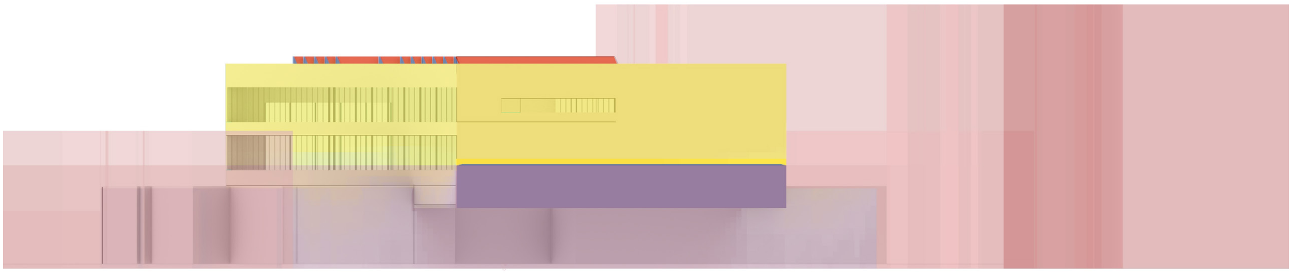


Fig 10.2a: Solar Radiation Analysis for the Pulse Building. Source: Author



South

Fig 10.2b: Solar Radiation Analysis for the Pulse Building. Source: Author

Hall 1 and Hall 2 on Ground Floor

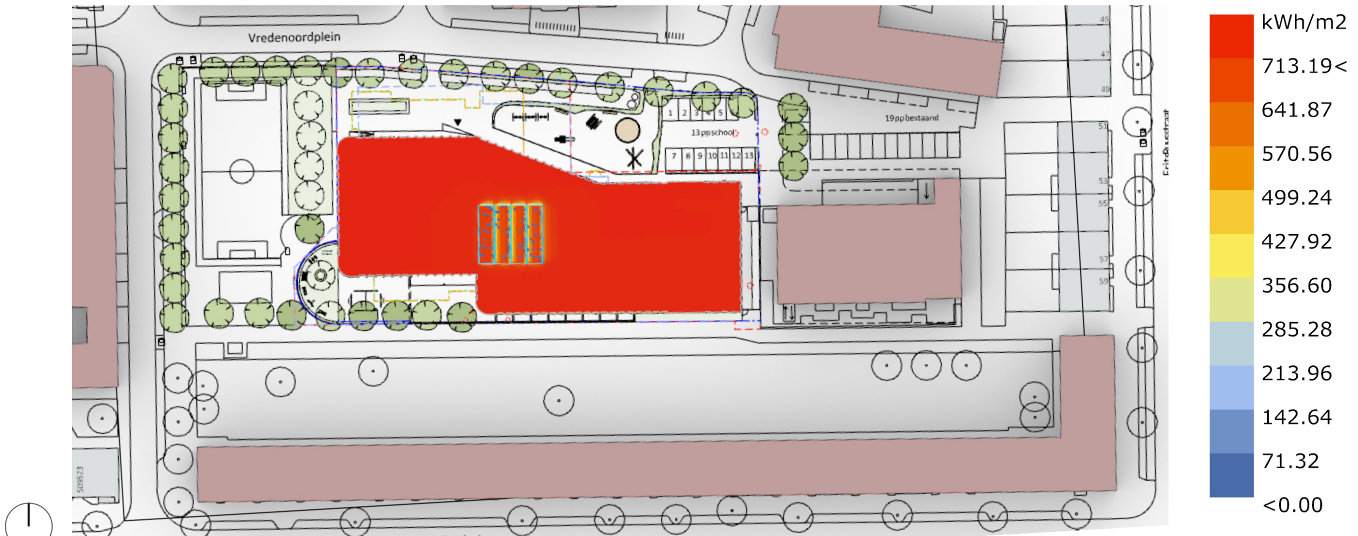
Hall 4 on Intermediate Floor

Hall 5 on First Floor

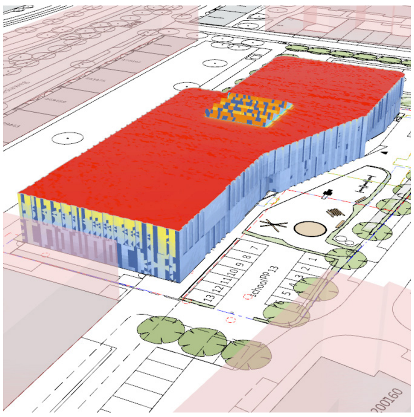
Hall 8,Hall9 and Hall 10 on Second Floor

Fig 10.3: Identified spaces in Pulse buildings which may overheat.

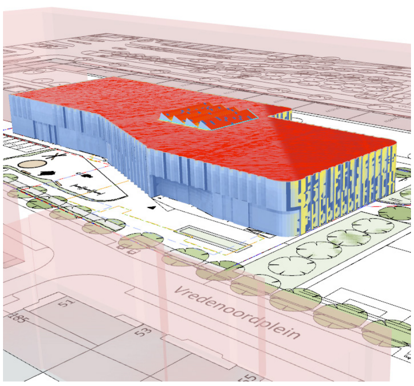
Figure 10.2a & 10.2b represents the radiation analysis for the pulse building. Considering the effect of the nearby buildings, it can be observed that the spaces on the south, south-east, North-East, and North-West are susceptible to overheating. However, looking at the spaces in these orientation (fig 10.3), lecture halls on the northeast direction on intermediate, first, and the second floor are susceptible to overheating. Another interesting observation was for the seminar halls on the ground floor because of solar gain through the roof; thus, they may also overheat.



Roof Plan

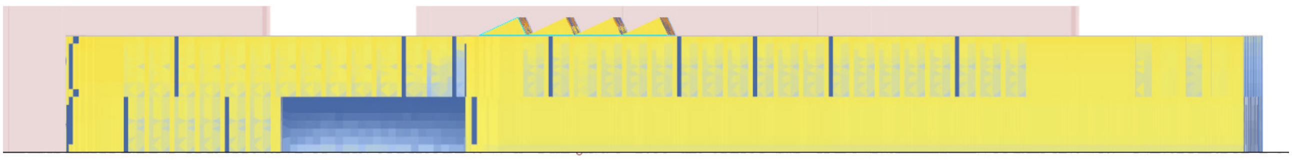


North-East



North-West

South-East



South

Fig 10.4: Solar Radiation Analysis for the Melanchthon School.

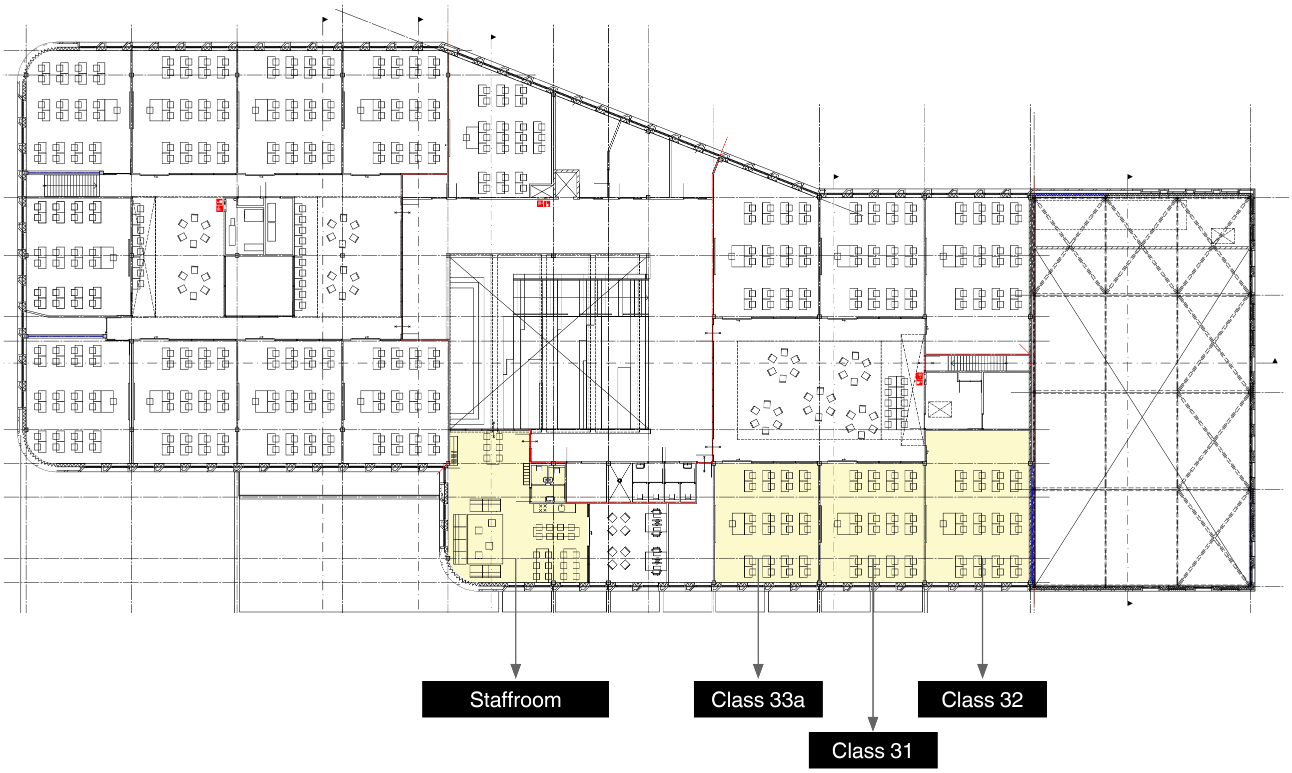


Fig 10.5: Identified spaces on second floor in School building which may overheat. Source: Author

Similarly, fig 10.4 represents the radiation analysis for the school building. From the analysis, it was observed that the spaces in South orientation and on the first floor are more susceptible to overheat. In the school building on the first floor (fig 10.5), the classrooms are located on the south façade, thus have the potential to overheat. Therefore, three spaces, staffroom, class 31 (similar to class 33a) and Class 32 were chosen.

10.4 Analytical Calculations

With the help of empirical studies and radiation analysis, a total of ten spaces (seven in Pulse, three in School) were identified, which may have a risk of overheating. Ideally, these spaces would now be analysed using dynamic simulation to look for the real risk of overheating. However, simulating ten spaces would be time-consuming. Therefore, analytical methods were first used for narrowing the spaces into typical cases. The Dutch standards also advocate the use of an analytical method first to indicate the risk and followed by dynamic simulations for confirmation. For the same, a TOjuly method is proposed by NTA8800, which indicates if the room would overheat or not.

10.4.1 TOjuly

The TOjuly method, as specified in NTA8800, is a static heat balance calculation model that indicates the probability of excess temperature in July. Therefore, the higher the TOjuly value, the higher the risk of overheating. To understand the risk of overheating from the TOjuly value, the value between 0-2 is considered to be a minimum risk. A value between 2-4 is considered as moderate risk, and a value higher then 4 indicates a high risk of overheating (Lente Akkord, 2019).

The TOjuly calculation is currently only applicable for residential and free-running buildings. It only considers ventilation as a source of reducing temperature. According to a report by Lente Akkord (2019), the TOjuly value for a free-running building should ideally be 1.0; if it exceeds 1.0, dynamic simulation must be used to identify the number of overheated hours according to GTO or ATG calculations. For buildings with active cooling, the TOjuly value is automatically set to 0.

10.4.2 Calculating TOJuly

Currently, the TOjuly value is only calculated for residential buildings by using a software called "UNIEC 2", which is developed by Dutch Enterprises. For the study, the TOjuly method, along with Hamidreza Shahriari, was simplified using Dutch Standards such as NEN5128, NEN7120, and NTA8800. The simplified method was then converted into an excel calculation sheet. To validate the simplified method, an example of a simple residence was used. The TOjuly was then calculated using the simplified method and UNIEC 2 software. The simplified method was further adjusted to obtain statistical similarity between the outputs of both the methods. A detailed description of the validation is mentioned in Appendix C.

Although the simplified method was validated enough to be used in place of UNIEC2 software, it is still valid for residential building only. Therefore, the TOjuly method was adapted for the educational buildings using the standards NTA8800, NEN 7120, and NEN 5128. The adapted method, however, still needs to be validated using dynamic simulation.

The TOjuly value can be calculated using equation 10.1, and a detailed calculation of the variables in the equation, along with the adjustment for educational buildings, is mentioned in Appendix D.

$$TO_{juli;i} = \frac{Q_{beh;koud;juli;i}}{(H_{T;koud;i} + H_{V;koud;i}).t} \quad (10.1)$$

Where :

$TO_{juli;i}$	Numerical Value for the risk of overheating in the month of July calculated for zone i	K
$Q_{beh;koud;juli;i}$	Cooling Requirnment for Zone i for the month of July	MJ
$H_{T;koud;i}$	Heat Loss Coefficient due to transmission of zone i.	W/K
$H_{V;koud;i}$	Heat Loss Coefficient due to ventilation of zone i.	W/K
t	Length of the month of July	Ms

10.4.3 Input Parameters

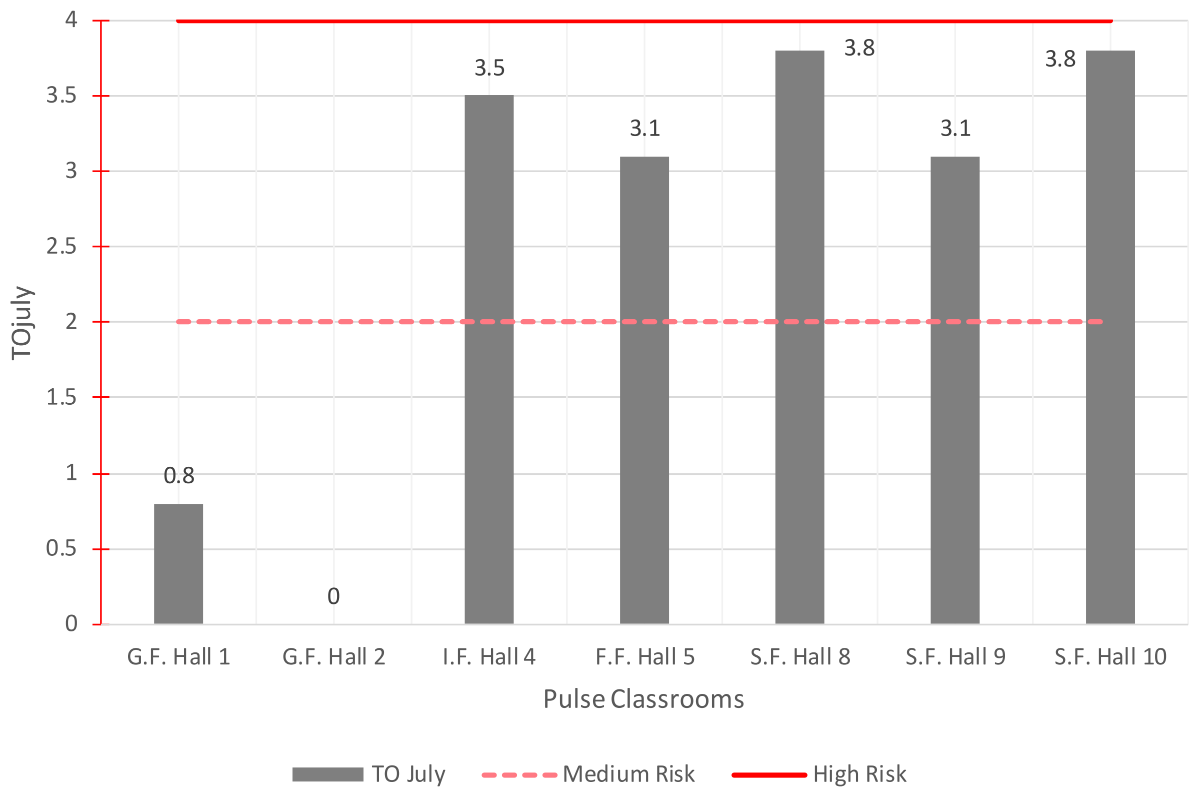
For the calculation, parameters mentioned in Table 10.2 were used as the input. The input parameters were reduced in the simplified method as compared to the detailed methods provided in NTA 8800. The input parameters are also the constraints which can generally be determined during the early phase of the design. Therefore, the simplified method can be used for the analysis of overheating in the early design phase and thus can reduce the valuable time before jumping to dynamic calculations.

Parameters	Description	Units
Dimensional Properties		
Zone Area	Area of the space excluding walls which needs to be analysed.	m^2
Zone Perimeter	Perimeter of the space which needs to be analysed.	m
Wall Area	This represents the total area of the façade including the opaque and transparent part.	m^2
Roof Area	Area of the roof of the space to be analysed.	m^2
WWR	Window to wall ratio of the space to be analysed.	-
Construction Properties		
Specific Effective Thermal Capacity	Thermal capacity value depended on the type of construction.	KJ/m^2K
Thermal Properties		
U-Value of Glass	U-value of the transparent/glass of the façade.	W/m^2K
g-value of Glass	Sun entry factor for daylight from opening	-
U-Value of Opaque Part	U-Value of the opaque part of the façade.	W/m^2K
U-Value of Roof	U-value of the roof	W/m^2K
U-Value of Floor	U-value of the floor	W/m^2K
Solar Shading Factor		
R(Shading Factor)	Dimensionless shading reduction factor for the external façade structure.	-
I_{sol}	Total Incident solar radiation for the orientation of the zone.	W/m^2
Internal Properties		
q_v	The amount of ventilation needed for cooling	dm^3/s
Internal Load	Combination of occupant, equipment and lighting load which will contribute towards internal load.	W/m^2

Table 10.2: Input Parameters for Simplified TOjuly Calculations.

10.5 Calculation Results

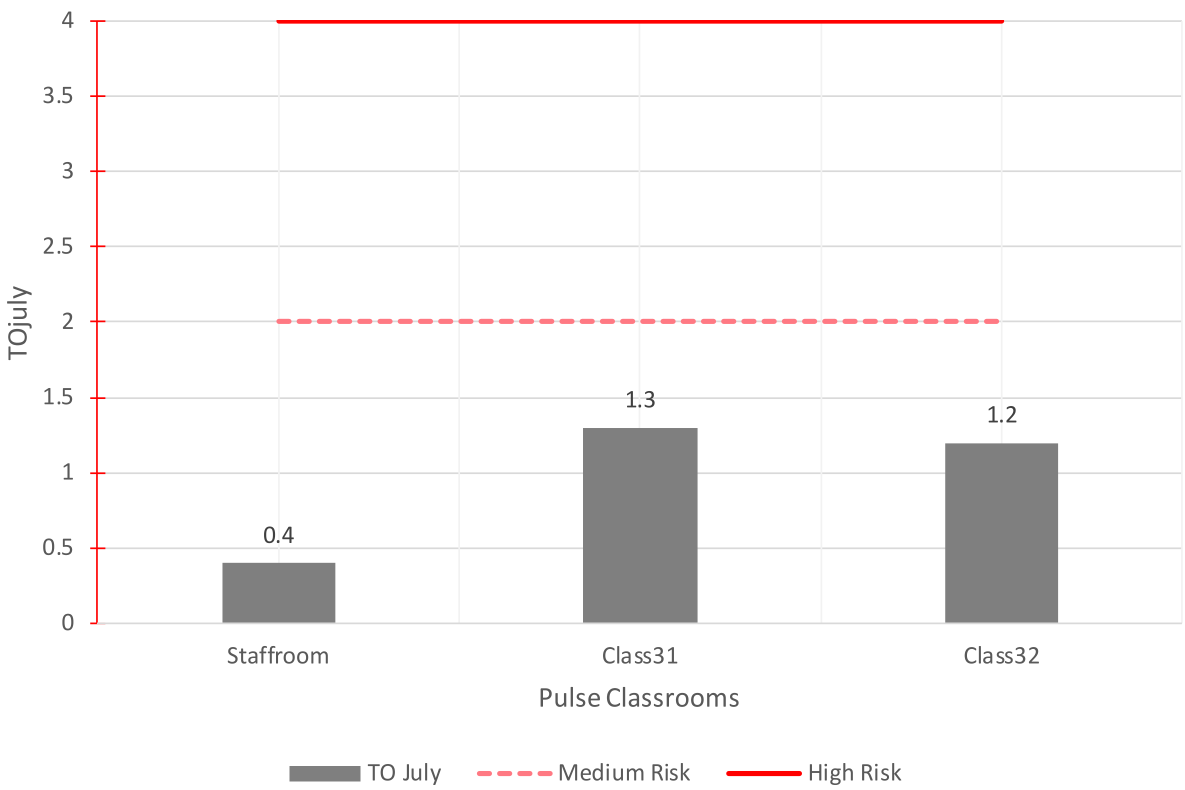
The ten spaces identified in both case studies were analysed using the simplified TOjuly method adapted for educational buildings. The parameters mentioned in table 10.2 were collected for each classroom and used as input in the excel calculation sheet. The values used for TOjuly calculation for all the selected spaces are mentioned in Appendix E. The calculated TOjuly values for each case study building were then compared. Graph 10.1 and 10.2 represent the TOJuly values for the Pulse Building and Melanchthon School, respectively.



Graph 10.1: TOjuly values for identified spaces in the Pulse Building.

From graph 10.1, it can be observed that the TOjuly value of the ground floor halls do not exceed 1, thus have a lower risk of overheating. On the other hand, the halls on the northeast side of the building have TOjuly value close to 4, thus indicating the risk of overheating. However, TOjuly does not consider any active cooling measure; that is why the TOjuly values are close to 4. In reality, Pulse building uses active cooling measures to cool the building. Therefore, dynamic simulations would be required to understand the extent of overheated hours.

For dynamic simulations, Hall 10 and Hall 8 were chosen since both the spaces showed a higher TOjuly value. These spaces are also located on the top floor, thus receives solar gain from roof and façade both.

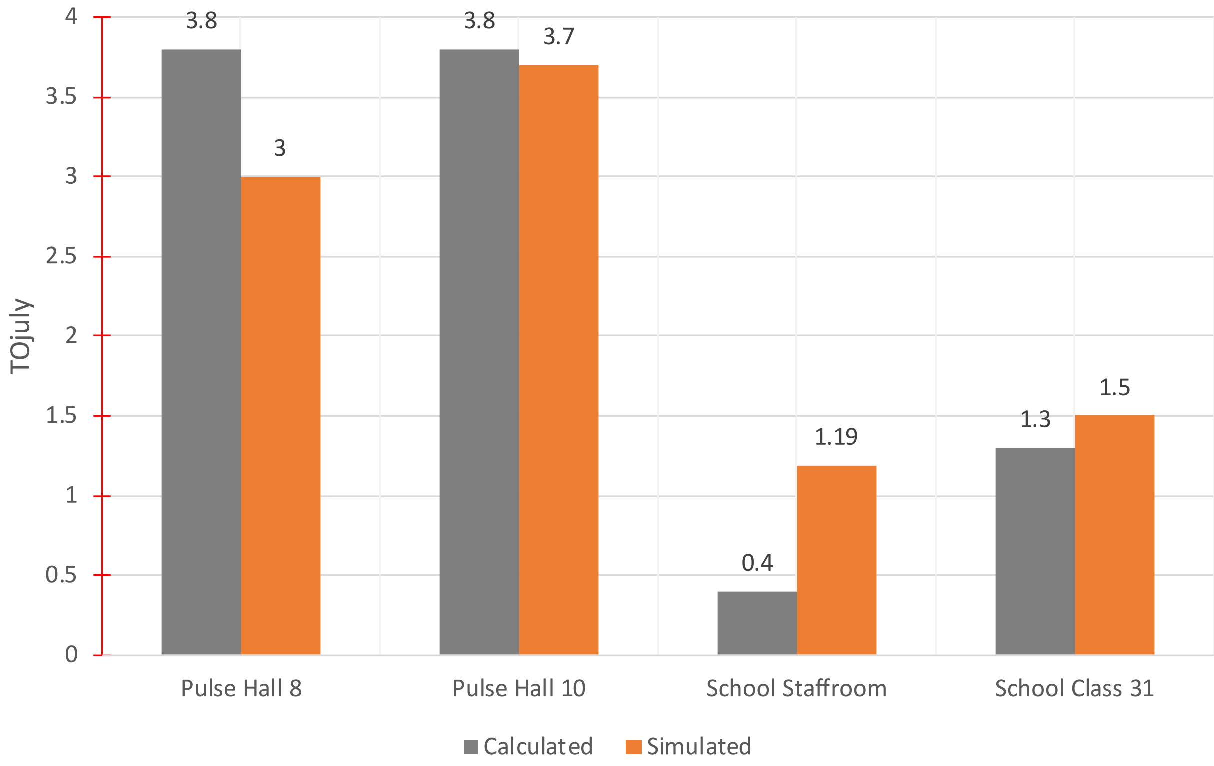


Graph 10.2: TOjuly values for identified spaces in the Melanchthon School .

Graph 10.2 for the school building shows that currently, the spaces have a very low risk of overheating. However, since class 31 and class 32 have their TOjuly values more then 1, the dynamic simulation would be needed to identify the extent of overheating. For dynamic simulation, class 31 was chosen since it represents a typical case of classrooms facing south. Ideally, TOjuly value should be calculated for each orientation, but for the corner staffroom, the solar radiation and WWR values were averaged. Therefore, the staffroom will also be simulated to check if taking the average is acceptable for TOjuly calculations for a corner room.

10.6 Validation of adjusted TOjuly method for educational buildings

From the simplified analytical calculation, the selected ten spaces were narrowed down to two typical cases in each case study. However, since the method was adjusted for educational buildings, it is essential to validate the results using building energy simulation model. The models were made using design builder software, which will be discussed thoroughly in chapter 11. The TOjuly value, as discussed, returns the excess temperature in the month of July. This excess temperature is calculated, keeping the average indoor temperature limit of 24^{O}C. Therefore, to validate the calculated TOjuly values, the difference between the average simulated air temperature for July and 24 ^{O}C was calculated. To validate the adjusted Tojuly method, the difference between simulated TOjuly value and calculated TOjuly value should not be more than 20%. Graph 10.3 illustrates the comparison between the calculated and simulated TOjuly value.



Graph 10.3: Comparison between simulated and Calculated TOjuly value .

From graph 10.3, it can be observed that the difference between calculated and simulated TOjuly values are within the acceptable limit of 20% except for staffroom in the school building. The simulated TOjuly indicates a higher value as compared to the calculated one. Since, the analytical method already takes the static equation, averaging data from two different orientations would affect the result. Therefore, the method cannot be applied for corner space, and dynamic simulation must be used.

10.7 Conclusions

From the empirical studies, it was observed that generally, learning spaces like the classroom and lecture halls are more susceptible to thermal comfort problems due to large occupant loads for a longer time. It was also observed that the spaces on South, South-East, North-West and North-East orientation are most likely to overheat. Lastly, the spaces on the top floors are susceptible to overheating in summers due to solar gains from the façade and the roof.

However, the studies are very much dependent on the context of the building. Therefore, to understand the impact of context in blocking the summer sun, a solar radiation analysis was performed on the case studies. The case studies were modelled in Rhino with a nearby context, and solar radiation analysis was done using the ladybug tool for grasshopper. From the analysis, it was observed that the spaces on the North-East , North-West, and South indeed receive high solar radiation. Therefore, the spaces located in these directions were identified from both the case studies.

In School Building, three spaces were considered for evaluation. From the analysis, the classrooms facing south and on the top floor might have a risk of overheating. Therefore, staffroom, class 31, and class 32 were chosen for further analysis.

Dynamic simulation of the selected ten spaces would cost a lot of time; therefore, TOjuly analytical method was first used to narrow down the spaces. The TOjuly indicates the temperature excess as an indicator of overheating. The method is generally used for residential buildings; for the study, the method was adapted for the educational buildings. The method was validated using dynamic simulation, and it was concluded that the adapted method could be used for education buildings; however, it cannot be used for corner spaces.

From TOjuly calculation, the ten identified spaces from each case study were narrowed down to Hall 8 and Hall 10 in the Pulse building, while classroom 31 from the school building. In the school building, the corner staffroom was also selected for dynamic simulations since the results from calculated TOjuly were inconclusive. Fig 10.6 illustrates the selected spaces for dynamic simulations.

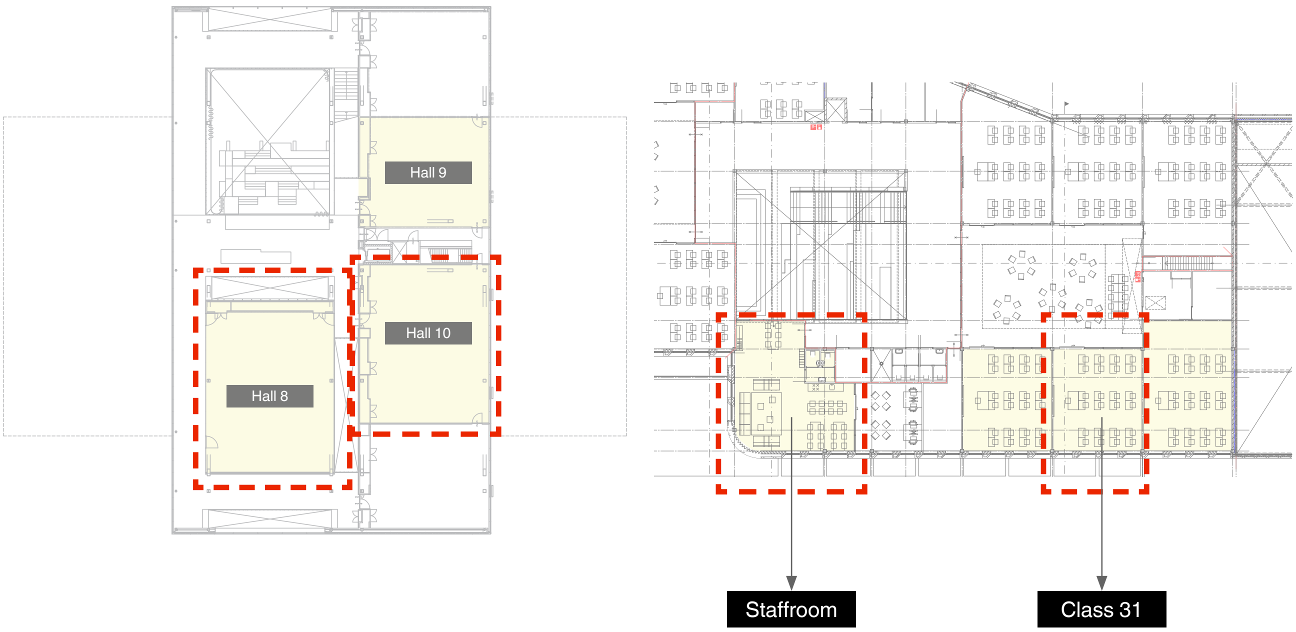


Fig 10.6: Identified typical case for dynamic simulations.

11. Dynamic Simulations

The analytical method was useful in narrowing down to common spaces that may overheat; however, there are limitations to such calculation models. Since the calculation is based on the static model, the dynamic effect of environmental parameters like solar radiation, air movements, rain are not considered correctly. Dynamic simulations thus are useful in determining the impact of climate onto the building more accurately. This chapter will discuss the workflow used for energy modelling, the input parameters, and identifying the extent of overheating in future climate compared to the baseline weather data.

11.1 Work flow Design

As discussed in section 10.1, dynamic simulation is the next step to evaluate the overheating risk in the selected spaces. The selected spaces were converted into a building energy model using "design Builder" software. The workflow adopted for dynamic simulations is illustrated in fig 11.1

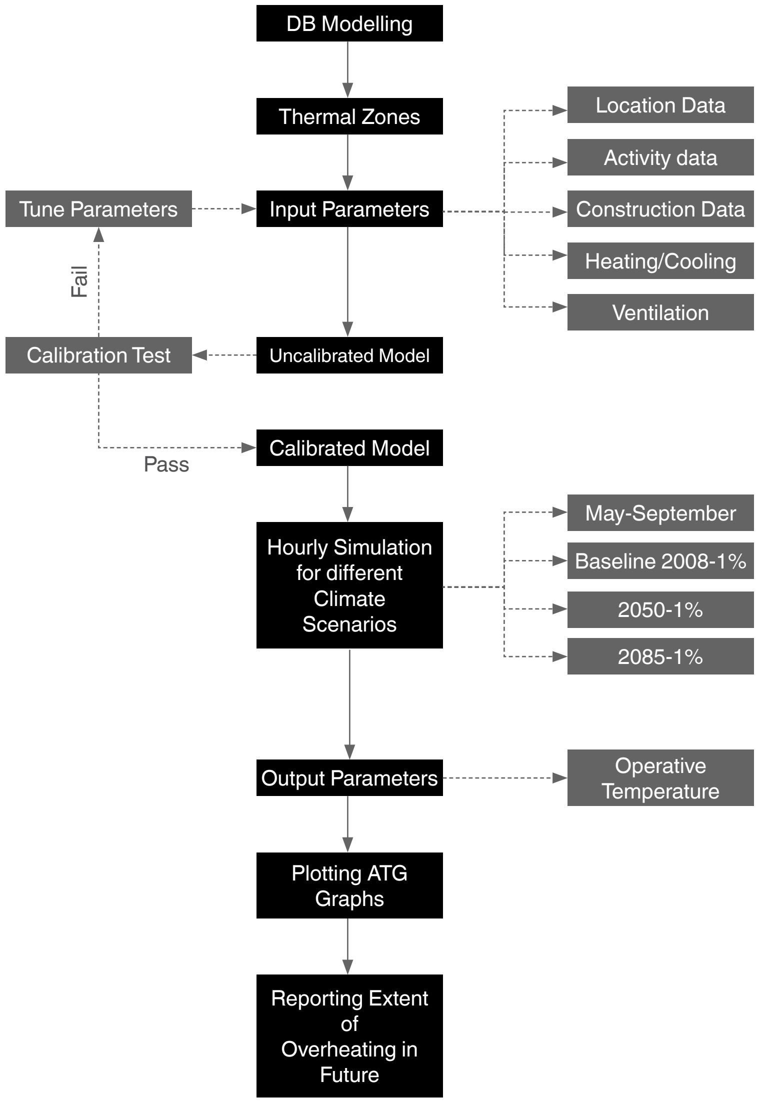


Fig 11.1: Detailed workflow for dynamic simulation and overheating prediction.

11.1.1 Design Builder Modelling and Thermal Zones

Design Builder is a dynamic simulation software used for comfort, energy, daylight, life cycle, and cost estimation in the design phase. The tool has its advantages in providing a graphical interface for the core energy plus simulation platform, which makes it acceptable under the architectural fraternity as well. However, like other simulation tools, the quote "trash in, trash out" also applies to design builder simulation. Therefore, the user must reduce the uncertainties of the input parameter as much as possible to obtain valid results.

As a first step to the simulation, a 3d model for both cases was prepared using the design builder's inbuilt modelling tools. The design builder models are sensitive towards the dimensional properties of the space, openings, shading devices, and nearby context. Out of which, the essential factors are the block and zone dimensions.

Blocks in Design Builder are the basic geometric shapes with designated dimensions, assembled to form the entire building. Whereas, thermal zones (zones) are internal divisions of the block to form spaces that are analysed. The design builder model uses a hierarchy of data transfer to assign properties to the model. A property assigned at the building level transfers to the individual surfaces of the zone. Design builder suggests two conventions of signifying the block and zone dimensions (fig 11.2). The UK NCM convention is applicable in the UK; for the study, the general convention was used for making blocks and zones.

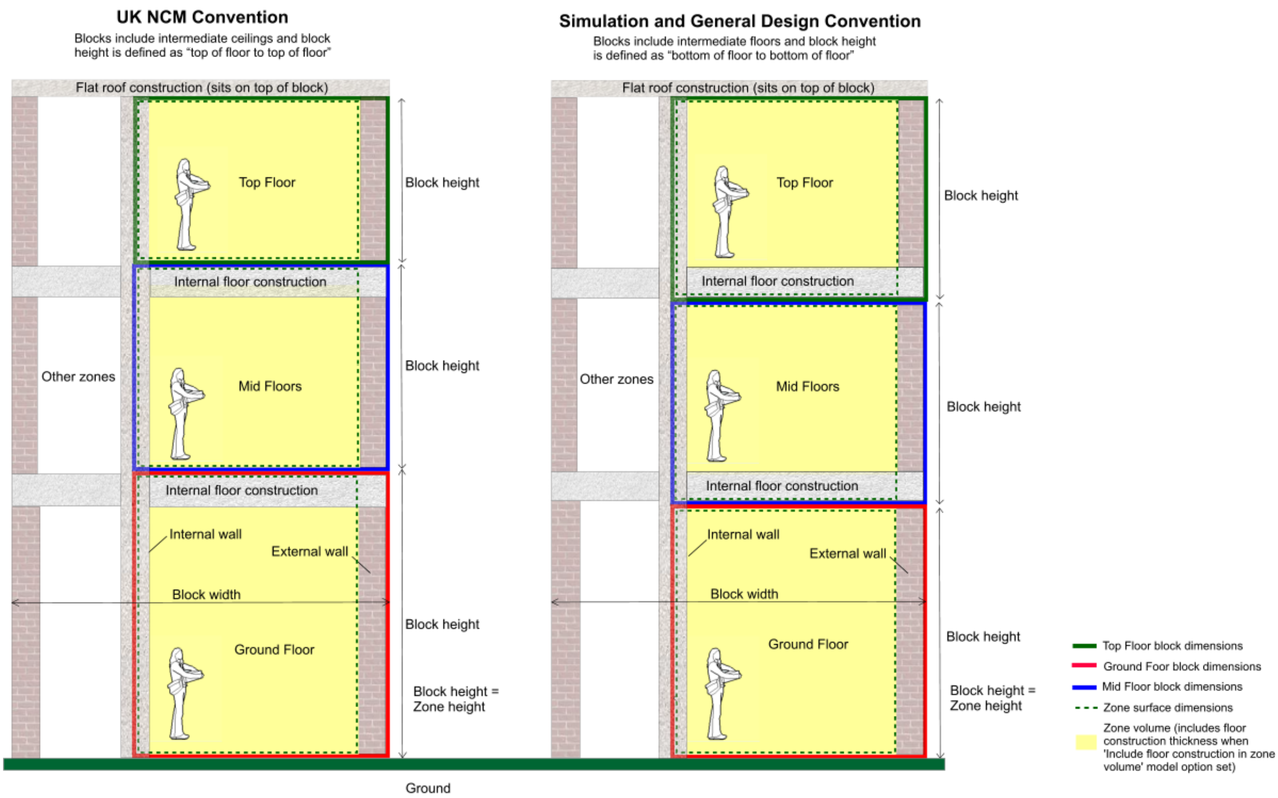


Fig 11.2: Design Builder Block Dimensioning Conventions. Source: Design Builder Simulation Document V6, 2019

11.1.2 Input Parameters

After successful modelling of the desired space, the design builder requires input parameters used for comfort analysis, daylight calculation, energy usage, cost, and lifecycle assessment. These parameters are illustrated in fig 11.3 and will be discussed individually for the case study buildings in the subsequent sections.

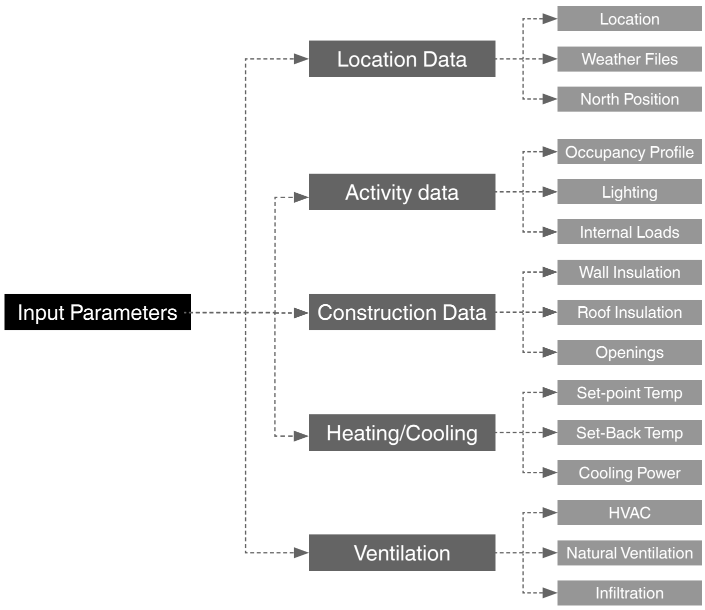


Fig 11.3: Input parameters used in design builder simulations.

11.1.3 Calibration Process

The simulation models prepared using Design Builder have the capability of producing results as close to the real scenario. However, the results are sensitive to the assumptions used for calculations. Therefore, it is essential to calibrate a simulation model to reduce the variation between the output of the simulations and the recorded data from the actual building. Although the calibration of simulation models is of utmost importance, there are no standards available internationally (Shadmanfar et al., 2019). However, there are some good practices and recommendations proposed by the ASHRAE Guideline 14 (Jeff S., Culp, & David E., 2005).

According to ASHRAE 2014, a numerical model for the dynamic simulation output must be produced, which can then be compared with the field data. (Jeff S. et al., 2005; Shadmanfar et al., 2019)The process is essentially iterative, where the goodness-of-fit is achieved by continuous iteration of changing parameters and re-comparing the output with the recorded data.

For comparing the datasets, ASHRAE guidelines suggest three indices namely Mean Bias Error (MBE), Coefficient of variation of Root mean square error [CV(RMSE)] and coefficient of determination (R2) (Leitão & Graça, 2017; Ruiz & Bandera, 2017; Shadmanfar et al., 2019).

1. **Mean Bias Error (MBE)**

The mean bias error measures the average error between the simulation and measured data in a particular period (Ruiz & Bandera, 2017). The MBE method is useful in providing insights towards the behaviour of the model too. A negative MBE value signifies the model being over predictive, while a positive value indicates the model being under predictive. An MBE value close to zero would indicate the model being calibrated. MBE can be calculated using the equation 11.1 (Leitão & Graça, 2017; Ruiz & Bandera, 2017).

$$MBE = \frac{\sum_{i=1}^{n}(m_i - s_i)}{n} \qquad (11.1)$$

Where :

MBE	Mean Bias Error
m_i	Measured data
s_i	Simulated data
n	Number of measured data points

2. **Coefficient of Variation of Root Mean Square Error [CV(RMSE)]**

The CV(RMSE) model measures the error variation between the calculated and simulated datasets. It is calculated as the ratio of Root mean square error and the mean of the dependent variable (UCLA, n.d.), where the Root mean square error represents the standard deviation of the error from the regression line ("RMSE: Root Mean Square Error - Statistics How To," n.d.). The CV(RMSE) is calculated according to equation 11.2 and represented in percentages.

$$CV(RMSE) = \frac{1}{\overline{m}}\sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n-p}} \cdot 100\% \qquad (11.2)$$

Where :

CV(RMSE)	Coefficient of Variation of Root Mean Square Error
$\overline{m}$	Mean of Measured Data
m_i	Measured data
s_i	Simulated data
n	Number of measured data points
p	Value is suggested as 1

The ASHRAE guideline suggests indicative values for the two indices to evaluate the calibration of the simulation model. These indicative values for MBE and CV(RMSE) are provided for both monthly as well hourly simulation (Leitão & Graça, 2017; Ruiz & Bandera, 2017) (table 11.1).

	Monthly Calibration	Hourly Calibration
MBE	<5%	<10%
CV(RMSE)	<15%	<30%

Table 11.1 Acceptance Criteria for calibrated simulation model. Author: Leitão & Graça, 2017; Ruiz & Bandera, 2017

11.1.4 Hourly Simulation and Weather Files

Since the focus is on summer comfort, the simulation will be run only for summer months. ISSO 32, determines summer months as between May and September. For comfort analysis, ISSO 32 indicates of using hourly simulation with a 1-hour time step. For determining the comfort conditions based on the ATG method, the TRY 1% exceedance weather file, according to NEN 5060 (2008), was considered (ISSO 74). As explained in chapter 6, the transformed weather files for the year 2050 and 2085 was used as future climate scenarios.

11.1.5 Plotting ATG Graphs

The Dutch adaptive thermal comfort model (ATG) is different from earlier versions of estimating the risk of overheating. In comparison to the GTO criterion, the ATG method does not provide the temperature exceedance hours but rather indicates the percentage of comfortable hours a space should satisfy according to comfort classes A, B, C (ISSO74). The method is also advantageous due to its hybrid nature of the application; that is, the method can be applied for both mechanically cooled buildings (Beta buildings) and Free-running buildings (Alpha buildings). The method was proposed in 2004 and was revised in 2014, which was based on the international European standard EN-15251. To access the comfort of the selected space in different climate scenarios fig 11.4 illustrates the steps taken. An example for an ATG graph is also illustrated in graph 11.1.

According to ISSO74, EN 15251, and “fresh school” guidelines, the classroom spaces have an expectation level of class B. As mentioned in table 4.3, in comfort class B, only 10% of the discomfort hours are allowed. As it can be observed in graph xx, that space, which is of Beta category, has almost 95% of the occupied hours (dots) underclass B limits. Only 5% of the hours exceed class B upper limit; thus, space can be considered as good. The dots which exceed class B are the overheated hours. Therefore, it should be kept within 10% for reducing any risk of overheating even in the future.

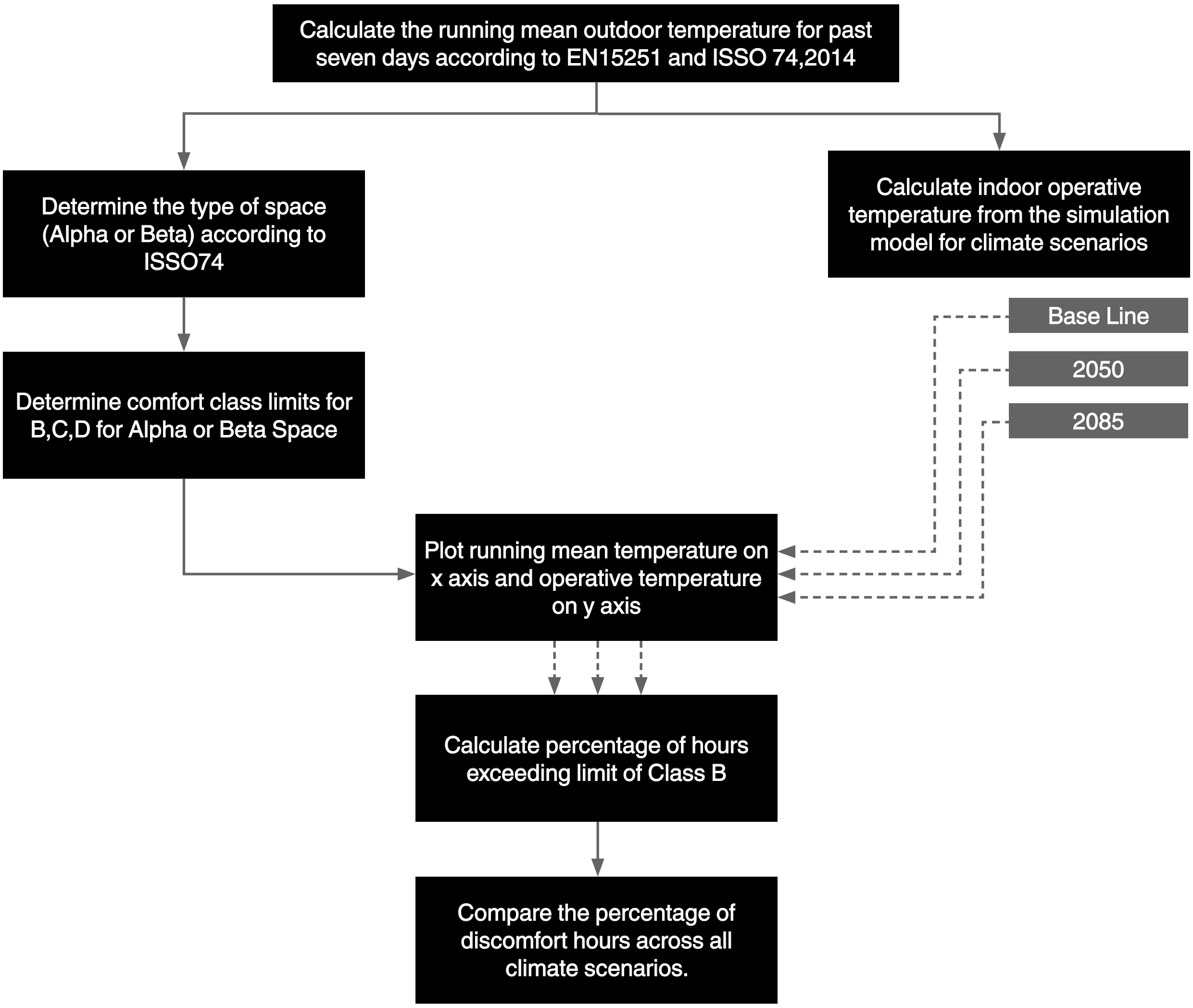
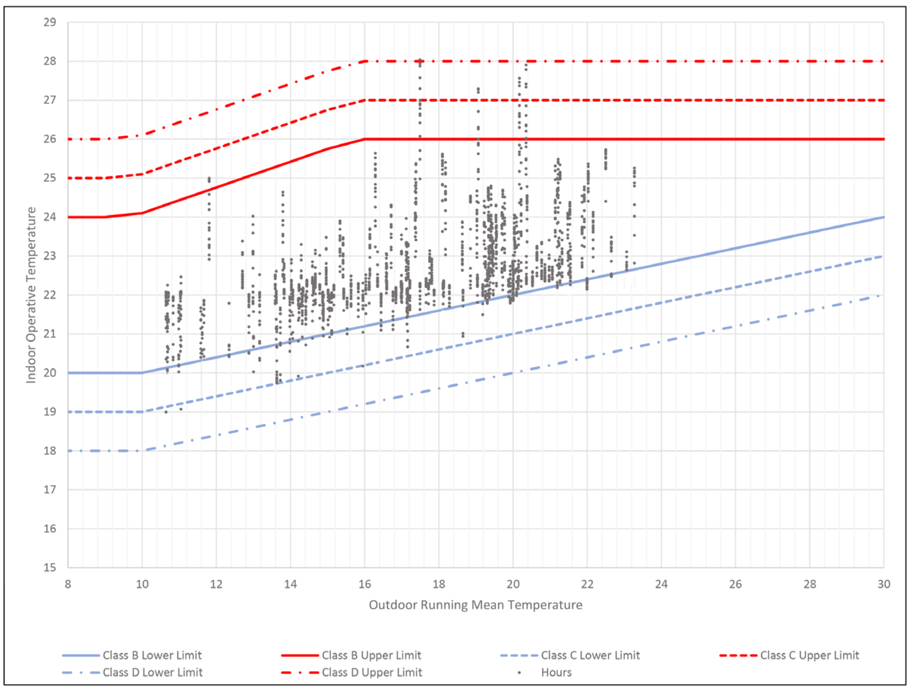
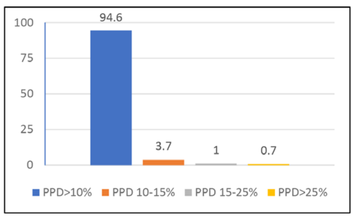


Fig 11.4: Steps taken for plotting ATG graphs for determining percentage of discomfort hours due to overheating. Source: Adapted from ISSO 74, Author



Building :	Pulse	
Room No.	Hall 10	
Room Type	Beta	
Temp. Type	Operative	
Analysis Period	May-Sept	
Occupied Hours	2448	
Thermal Performance	Good	
Class	Class B	
Comfort Bandwidth	No. of Hours	% of Time
Class B	2317	94.6
Class C	91	3.7
Class D	24	1
Above D	16	0.7



Graph 11.1: Example of an ATG graph for Pulse building, in baseline climate scenario.

It is to be noted that the percentage of discomfort hours (PPD) is calculated for the exceedance of both upper and lower limits. However, for the study, only the number of hours that exceed the upper limits are calculated as PPD% to show the overheating hours clearly.

11.2 Pulse, TU Delft Campus

11.2.1 Model and Thermal Zones

The pulse building was modelled with the nearby context and ground till the first floor as component blocks. Only the second floor was created as a zone. According to the analytical results in chapter 10, thermal zones for hall 8 and hall 10 were prepared to further analysis (Appendix F).

11.2.2 Input Parameters

After thermal modelling, data for location, activity, construction, heating/cooling, and ventilation were extracted from the data collected. The exact materials and finishes used in the building were entered into the Design Builder with as little approximation as possible.

Location Data

Parameters	Input
Location	Rotterdam The Hague
Simulation Weather File	Baseline 2008 1% 2050 1% 2085 1%
Site Orientation (North)	-23 from true North

Activity Data (Hall 8 and Hall 10)

Parameters	Input	Remarks
Template	Hall /Lecture Theatre/ Assembly Area	
Hall 8 Floor Area and Volumes	252.79 m^2, 1061.7 m^3	
Hall 10 Floor Area and Volumes	181.78 m^2, 763.49 m^3	
Hall 8 Occupancy Density	0.33 (people/m^2)	Calculated from capacity of 85 students including tutor.
Hall 10 Occupancy Density	0.46 (people/m^2)	
Schedule	Mon-Sun (8:00 - 00:00)	Schedule for week was determined from calibration and Data from BMS system.
Metabolic Activity	Reading Seated	

Parameters	Input	Remarks
Clothing	Winter :1 clo, Summer .5 clo	
Cooling Set point	21°C	As specified by Building Facility Manager and Calibration
Cooling Set Back	24°C	Set Back temperature for Radiative Cooling.
Minimum Fresh Air	10L/s per person	Back calculated from the mechanical ventilation capacity.
Lighting	9W/m²	As specified by DGMR
Equipment	20W/m²	As specified by DGMR
Note 1: The gains data for the calculation was set to simple instead of lump. Note 2: Heating was not included into the simulation process.		

Construction Data

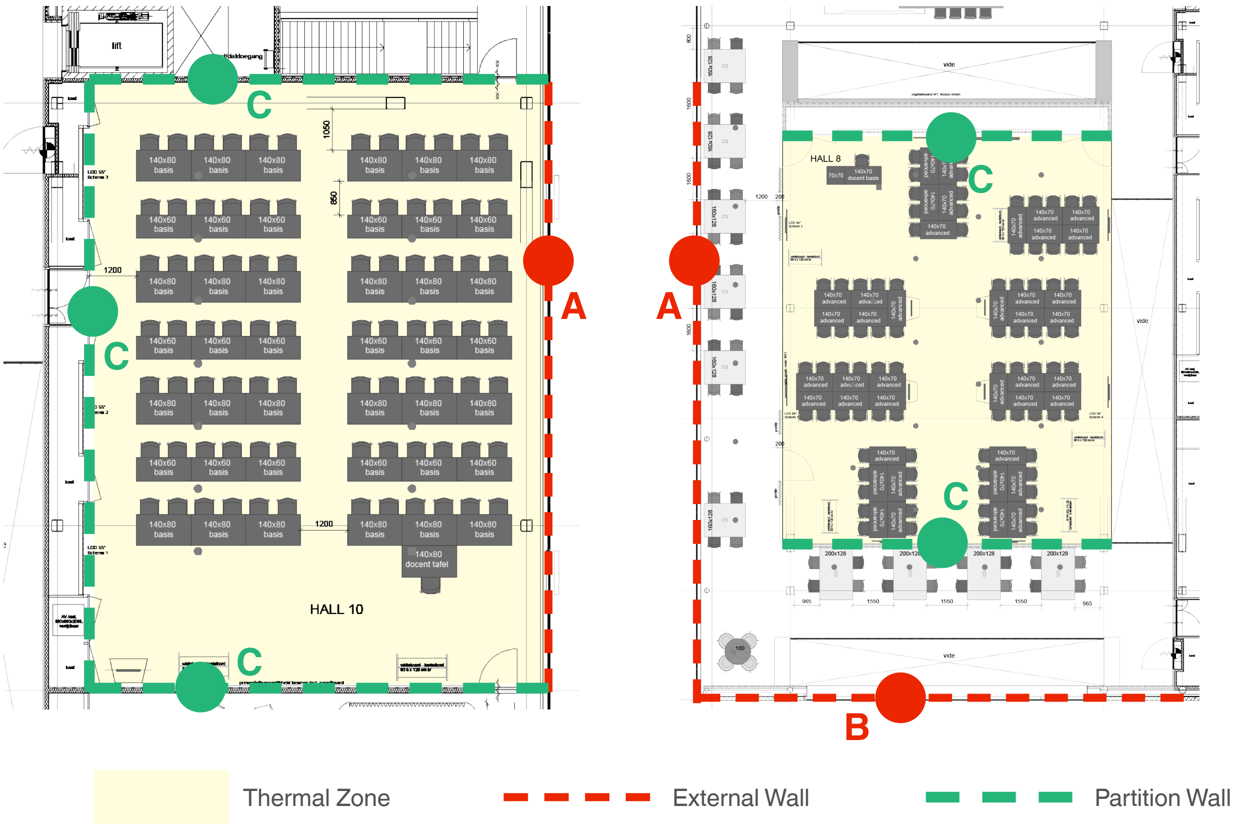


Fig 11.5: Construction data legend for Hall 8 and Hall 10.

External Wall A (Facade Opaque elements)		
Category		Walls
Region		Netherlands
Definition Method : Layers		
Outer Layer		
1	Material	Soda Lime Glass
	Thk. (m)	.0060
2	Material	Air Gap
	Thk. (m)	.01
3	Material	Foam -Phenol
	Thk. (m)	.250
4	Material	Plasterboard
	Thk. (m)	.0125
Inner Layer		
Avg. Thickness (m)		.275
R-Value (calculated)		7.46 m²K/W
R-Value (specified)		≥7 m²K/W

External Wall B (Facade Opaque elements) and Skylights		
Category		Walls
Region		Netherlands
Definition Method : Layers		
Outer Layer		
1	Material	Metal-aluminium cladding
	Thk. (m)	.0010
2	Material	Foam Phenol
	Thk. (m)	.148
3	Material	Metal-aluminium cladding
	Thk. (m)	.0010
4	Material	NCM-Unventilated Cavity
	Thk. (m)	.290
5	Material	Plasterboard
	Thk. (m)	.00125
6	Material	Mineral Fibre (wool)
	Thk. (m)	.100
7	Material	Plasterboard
	Thk. (m)	.00125
Inner Layer		
Thickness (m)		.565
R-Value (calculated)		7.2 m²K/W
R-Value (specified)		≥7 m²K/W

Note 3: The internal floor was made adiabatic surfaces, however, construction of floor is still required to include any effect of thermal mass.

Partition Wall C		
Category		Partitions
Region		Netherlands
Definition Method : Layers		
Outer Layer		
1	Material	Plasterboard (CIBSE)
	Thk. (m)	.0250
2	Material	Mineral Fibre (wool)
	Thk. (m)	.100
3	Material	Plasterboard (CIBSE)
	Thk. (m)	.0250
Inner Layer		
Thickness (m)		.15
R-Value (calculated)		3.2 m²K/W
R-Value (specified)		3.5 m²K/WK

Internal Floors		
Category		Slabs
Region		Netherlands
Definition Method : Layers		
Outer Layer		
1	Material	Cement Screed
	Thk. (m)	.080
2	Material	Cast Concrete
	Thk. (m)	.395
Inner Layer		
Thickness (m)		.475
R-Value (calculated)		2.3 m²K/W

Roof		
Category		Roof
Region		Netherlands
Definition Method : Layers		
Outer Layer		
1	Material	Prefab (roofing)
	Thk. (m)	.075
2	Material	Foam Polyisocyanate
	Thk. (m)	.165
3	Material	Concrete Cast-Cellular
	Thk. (m)	.320
Inner Layer		
Avg. Thickness (m)		.560
R-Value (calculated)		7.0 m²K/W
R-Value (specified)		≥7 m²K/W

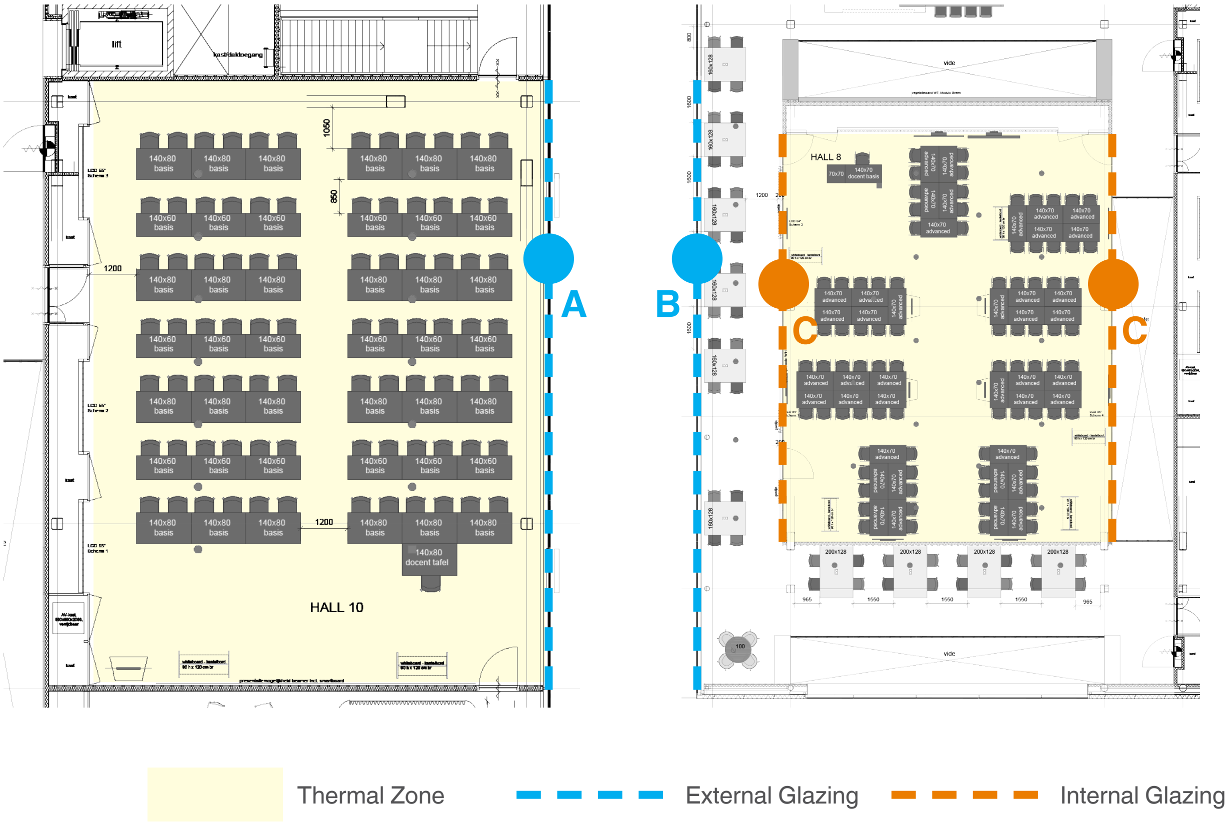


Fig 11.5: Glazing data legend for Hall 8 and Hall 10.

External Glazing A (Facade Transparent elements)	
Category	Double Glazing
Region	Netherlands
Definition Method : Simple	
G-Value	0.4
Light Transmission	.7
U-Value	1.0 W/m²K
U-Value (specified)	≤ 1.65 W/m²K
Solar Shading	
Internal Blinds	Shading Roll-Medium Translucent
Position	Internal
Control	Solar (according to ISSO 32) Setpoint : 250 W/m²
Operation	8:00 - 18:00

Internal Glazing C	
Category	Single Glazing
Region	Netherlands
Definition Method : Layers	
Material	Sgl Loe
Thk. (m)	.009
G-Value	0.7
Light Transmission	.8
U-Value	3.7 W/m²K

Note 4: The external glazing B on the SW side of the building is similar to external glazing A except it does not have any internal shading devices.

HVAC and Ventilation (Hall 8 and Hall 10)

Parameters	Input	Remarks
Infiltration		
Hall 8 & Hall 10 (m^3/h-m^2 at 4Pa)	.27	Calculated linearly from .15dm³/s-m² at 10Pa
Mechanical Ventilation		
Hall 8 & Hall 10 Outside Air Definition	Minimum fresh air per person	It is used for determining the capacity of AHU for supply ventilation.
Hall 8 & Hall 10 Operation Schedule	00:00 - 7:00 , 20% Capacity 8:00-23:00 , 100% Capacity	As noticed from BMS system and updated using calibration
Cooling		
Hall 8 Cooling Capacity	12.5 KW	Updated from calibration
Hall 10 Cooling Capacity	13 KW	Updated from calibration
COP	20	ATES can achieve a COP of 30, Design builder does not allow COP more then 20.
Minimum Supply Temperature	16°C	According data collected and calibration
Hall 8 Operation Schedule	00:00 - 2:00 , off 3:00-23:00 , 100% Capacity	Since, radiative cooling is difficult to model with Simple HVAC operation, cooling schedule was used in mimicking, cooling through climate ceilings. The schedule was fine tuned during calibration process on sub hourly level.
Hall 10 Operation Schedule	00:00 - 2:00 , off 3:00-23:00 , 100% Capacity	Since, radiative cooling is difficult to model with Simple HVAC operation, cooling schedule was used in mimicking, cooling through climate ceilings. The schedule was fine tuned during calibration process on sub hourly level.
Note 5: Simple HVAC was used for modelling mechanical cooling and ventilation. Note 6: Since, simple HVAC does not support modelling of radiative slow system. It was incorporated by adding cooling schedules according to the radiative climate ceiling operation according to BMS and was fine tuned through calibration. Note 7: Economisers or Free cooling is possible by the system but it is not monitored or used in the present scenario. Therefore was excluded from the input parameters.		

11.2.3 Calibration Process

As mentioned in section 10.1.3, the design builder model is required to be calibrated with the actual data from the building to represent a correct baseline model for further analysis.

Pulse building is a smart building with an active Building management system to monitor the operation of the building. Through the BMS system, the real-time data and recorded data from past months can be extracted concerning the occupancy schedule, operation of mechanical ventilation, operation of radiative cooling, indoor air temperature, and CO_2 levels. For the calibration process, recorded indoor air temperature for July 2019 and simulated indoor air temperature was compared. Fig 11.6 illustrates the workflow adopted to calibrate Hall 10 and Hall 8. Another important point to note is that Hall 8 is surrounded by corridor and workplaces, which are less conditioned as compared to the hall itself.

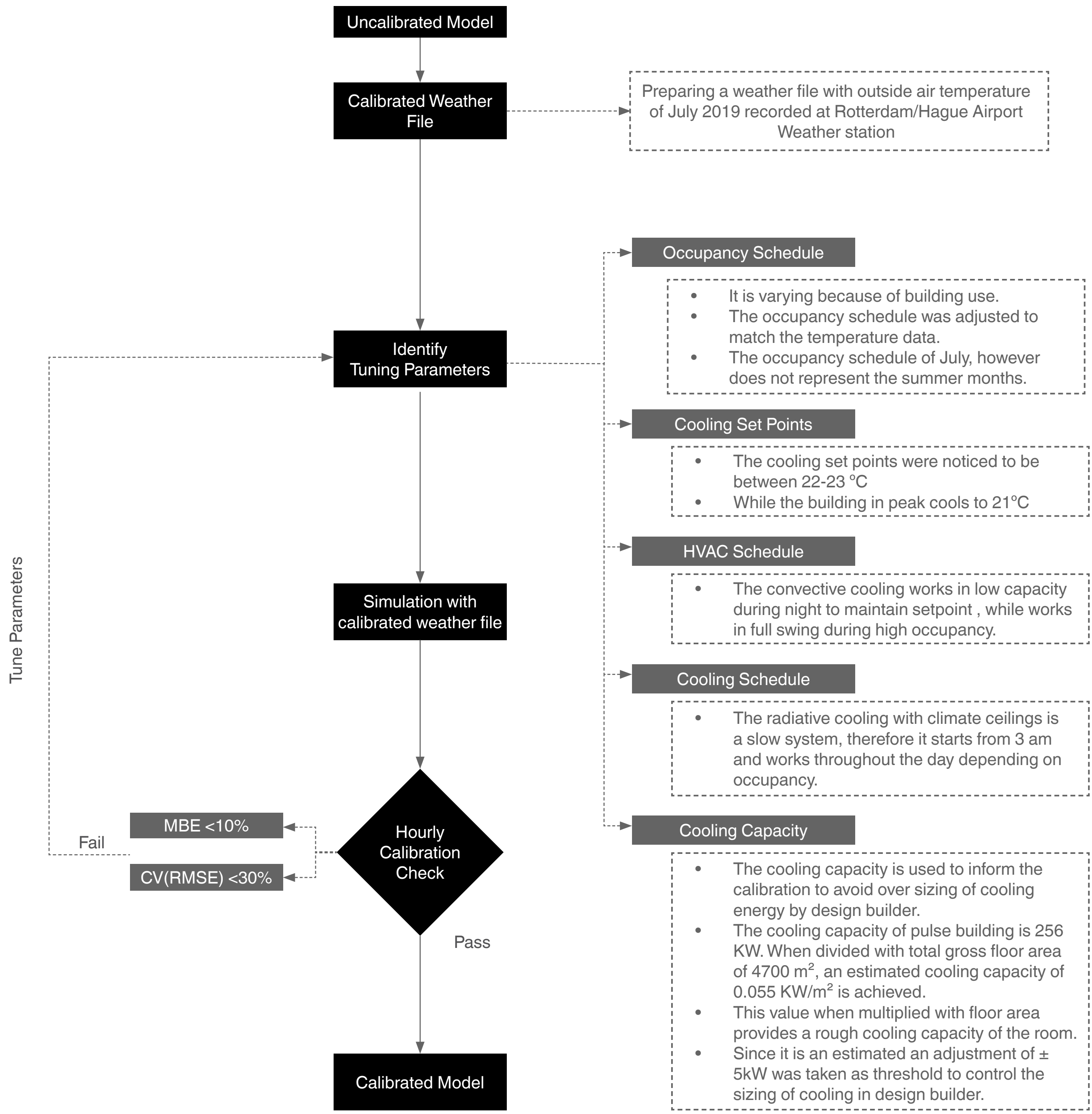


Fig 11.6: Steps taken for calibrating design builder model.

Appendix G illustrates the comparison between measured and simulated indoor temperatures, while the MBE and CV(RMSE) values are illustrated in table 11.2

Statistical Model	Limit	Hall 10	Corridor	Hall 8
No. of Iterations	-	85	37	28
MBE	< 0.1	.01	.08	.02
CV(RMSE)	< 0.3	.03	.06	.03
Result		**Calibrated**	**Calibrated**	**Calibrated**

Table 11.2: Calibration check for Hall 8,10 and Corridor for Pulse Building.

11.2.4 ATG Graphs and Results

The calibrated models were used for simulating the baseline, 2050, and 2085 weather files for the summer season that is May-September. The indoor operative temperature was then used to plot ATG Graphs, and the percentage of discomfort hours was determined. The ATG graphs for Hall 8 and Hall 10 are mentioned in Appendix H. The comparison between the discomfort hours in baseline and future climate scenarios is described in 11.4.

11.3 Melanchthon School, Rotterdam

11.3.1 Model and Thermal Zones

The school building was modelled with ground floor as component blocks. Only the second floor was created as a zone. According to the analytical results in chapter 10, thermal zones for corner staffroom and class 31 were prepared for further analysis (Appendix F).

11.3.2 Input Parameters

After thermal modelling, data for location, activity, construction, heating/cooling, and ventilation were extracted from the data collected. The exact materials and finishes used in the building were entered into the Design Builder with as little approximation as possible.

Location Data

Parameters	Input
Location	Rotterdam The Hague
Simulation Weather File	Baseline 2008 1% 2050 1% 2085 1%
Site Orientation (North)	-0 degree from true North

Activity Data (Staffroom and Class 31)

Parameters	Input	Remarks
Staffroom Template	Office and Consulting Area	
Class 31 Template	Teaching Areas	
Staffroom Floor Area and Volumes	71.81 m^2, 239.59 m^3	
Class 31 Floor Area and Volumes	53.27 m^2, 175.79 m^3	
Staffroom Occupancy Density	0.417 (people/m^2)	Calculated from capacity of 30 teachers.
Hall 10 Occupancy Density	0.469 (people/m^2)	Calculated from capacity of 24 students and 1 teacher.

Parameters	Input	Remarks
Schedule	Mon-Fri (9:00 - 16:00)	According to ISSO 32
Staffroom Metabolic Activity Template	Light office work/standing/ walking	
Classroom 31 Metabolic Activity Template	Reading Seated	
Clothing	Winter :1 clo, Summer .5 clo	According to ISSO 32
Cooling Set point	24°C	Cooling setpoint for mechanical ventilation beyond which free cooling will be used.
Natural Ventilation	22°C	Natural Ventilation setpoint beyond which occupants will tend to open windows.
Minimum Fresh Air	8.5L/s per person	According to ISSO 32, Fresh School Class B
Lighting	8W/m²	Lighting control with linear control type. Specified by Wolf+Dikken Building Physics Consultants.
Staffroom Equipment and Computers	9 W/m²	Calculated from ISSO 32
Class 31 Equipment and Computers	7.5 W/m²	Calculated from ISSO 32
Staffroom Internal Loads Schedule	80% operation during lunch hours. 40% operation rest	Assumed
Class 31 Equipment and Computers	40% operation during lunch hours. 80% operation rest	Assumed
Note 1: The gains data for the calculation was set to simple instead of lump. Note 2: Calculated natural ventilation is considered for understanding the effect of window openings.		

Construction Data

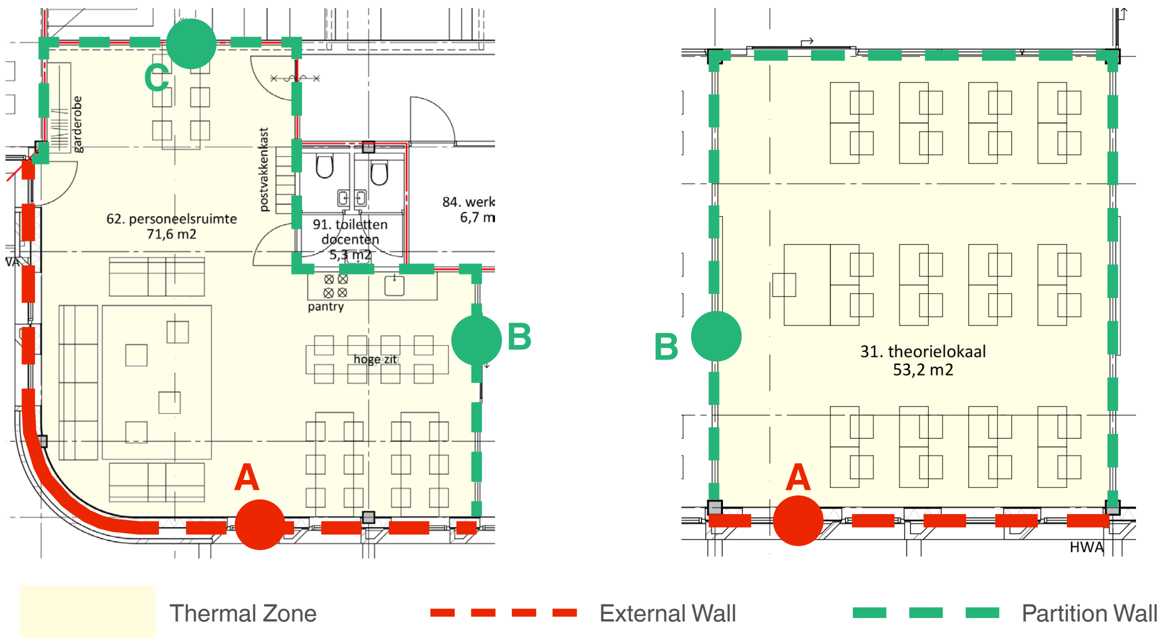


Fig 11.7: Construction data legend for Staffroom and Class 31.

External Wall A (Facade Opaque elements)		
Category		Walls
Region		Netherlands
Definition Method : Layers		
Outer Layer		
1	Material	Brick tiles
	Thk. (m)	.020
2	Material	Elastomeric Foam, Flexible
	Thk. (m)	.020
3	Material	Glass Fibre/Wool-fibre Quilt
	Thk. (m)	.20
4	Material	Plasterboard
	Thk. (m)	.025
Inner Layer		
Avg. Thickness (m)		.265
R-Value (calculated)		4.55 m²K/W
R-Value (specified)		≥4.5 m²K/W

Partition Wall B		
Category		Partitions
Region		Netherlands
Definition Method : Layers		
Outer Layer		
1	Material	Plasterboard (CIBSE)
	Thk. (m)	.0250
2	Material	Mineral Fibre (wool)
	Thk. (m)	.50
3	Material	Plasterboard (CIBSE)
	Thk. (m)	.0250
Inner Layer		
Thickness (m)		.10
R-Value (calculated)		1.8 m²K/W

Roof		
Category		Roof
Region		Netherlands
Definition Method : Layers		
Outer Layer		
1	Material	Cast Concrete
	Thk. (m)	.07
2	Material	PVC
	Thk. (m)	.0015
3	Material	Foam-Polyisocyanate
	Thk. (m)	.14
4	Material	EPS
	Thk. (m)	.030
5	Material	Concrete Cast - Compacted
	Thk. (m)	.320
5	Material	Plastervboard
	Thk. (m)	.075
Inner Layer		
Avg. Thickness (m)		.636
R-Value (calculated)		6.07 m²K/W
R-Value (specified)		≥6 m²K/W

Internal Floors		
Category		Slabs
Region		Netherlands
Definition Method : Layers		
Outer Layer		
1	Material	Linoleum tile
	Thk. (m)	.001
2	Material	Cast Concrete(Dense)
	Thk. (m)	.070
2	Material	Aerated Concrete slab
	Thk. (m)	.260
Inner Layer		
Thickness (m)		.331
R-Value (calculated)		2 m²K/W

Note 3: The internal floor was made adiabatic surfaces, however, construction of floor is still required to include any effect of thermal mass.

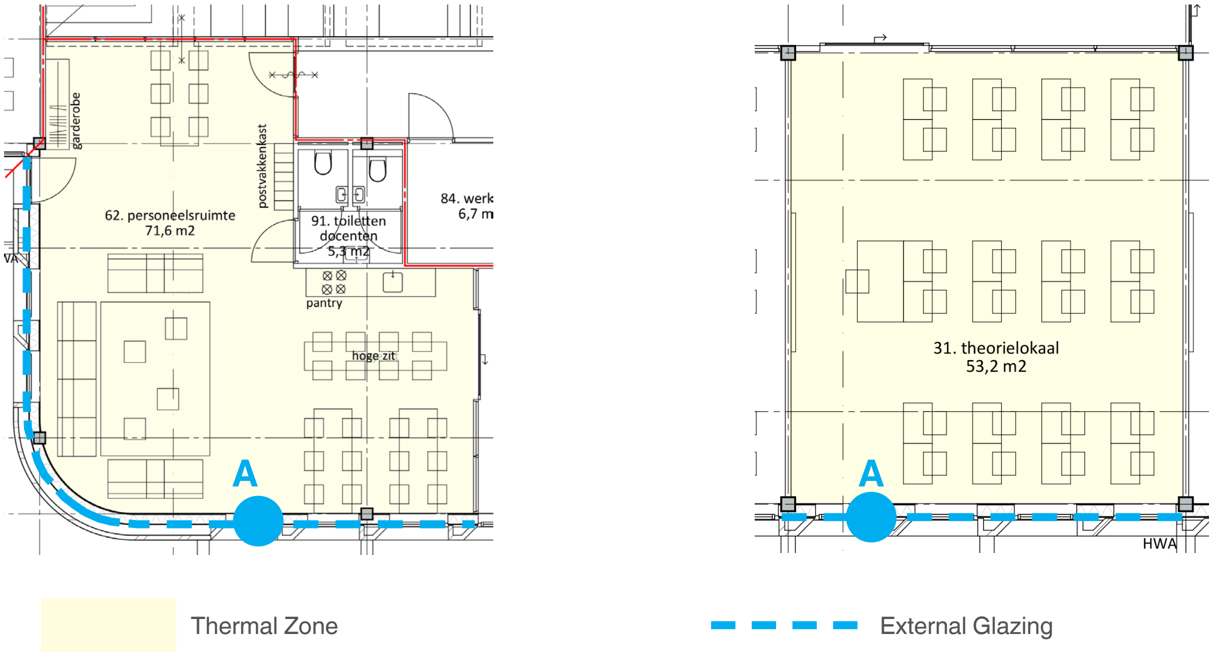


Fig 11.8: Glazing data legend for Staffroom and Class 31.

External Glazing A (Facade Transparent elements)		Remarks
Category	Double Glazing	
Region	Netherlands	
	Definition Method : Simple	
G-Value	0.35	
Light Transmission	.6	
U-Value	1.1 W/m²K	
U-Value (specified)	≤ 1.65 W/m²K	
	Solar Shading	
Internal Blinds	Shading Roll-Light Opaque	
Position	Outside	
Control	Solar Setpoint : 250 W/m²	ISSO 32
Operation	9:00 - 18:00	
Free aperture	20% of total glazing area	In reality 40% of the total window is openable manually. Considering the fact opening all windows would cause local discomfort, a 20% of opening factor is considered.
Opening Position	Left	
Opening Schedule	9:00-16:00	According to Occupancy Schedule
Discharge Coefficient	0.65	

HVAC and Ventilation (Staffroom and Class 31)

Parameters	Input	Remarks
Infiltration		
Staffroom & Class 31 (m^3/h-m^2 at 4Pa)	.6	Calculated linearly from .42dm³/s-m² at 10Pa
Mechanical Ventilation		
Staffroom & Class 31 Outside Air Definition	Minimum fresh air per person	It is used for determining the capacity of AHU for supply ventilation.
Staffroom & Class 31 Operation Schedule	9:00-16:00	Similar to Occupancy Schedule
Economiser (Free Cooling) Capacity of AHU	5ACH	Specified by Wolf and Dikken
Cooling		
Staffroom & Class 31 Cooling Capacity	0 KW	In Simple HVAC modelling, free cooling or summer bypass is used for cooling with Cooling Capacity as 0KW to avoid any active cooling.
COP	20	COP of free cooling according Spoel,2019
Minimum Supply Temperature	16°C	Assumed
Staffroom & Class 31 Operation Schedule	Always On	The school building uses summer bypass for using natural ventilation for cooling. Therefore, the cooling with economiser must work whenever, inside temperature exceeds cooling setpoint and outside temperature is lower then indoor temperature.
Natural Ventilation through windows		
Staffroom & Class 31 Operation Schedule	9:00-16:00	
Wind Factor	0.8	Taking into account for the nearby trees which will affect the wind pressure and velocities.
Modulate openings	Min Tin-Tout = 5°C	Windows opening completely till the Min. difference between inside and outsdie air temperature is 5°C
	Max Tin-Tout = 16°C	Windows are shut when the maximum difference between inside and outside air temperature is 16°C
Limit Factor for openings	0.010	Factor used for closing windows between min and max temp difference.
Note 5: Simple HVAC was used for modelling mechanical cooling , free cooling. Note 6: Calculated natural ventilation is used to calculate the effect of openings Note 7: Economisers or Free cooling is modelled from the guide by Spoel,2019.		

11.3.3 Calibration Process

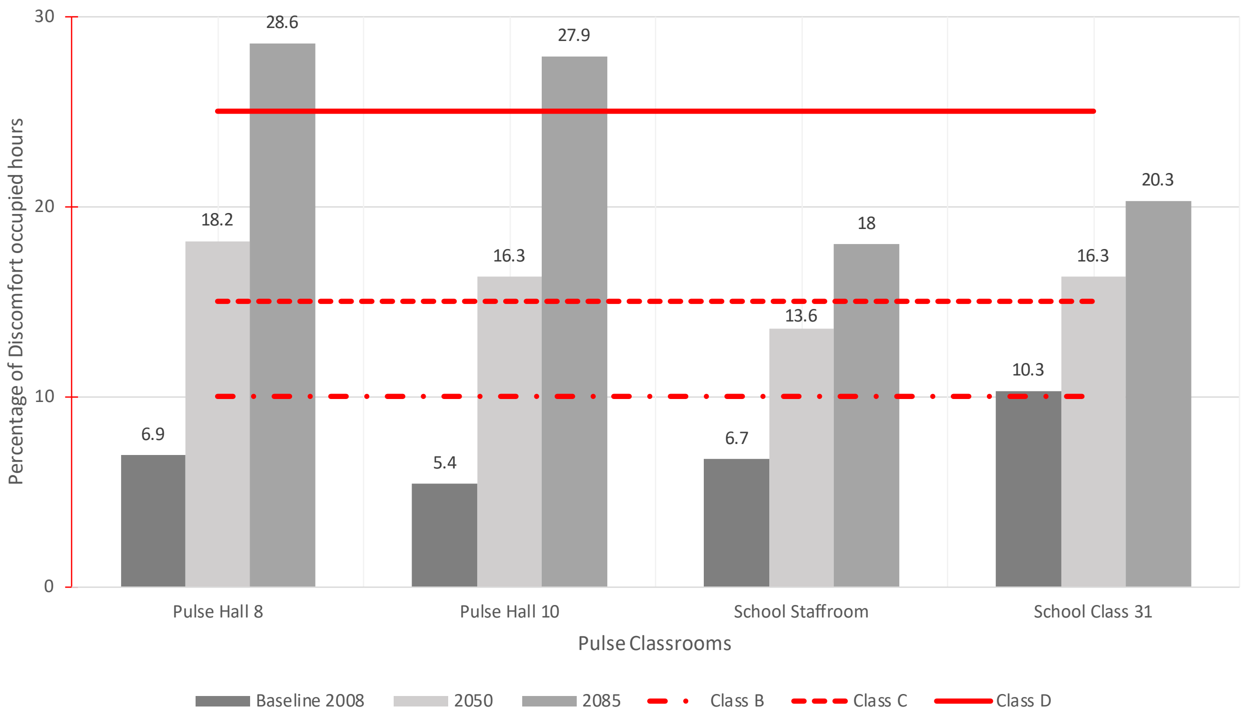
There was no data available through the BMS system or could be recorded. Therefore, the model was calibrated by comparing simulations and analytical calculations.

11.3.4 ATG Graphs and Results

The calibrated models were used for simulating the baseline, 2050, and 2085 weather files for the summer season that is May-September. The indoor operative temperature was then used to plot ATG Graphs, and the percentage of discomfort hours was determined. The ATG graphs for Hall 8 and Hall 10 are mentioned in Appendix H. The comparison between the discomfort hours in baseline and future climate scenarios is described in section 11.4.

11.4 Discussion of Results

From the dynamic simulation of identified spaces from Pulse and Melanchthon School, the percentage of discomfort hours were calculated. As discussed in previous sections, the percentage of discomfort hours are the occupied hours whose indoor operative temperature exceeded the upper-temperature limit of Class B determined by Alpha or Beta case. According to ISSO74, 2014, for class B, only 10% of the occupied hours are allowed to exceed the upper limit. The results from the case studies in all three climate scenarios are summarised in graph 11.2.



Graph 11.2: Comparison of percentage discomfort hours due to overheating in all baseline,2050 and 2085 climate scenario.

From the graph, it can be observed that the identified spaces in the Pulse building are comfortable in the baseline climate scenario, but eventually, as the outdoor climate changes in the future, the spaces become uncomfortable. Currently, there is no monitoring of the use of free cooling by the mechanical ventilation system; therefore, it was not modelled. Although, according to the facility manager, the system is capable of summer bypass to use outdoor air to cool the space. On the other hand, the effect of summer bypass can be seen in the Melanchthon school, where it could reduce the discomfort due to overheated hours up to some extent in 2050.

Hall 10 in Pulse building is possibly overheated in the future due to the lightweight construction of the façade. The surface temperature of the façade increases due to direct radiation from the morning sun on the North East Façade and the absence of any solar shading. The surface temperature continues to increase due to high outdoor air temperature in the future climate, resulting in heat gain in the lecture hall. Hall 8, on the other hand, has low insulation values of the partition walls. The partition wall on the southwest orientation receives direct solar radiation, which may contribute to overheating. No effect of heat gain from skylights was observed in hall 8.

With regards to solar radiation, in the transformed weather files, the solar radiation values are not changed from the baseline data. However, it is estimated that due to more clear skies, the solar radiation will increase up to 1.2% and 1.4% in 2050 and 2085, respectively, in Wh climate scenarios (KNMI,2015). Thus, it could cause higher surface temperatures for the building envelope.

Comparing the same observation with the Melanchthon School, the South façade is susceptible to high solar radiation throughout the day, which is curbed to a great extent by the sided fins and overhangs. The façade is also lightweight with timber frame construction. However, it was observed that the unventilated side fins cavity add the necessary thermal mass to the façade to reduce heat gain. The window also has external blind control, which works better to reduce heat gain as compared to internal blinds of Hall 10 in Pulse building.

Heat Removal through ventilation is an essential factor for reducing overheating. In the school building, the staffroom is comparatively comfortable from class 31 due to the possibility of cross ventilation, whereas class 31 uses single-sided ventilation through windows. However, the use of ventilation is greatly depended on the context. The school also uses night-time ventilation through summer bypass, which helps reduce heat from the interior surfaces. However, in the Pulse building, night ventilation is not used. This is because the building is not in operation from 00:00 – 7:00, with radiative cooling starting at 4:00, which does not give enough time for the purge ventilation to cool the building.

11.5 Conclusions

The spaces identified using the analytical method described in Chapter 10, were modelled in the Design Builder tool for dynamic simulation. The design builder tool provides a graphical interface for the core energy plus simulation platform. As a first step, simplified models representing as close as possible to the actual building were modelled by carefully considering the modelling conventions and data from the building drawings, details, and BMS system.

The simulation model was then subjected to the calibration process to reduce variation between simulated output and output from actual operation. For the Pulse Building, Indoor air temperature for July 2019 was extracted from the BMS system for calibration. However, the school building was calibrated based on the reliability of data provided and analytical calculations. For calibration, statistical models suggested by ASHRAE that is MBE and CV(RMSE) were used.

The calibrated models were then simulated for summer months (May-September) for baseline, 2050, and 2085 climate files. The indoor operative temperature was used from the output to plot the ATG Graphs. The ATG Graphs are instrumental in providing the percentage of discomfort hours. According to ISSO 74, for educational buildings, comfort Class B is essential, which allows only 10% of the occupied discomfort hours. The results from the ATG graphs from identified spaces of both the case studies were then compared.

From the graphs, it was observed that the Pulse building is subjected to overheating in future climate scenarios. To maintain comfort in the future, the spaces would require higher cooling loads, which will lead to an increase in energy demands. Therefore, it is imperative to analyse the impact of passive design strategies into the building envelope to limit the discomfort hours to 10%, even in the future climate.

The Melanchthon school, which is a free-running building, also performs within the comfort Class B in baseline climate; however, as compared to Pulse building, the Melanchthon School performs better in the future climate. The Melanchthon school exhibits a good example of integrated passive design strategies on all levels of design. Although, it would be interesting to observe how far the passive design strategies can help in reducing overheating risk.

Part 5

Robust Design Solutions

12. Adaptive Solution Set

As discussed in previous chapter, the risk of overheating in future climate scenarios is high in both mechanically cooled and passive building. However, as compared to buildings with active cooling, building with integrated passive design solutions at the building envelope is better at controlling, protecting, and removing heat. The following chapter would look into the selection of adaptive passive design strategies discussed in chapter 7 for the building envelope, instrumental in reducing overheating for future climate scenarios. The strategies will be selected within the context of the case study buildings. Furthermore, through dynamic simulations, different solutions will be simulated individually and collectively to understand the combined effect. Finally, the chapter will also focus on evaluation of robustness of the selected strategies

12.1 Selection of Strategies (Analytical Method)

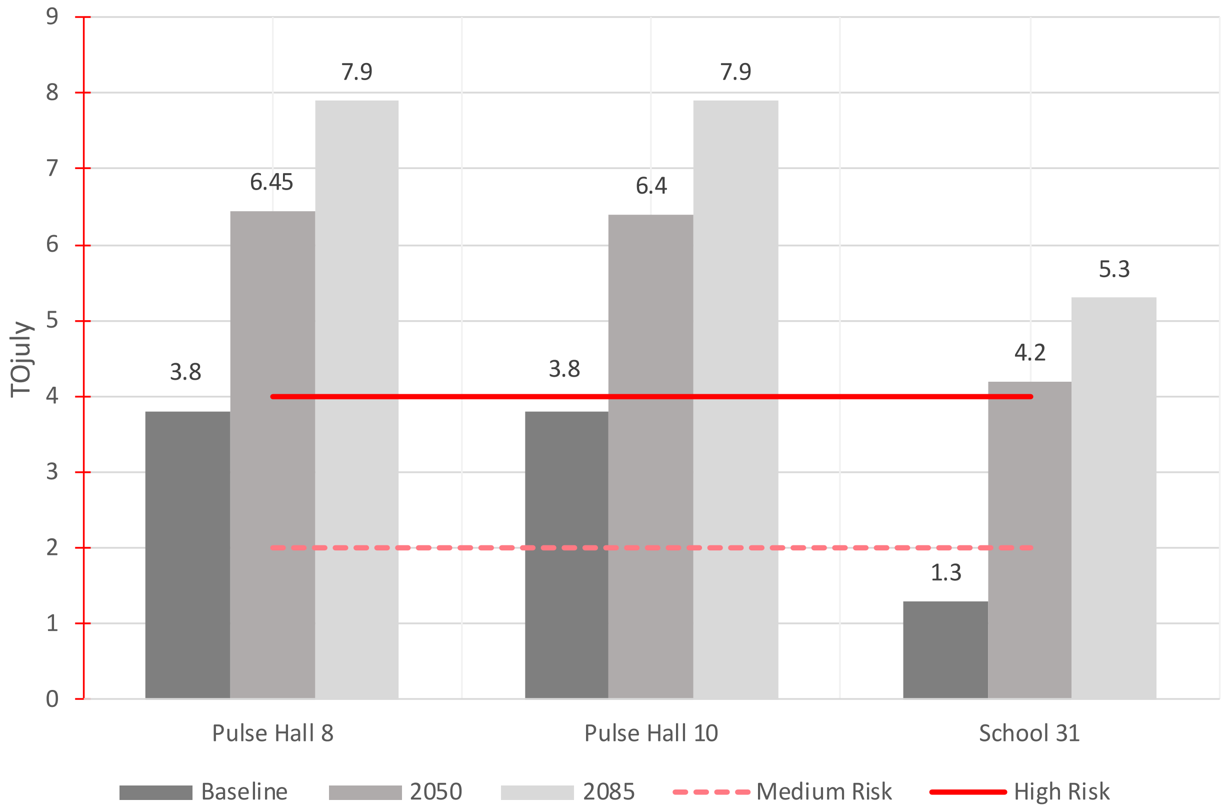
As discussed in chapter 7.5, around 40 different solutions could apply to the building envelope to reduce overheating by protecting, controlling, and removing heat. However, even if we chose one strategy, each it could give rise to almost 9,880 different solution set. Dynamic simulation of all the combinations of solutions would cost much time. Therefore, an analytical method was used to filter the solutions which have the maximum impact.

As discussed in chapter 10, the TOjuly method can successfully indicate the overheating risk; therefore, it was used again to narrow down the number of dynamic simulations. Since TOjuly does not consider any active cooling, the method was proved beneficial in indicating the effect of passive design strategies in reducing overheating.

To understand the effect of passive strategies on all three climate scenarios, TOjuly value was calculated for 2050 and 2085. According to equation D.8 mentioned in appendix D, the analytical method uses 17.6°C as the average outdoor temperature for July. This value was changed to 20.2 and 21.7°C for 2050 and 2085, respectively. These values were calculated from the transformed weather files for July. Graph 12.1 illustrates the TOjuly value for the spaces in Pulse and Melanchthon School, respectively. The analytical method used for the Pulse building does not consider any active cooling applied in the real case. The TOjuly value for corner staffroom is inconclusive from the adapted simplified method; therefore, it was excluded for analysis.

The analytical method is essentially a static heat balance model which does not consider any dynamic effects. When TOjuly value for 2050 and 2085 was compared to the baseline TOjuly, it was found that the values are proportional to the difference between the average outdoor temperature of baseline climate (17.6°C) and 2050(20.2°C) and 2085(21.7°C). Therefore, TOjuly value for only 2050 will be used to observe the reduction from passive design strategies.

Table 12.1 illustrates the parameters used for calculating TOjuly, along with that the parameters which will be changed are also indicated.



Graph 12.1: TOjuly values for selected spaces in Pulse and Melanchthon school for baseline,2050 and 2085 climate scenarios.

Parameters	Description	Units	Strategy
Dimensional Properties			
Zone Area	Area of the space excluding walls which needs to be analysed.	m^2	
Zone Perimeter	Perimeter of the space which needs to be analysed.	m	
Wall Area	This represents the total area of the façade including the opaque and transparent part.	m^2	**Heat Protection :** **Avoiding Over glazing**
WWR	Window to wall ratio of the space to be analysed.	-	
Roof Area	Area of the roof of the space to be analysed.	m^2	
Construction Properties			
Specific Effective Thermal Capacity	Thermal capacity value depended on the type of construction.	KJ/m^2K	
Thermal Properties			
U-Value of Glass	U-value of the transparent/glass of the façade.	W/m^2K	**Heat Control:** **Insulation** **Glazing Type**
g-value of Glass	Sun entry factor for daylight from opening	-	
U-Value of Opaque Part	U-Value of the opaque part of the façade.	W/m^2K	
U-Value of Roof	U-value of the roof	W/m^2K	
U-Value of Floor	U-value of the floor	W/m^2K	

Parameters	Description	Units	Strategy
Solar Shading Factor			
R(Shading Factor)	Dimensionless shading reduction factor for the external façade structure.	-	**Heat Protection:** **Sun Protection**
I_{sol}	Total Incident solar radiation for the orientation of the zone.	W/m²	
Internal Properties			
q_v	The amount of ventilation needed for cooling	dm³/s	**Heat Removal :** **Ventilation**
Internal Load	Combination of occupant, equipment and lighting load which will contribute towards internal load.	W/m²	**Heat Protection:** **Soft Adaptation**

Table 12.1: Parameters that will be changed to analyse the effect of different strategies on TOjuly value . Source: Author

Hall 8 is planned towards the center of the building (fig 12.1) due to which only a limited number of strategies could be applied. Therefore, to reduce overheating, strategies such as ventilation through the skylight, decreasing the U-Value of partition walls, night ventilation with thermal mass, increase albedo effect for roofs, and reduced occupancy can be used. It was found that calculating TOjuly for such limited options would not be beneficial; therefore, for hall 8, dynamic simulations were done to observe the effect of these strategies.

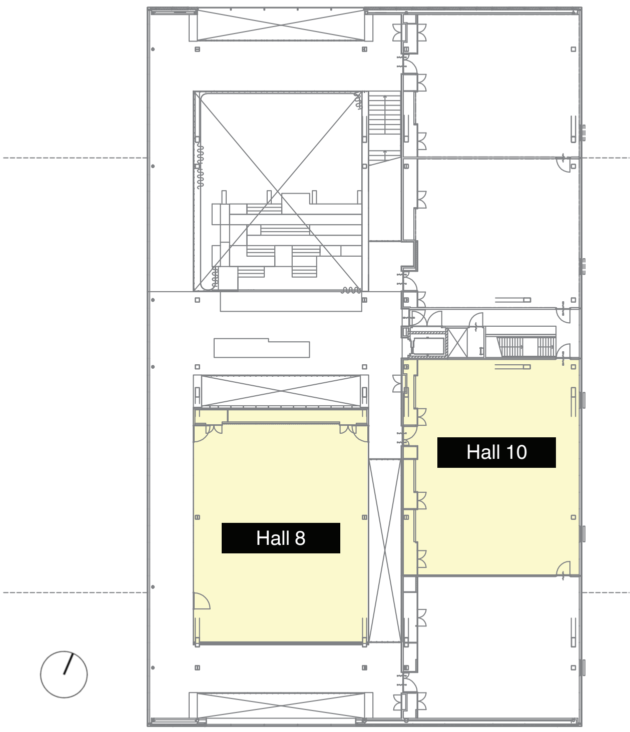


Fig 12.1: Hall 8 and Hall 10 in Pulse Building.

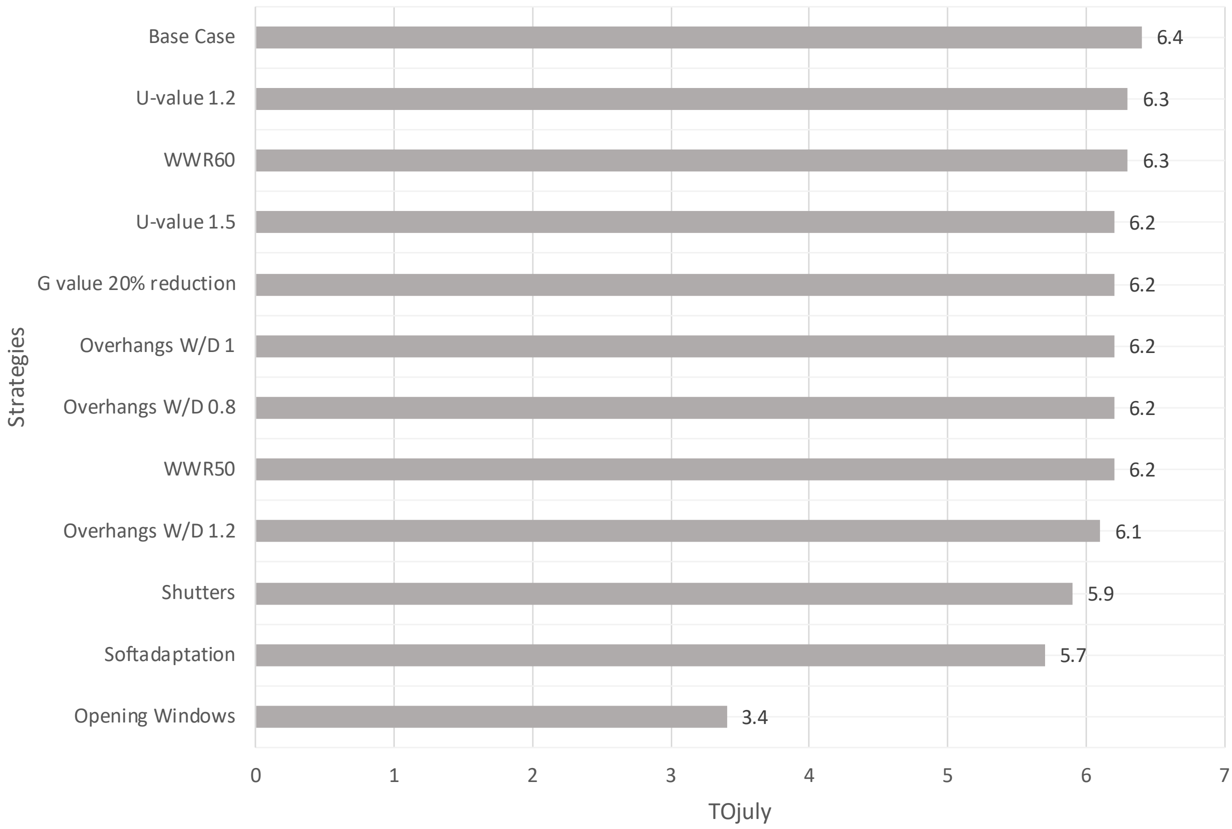
Hall 10 faces northeast orientation (fig 12.1). The heat gain in Hall 10 is directly related to the building envelope components, both opaque and transparent parts. In reducing overheating in hall 10, the first approach was to protect from heat. As mentioned in fig 7.5, reducing WWR, applying shading strategies, reducing g-value, use of shutters, blinds, or electrochromic glazing can be applied. However, applying all of them together would be counterproductive for daylight and duplicity of functionality.

Therefore, these strategies were analysed through TOjuly, and the strategies with a considerable reduction in the value would be chosen for dynamic simulations. The building envelope is highly insulated and airtight and good enough to control heat gain. However, it was essential to look at the impact of increased ventilation. A reduction in the occupancy was also tested to observe its impact in reducing overheating. Table 12.2 illustrates the changes from the base case in response to the strategies discussed for reducing TOjuly value.

<table>
<tr><th>Parameters</th><th>Description</th><th>Base Case</th><th colspan="2">Propsed Changes</th></tr>
<tr><td colspan="5"></td></tr>
<tr><td colspan="5">Dimensional Properties</td></tr>
<tr><td>WWR</td><td>Window to wall ratio of the space to be analysed.</td><td>.75</td><td colspan="2">.50, .60</td></tr>
<tr><td></td><td></td><td></td><td colspan="2"></td></tr>
<tr><td colspan="5">Thermal Properties</td></tr>
<tr><td>U-Value of Glass</td><td>U-value of the transparent/glass of the façade.</td><td>1.1 W/m²K</td><td colspan="2">1.2,1.5 W/m²K</td></tr>
<tr><td>g-value of Glass</td><td>Sun entry factor for daylight from opening</td><td>.4</td><td colspan="2">Reduce by 20% (.32)</td></tr>
<tr><td></td><td></td><td></td><td colspan="2"></td></tr>
<tr><td colspan="5">Solar Shading Factor</td></tr>
<tr><td rowspan="5">R(Shading Factor)</td><td rowspan="5">Dimensionless shading reduction factor for the external façade structure.</td><td rowspan="5">.8 (no shading device)</td><td>Width/Depth Ratio</td><td>Shading factor</td></tr>
<tr><td>.8</td><td>.59</td></tr>
<tr><td>1</td><td>.57</td></tr>
<tr><td>1.2</td><td>.55</td></tr>
<tr><td>Shutters</td><td>.28</td></tr>
<tr><td></td><td></td><td></td><td colspan="2"></td></tr>
<tr><td colspan="3">Internal Properties</td><td colspan="2"></td></tr>
<tr><td>q_v</td><td>The amount of ventilation needed for cooling</td><td>5.5 $dm^3/s/m^2$
only mechanical ventilation</td><td colspan="2">8.5 $dm^3/s/m^2$
Increased ventilation by opening existing windows</td></tr>
<tr><td>Internal Load</td><td>Combination of occupant, equipment and lighting load which will contribute towards internal load.</td><td>58 W/m^2</td><td colspan="2">52.2 W/m^2
Reducing internal load by 10%</td></tr>
</table>

Table 12.2: Values used to calculate the effect of different strategies on reduction of TOjuly.

Graph 12.2 illustrates the impact of different strategies over TOjuly values. When compared with the base value of 6.4, it was observed that ventilation strategies have the highest impact. Night ventilation with thermal mass, using summer bypass, or opening the existing windows are the options that will be tested during the dynamic simulation. Reducing the internal loads also has the biggest impact since it directly reduces the internal heat gain. Under shading strategies, the shutters have the highest impact, followed by an overhang with a width to height ratio of 1.2. However, a width to height (W/H) ratio of 1.2 already means an overhang of 1.2 m, which would be counter-productive for daylight and may block useful sunlight during winters. Although adding an overhang does reduce TOJuly value; therefore, it needs to be taken into account. Similarly, a



Graph 12.2: Reduction in TOjuly Values by applied strategies from base case.

WWR of .50 is more effective than .60. It was also observed that increasing U-Value by 1.2 also affects TOjuly value; however, its effect during dynamic calculations need to be cross-checked.

Thus to reduce overheating for Hall 10 strategies such as reducing WWR to .50, fixed shading devices with max W/H ratio of 1.2, shutters, reducing U-Value, ventilation strategies, and reducing internal loads will be tested for dynamic simulations.

In Melanchthon school, the corner staffroom cannot be analysed using the TOjuly method. Even, for class 31, most of the passive design strategies are already included in the design. It was concluded that TOjuly analytical method would not help decide any more strategies.

12.2 Selection of Strategies (Dynamic Simulation)

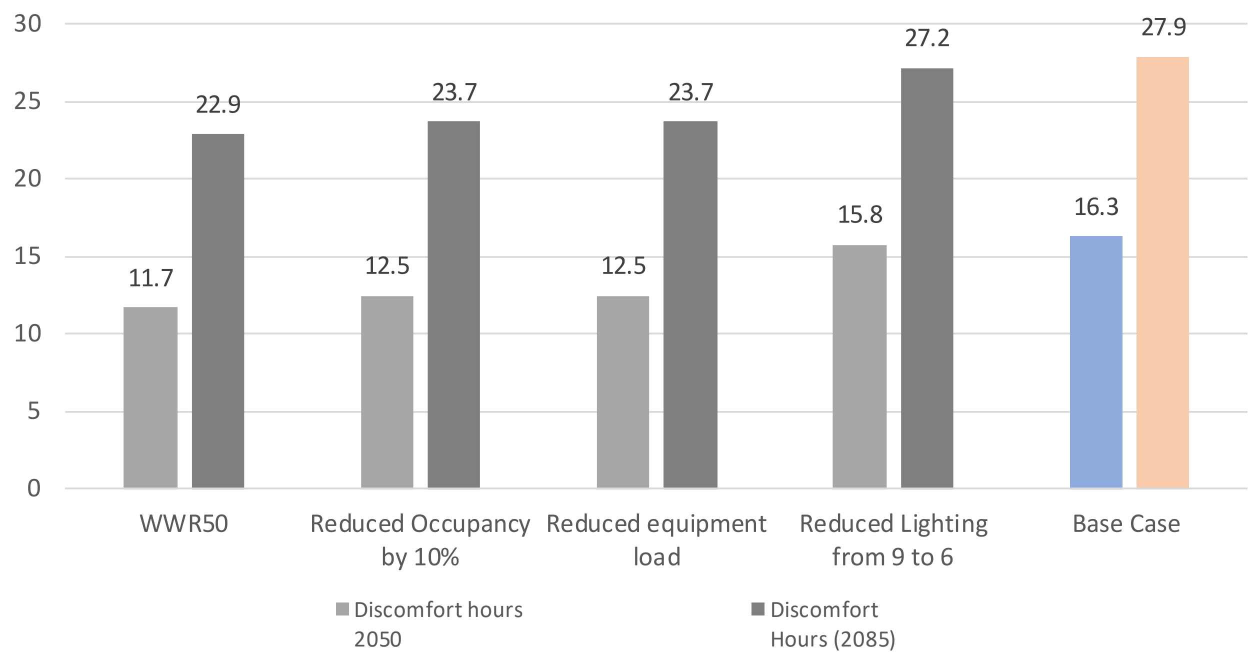
To reduce the number of strategies earlier, it was decided to use the analytical method. However, the method can provide only limited insight over the real effect of the strategies. Hence, the dynamic simulations were used to test the individual effect of the strategies. Although from the analytical method, it was also observed that not all spaces provide an opportunity to include different strategies. Hall 10 from the Pulse building was found to have maximum potential to include different strategies. Therefore, only hall 10 was simulated with different strategies to see the individual effect on reducing overheating risk. The observations from studying Hall 10 were translated to prepare solutions sets for other spaces to reduce overheating in the future.

Heat Protection

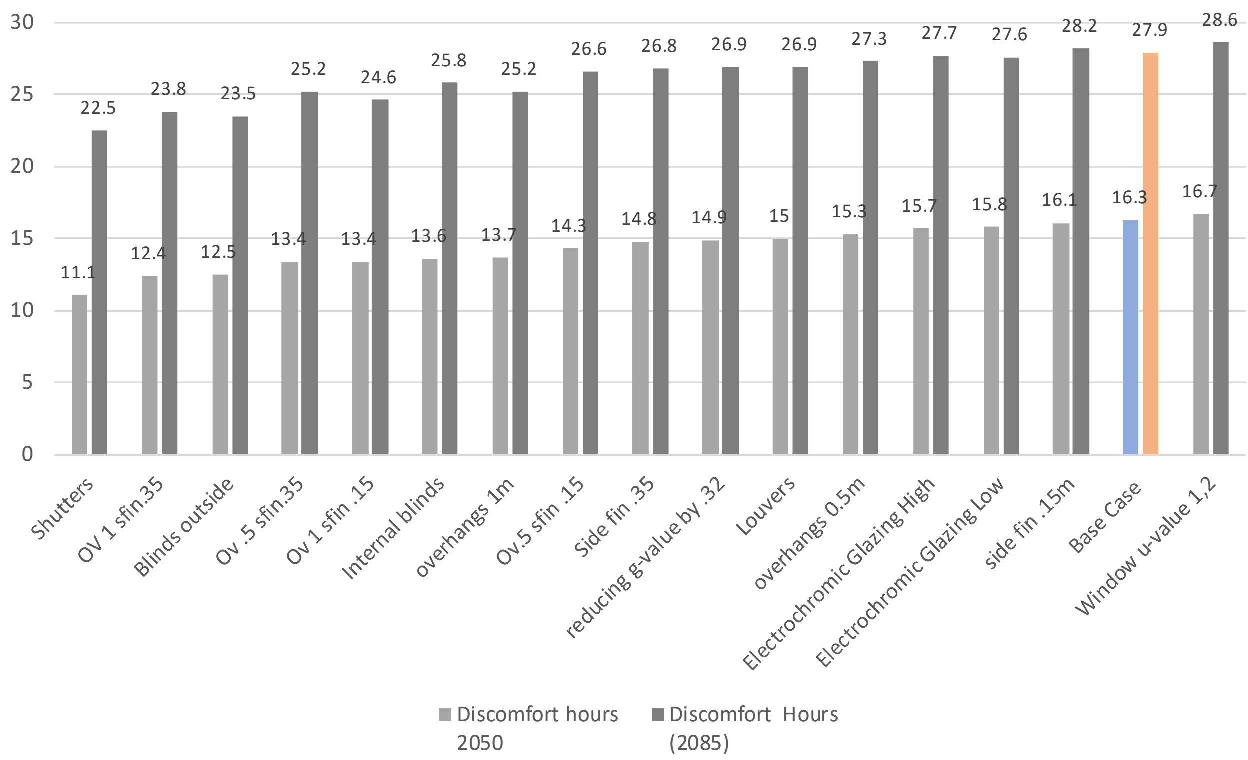
To study the impact of heat protection, the strategies available are reducing the occupancy, lighting, or equipment loads. Many studies suggest that a soft adaptation of reducing the number of occupants could reduce the internal loads. In the future, it was considered that the equipment would be transformed into thin client technology, which only uses 5W/m^2 and whereas the lighting loads in the future might be reduced to 6W/m^2. Another strategy is to reduce the WWR to 50% as compared to the current building design, where the WWR is 75%.

The other strategies to protect from heat gain were the fixed and moveable shading devices. The analytical method indicated the effect of overhang with the W/H ratio of 1.2, which could result in a long overhang reducing daylight. Therefore, the shading device calculator from climate consultant was used to estimate the angle of inclination for overhangs and side fins. From climate consultant, it was found that an overhang of 0.5 m and 1 m, while a side fin of 0.35 m and 0.5 m would be required to reduce the solar gain from the morning sun. Therefore, they were simulated individually and together to analyse the effect. Apart from fixed shading devices, moveable shading devices such as roller blinds, shutters were also simulated. Hall 10 has internal blinds; therefore, a variation with external blinds was simulated. Different variations of electrochromic glazing and an increase in the U-Value to 1.2 was also simulated.

Graph 12.3 and 12.4 represents the reduction in discomfort hours as compared to the base case for different strategies.



Graph 12.3: Effect of Individual Strategies in reducing discomfort hours due to overheating.



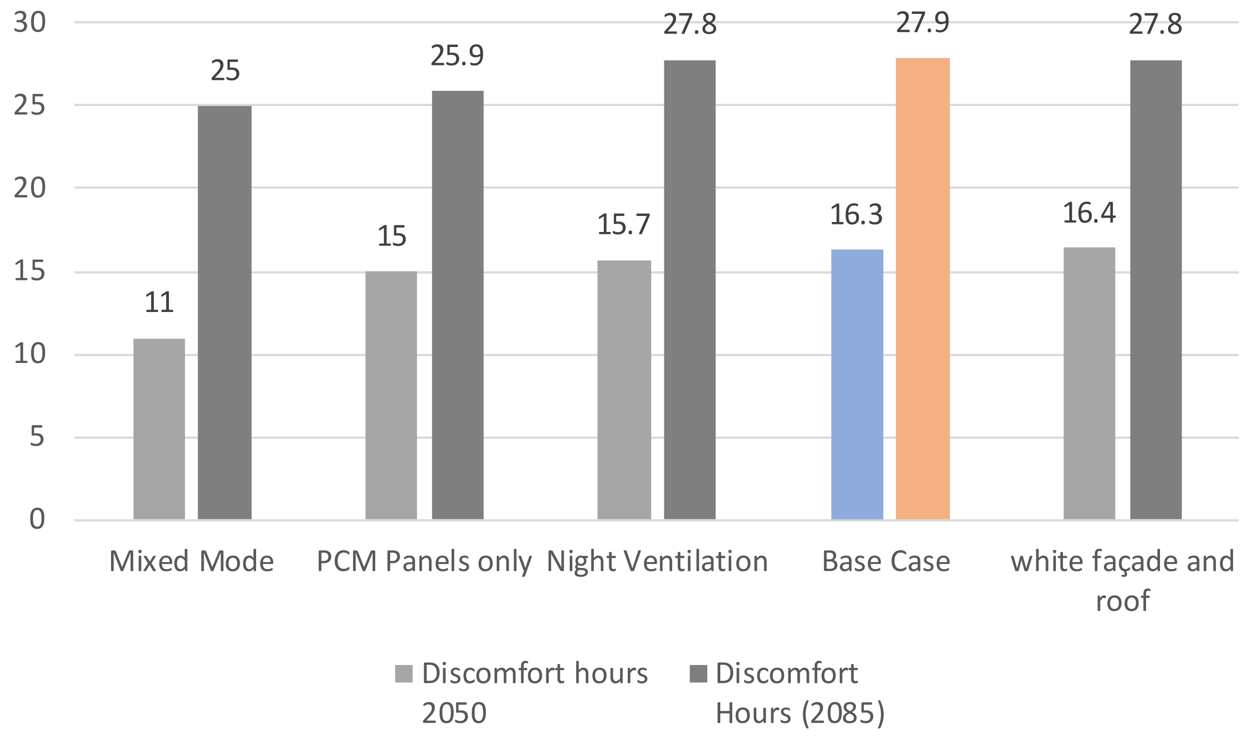
Graph 12.4: Effect of Individual Strategies in reducing discomfort hours due to overheating.

From both the graphs, it was observed that WWR 50% reduces the discomfort in both 2050 and 2085. The reduced WWR also reduces the glazing and increases the opaque part of the façade. However, it must be noted that the opaque part of the façade would require to have high insulation too. As expected, reducing occupancy, efficient light, and equipment also contribute to reducing overheating. The reduction in lighting energy does not contribute significantly since the Pulse building is equipped with efficient lighting already.

Concerning fixed and moveable shading strategies, shutters have the highest impact. The combination of 0.5 and 1m overhangs with side fins of 0.35m is much more effective than individual application. The external blinds are more effective than internal blinds since it restricts radiation entry into space altogether. These strategies indicate the most significant effect in reducing discomfort hours as compared to others. Therefore, for making an adaptive solution set for heat protection, only the discussed strategies will be used.

Heat Control and Removal

The case study buildings are highly insulated to control heat gain from the high surface temperature. Reducing the surface temperature by making light coloured exterior surfaces contributes to the albedo effect. Increasing the albedo effect would not only reduce surface temperature but would also be beneficial in reducing the Urban heat island effects. Ventilation is regarded as the quintessential strategy for reducing overheating. To observe the dynamic effect of ventilation, two strategies, night ventilation, and mixed-mode strategies were simulated. The lightweight construction of the façade contributes to overheating as it can heat faster as compared to heavy construction. Therefore PCM panels were selected as a means to increase the thermal mass of the façade without adding unintended structural loads.

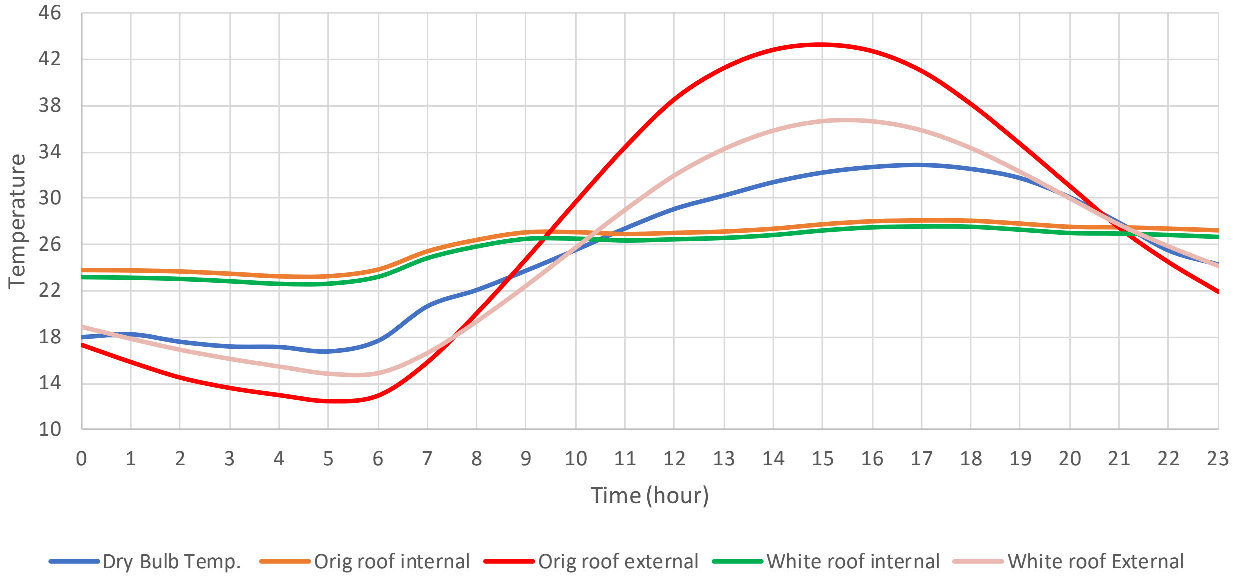


Graph 12.5: Effect of Individual Strategies in reducing discomfort hours due to overheating.

According to graph 12.5, a mixed-mode ventilation system reduces the risk of overheating. In mixed-mode ventilation, the system switches between natural ventilation when outside conditions are comfortable and cooling when outside conditions are harsh. This hybrid system can be designed as concurrent where both systems are working together, zoned where both systems are present in different parts of the building and changeover where systems switch between both systems. For simulating mixed-mode strategy in hall 10, concurrent system was considered.

Night ventilation, on the other hand, does not reduce the discomfort hours as compared to mixed mode, because the Pulse building is not operational between 0:00-7:00 with radiative system starting at 4:00. Thus, it only provides three hours for night ventilation to be used. However, it was also observed that the average temperature during the night is likely to rise, which may become counterproductive for cooling buildings.

The PCM Panels have similar impact like night ventilation on reducing the discomfort percentage however, PCM when combined with night ventilation can further provide comfort hours. The white surfaces were added to the roof and façade of Hall 10; however, it does not have any impact on the reduction of overheating. However, various literature advocates the positive aspects of the albedo effect in reducing overheating. Therefore a comparative graph (graph 12.6) was plotted between the external surface temperature of the façade, internal surface temperature, and outside air temperature with and without white surfaces.



Graph 12.6: Effect of white surfaces on reducing external surface temperature.

From the graph, it was observed that because of the high thermal insulation, the effect of the roof colour is not noticeable on the inside for reducing the internal surface temperature. Another possibility is that a WWR of 75% does not provide enough surface area for the substantial effect of white surfaces.

12.3 Selected Solution Set

From the analysis of different strategies on Hall 10 of the pulse building, it was observed that for controlling heat, passive design strategies such as WWR and fixed or moveable shading are most effective. In terms of heat control, increasing the albedo effect by adding white surfaces to the building envelope can be helpful, but it is more effective when the WWR is less as compared to 75 %. For heat removal, ventilation strategies are promising, but it will depend on the system design for mixed-mode and outside air temperature at night for effective cooling of the space. Adding PCM panels to increase thermal mass could be helpful for lightweight constructions but only in the presence of night ventilation.

The individual assessment of strategies represents the potential of passive design strategies in adapting to future climate to reduce overheating; however, when integrated with other strategies, the combined effect can further reduce the overheating. Therefore, different solutions set were prepared for each case study based on the above presented study and the context of the building. These solutions set for all four identified spaces for each case study are illustrated in table 12.3.

Code	Solution Set	Remarks
Pulse Hall 8		
H8.1.	Reduce U-Value of partition Walls	U-value to 1.65 W/m²K
H8.2.	Reduce U-Value of partition Walls	U-Value to 1 W/m²K
H8. 3.	Reduced U-Value + White Surfaced Roof	
H8. 4.	Reduced U-Value + White Surfaced Roof+ WWR 70%	WWR 70% from 100%
H8. 5.	Reduced U-Value + White Surfaced Roof+WWR 70%	R-Value of opaque parts increased 3 m²K/W G-value of transparent parts to .4
H8. 6.	Reduced U-Value + White Surfaced Roof+ WWR 70 % +Mixed mode	Opening skylight windows
H8. 7.	Reduced U-Value + White Surfaced Roof+ WWR 70 % +Mixed mode + PCM Panels	
Pulse Hall 10		
H10. 1.	WWR 75% + White Surfaced roof and Facade	
H10. 2.	WWR 75% + White Surfaced roof and Facade+External Roller Blinds	
H10. 3.	WWR 75% + White Surfaced roof and Facade+ 0.5 m overhang and 0.35 m sidefins.	
H10. 4.	WWR 75% + White Surfaced roof and Facade+ 1 m overhang and 0.35 m sidefins.	
H10. 5.	WWR 75% + White Surfaced roof and Facade+ shutters	
H10. 6.	WWR 75% + White Surfaced roof and Facade+ mixed mode +PCM Panels	Existing two windows openings with 40% openable area operating through out the day
H10. 7.	WWR 75% + White Surfaced roof and Facade+ mixed mode +PCM Panels+external blinds	Existing two windows openings with 40% openable area operating through out the day
H10. 8.	WWR 75% + White Surfaced roof and Facade+ mixed mode +PCM Panels+0.5 m overhang and 0.35 m sidefins.	Existing two windows openings with 40% openable area operating through out the day
H10. 9.	WWR 75% + White Surfaced roof and Facade+ mixed mode +PCM Panels+1 m overhang and 0.35 m sidefins.	Existing two windows openings with 40% openable area operating through out the day
H10. 10.	WWR 75% + White Surfaced roof and Facade+ mixed mode +PCM Panels+shutters	Existing two windows openings with 40% openable area operating through out the day
H10. 11.	WWR 50% + White Surfaced roof and Facade	
H10. 12.	WWR 50% + White Surfaced roof and Facade+External Roller Blinds	
H10. 13.	WWR 50% + White Surfaced roof and Facade+ 0.5 m overhang and 0.35 m sidefins.	
H10. 14.	WWR 50% + White Surfaced roof and Facade+ shutters	

Code	Solution Set	Remarks
H10. 15.	WWR 50% + White Surfaced roof and Facade+ mixed mode + PCM Panels	Existing two windows openings with 40% openable area operating through out the day
H10. 16.	WWR 50% + White Surfaced roof and Facade+ mixed mode + PCM Panels +external blinds	Existing two windows openings with 40% openable area operating through out the day
H10. 17.	WWR 50% + White Surfaced roof and Facade+ mixed mode +PCM Panels +0.5 m overhang and 0.35 m sidefins.	Existing two windows openings with 40% openable area operating through out the day
H10. 18.	WWR 50% + White Surfaced roof and Facade+ mixed mode + PCM Panels +shutters	Existing two windows openings with 40% openable area operating through out the day
Melanchthon School Staffroom		
S.1.	White Surfaced roof and Facade	
S. 2.	White Surfaced roof and Facade+PCM Panels	Night ventilation already present by summer bypass.
S. 3.	White Surfaced roof and Facade+2 m width pergola	extension of pergola on ground floor to first floor
S. 4.	White Surfaced roof and Facade+2 m width pergola +PCM Panels	extension of pergola on ground floor to first floor
Melanchthon School Class 31		
C.1.	White Surfaced roof and Facade	
C. 2.	White Surfaced roof and Facade+PCM Panels	Night ventilation already present by summer bypass
C. 3.	White Surfaced roof and Facade+2 m width pergola	Extension of pergola on ground floor to first floor
C. 4.	White Surfaced roof and Facade +PCM Panels+WWR 50%	
C. 5.	White Surfaced roof and Facade +PCM Panels + combination of openings	BMS controlled Ventilator at top with manual opening windows at the bottom
C. 6.	White Surfaced roof and Facade +PCM Panels+ combination of openings+ 2 m width pergola	BMS controlled Ventilator at top with manual opening windows at the bottom Extension of pergola on ground floor to first floor

Table 12.3: Different adaptive solutions set for reducing overheating for case studies.

12.4 Robustness Assessment

A robust design would be a design with minimum performance variation in the presence of any uncertainties. In the context of this study, the solutions which are capable of controlling overheating even in the worst-case scenario of climate change would be regarded as a robust design solution. As discussed in chapter 8, three statistical methods were identified to evaluate robustness, out of which the "best-case and worst-case scenario" method will be used. In this method, the design solutions will be compared with each other across all climate scenarios through performance deviation. The performance deviation is the difference between the best performance of the entire design space and the worst performance of design across considered scenarios. The robust solutions will be the one with minimum or ideally zero performance deviation. Fig 12.2 illustrates the workflow used for assessing the robustness of design solutions individually for each case study.

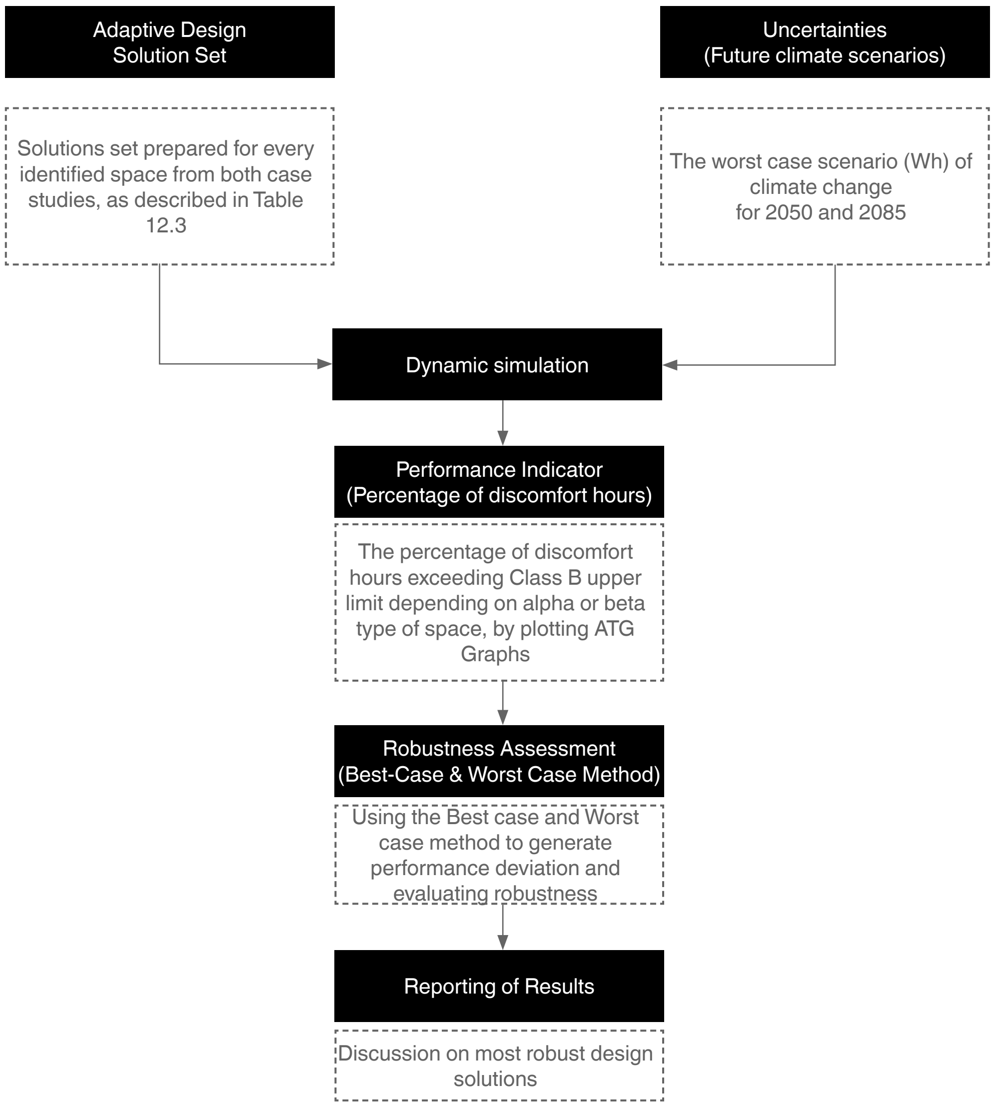
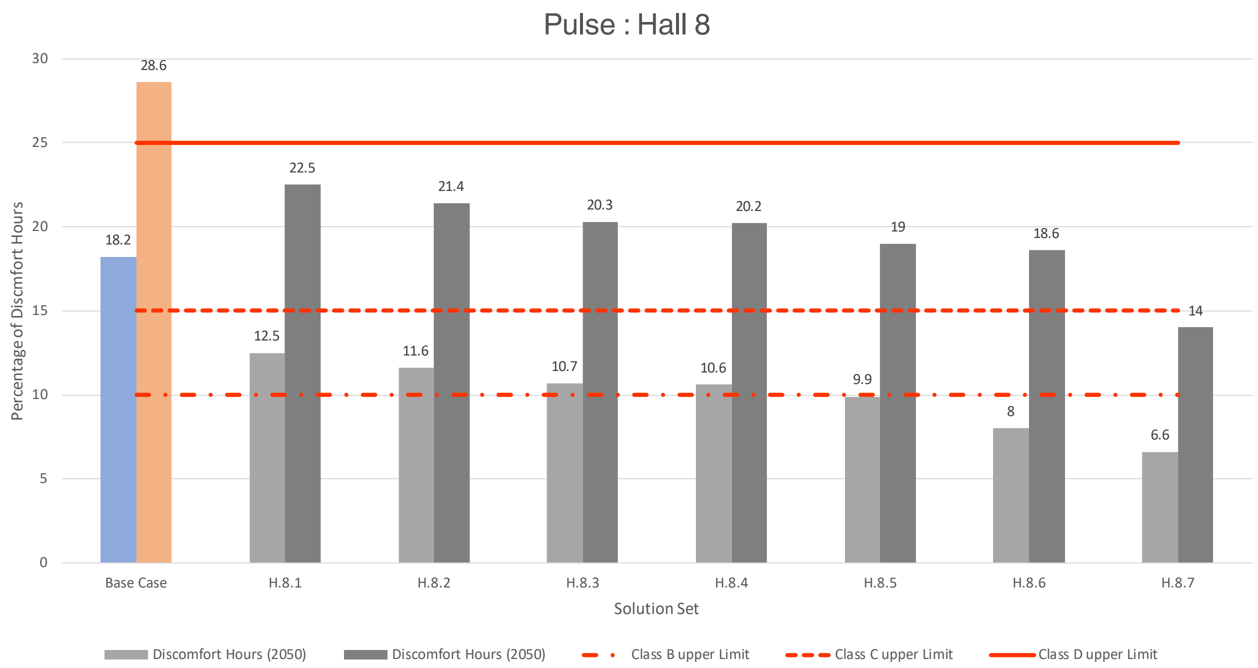
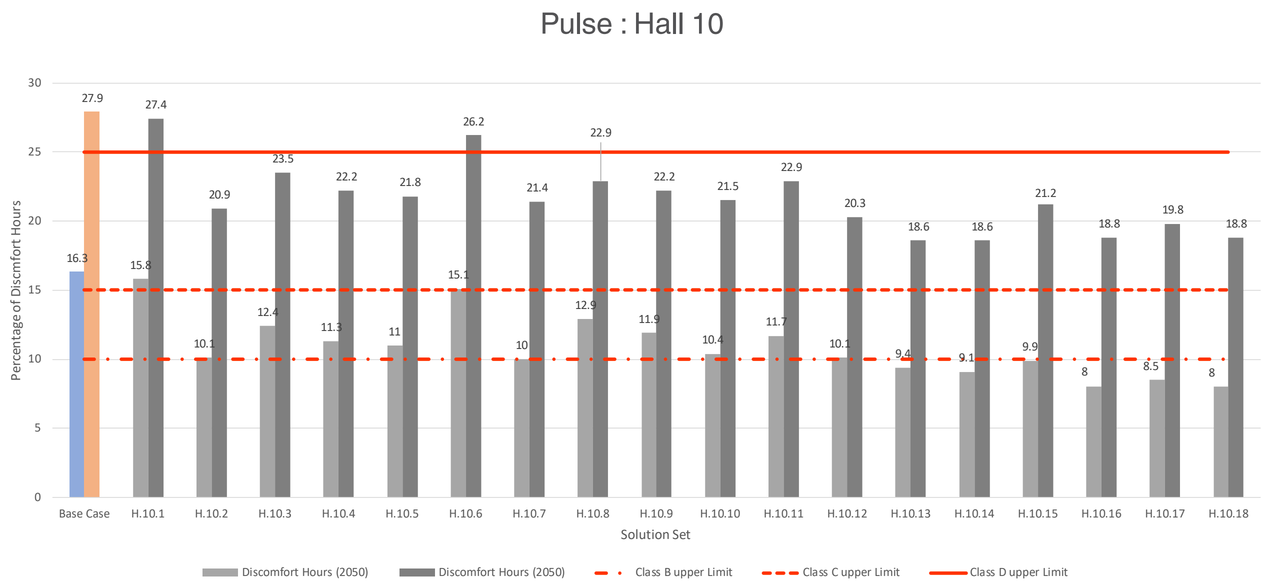


Fig 12.2: Workflow for evaluating robustness of design sample space against future climate and percentage of discomfort hours.

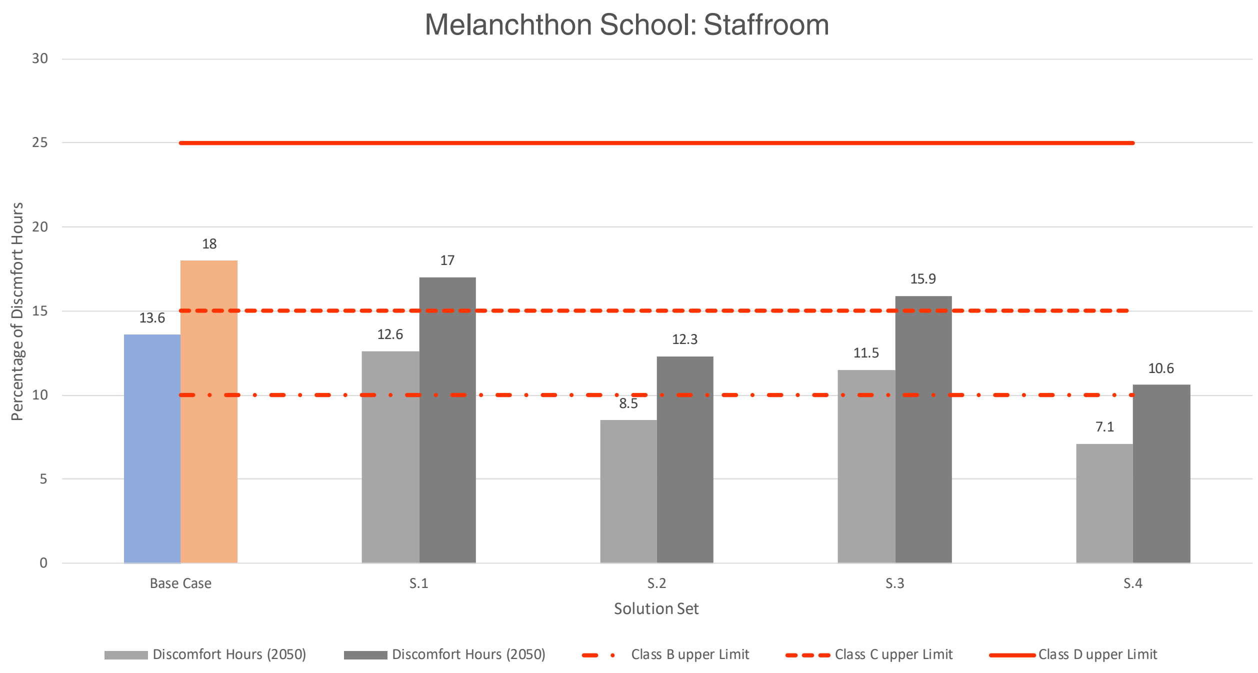
As a first step for evaluating robustness, the solutions described in table 12.3 were modelled and simulated in design-builder. The indoor operative temperature was taken as output to plot ATG graphs and percentage of discomfort hours exceeding Class B limits. Graph 12-7-12.10 indicates the effect of the different solution set on reducing percentage discomfort hours due to overheating in 2050 and 2085 climate in comparison to the base case.



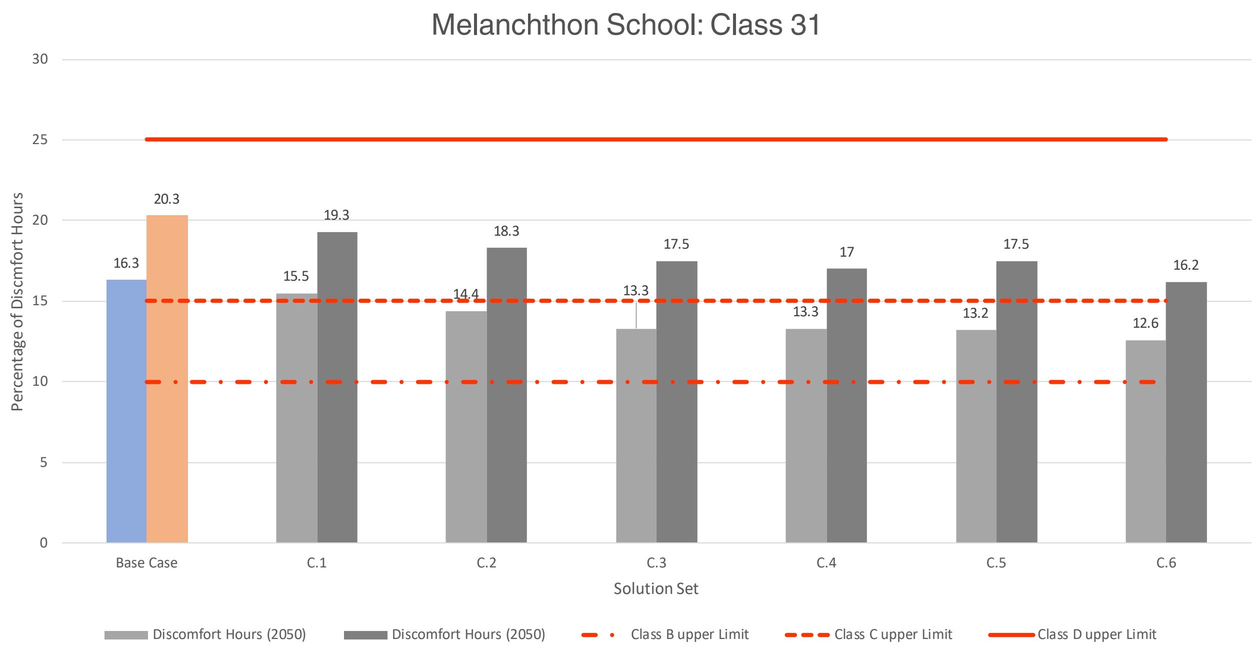
Graph 12.7: Comparison of the effect of different design strategies on the percentage of discomfort hours for Hall 8 in Pulse Building.



Graph 12.8: Comparison of the effect of different design strategies on the percentage of discomfort hours for Hall 10 in Pulse Building.



Graph 12.9: Comparison of the effect of different design strategies on the percentage of discomfort hours for Staffroom in Melanchthon School.



Graph 12.10: Comparison of the effect of different design strategies on the percentage of discomfort hours for Class 31 in Melanchthon School.

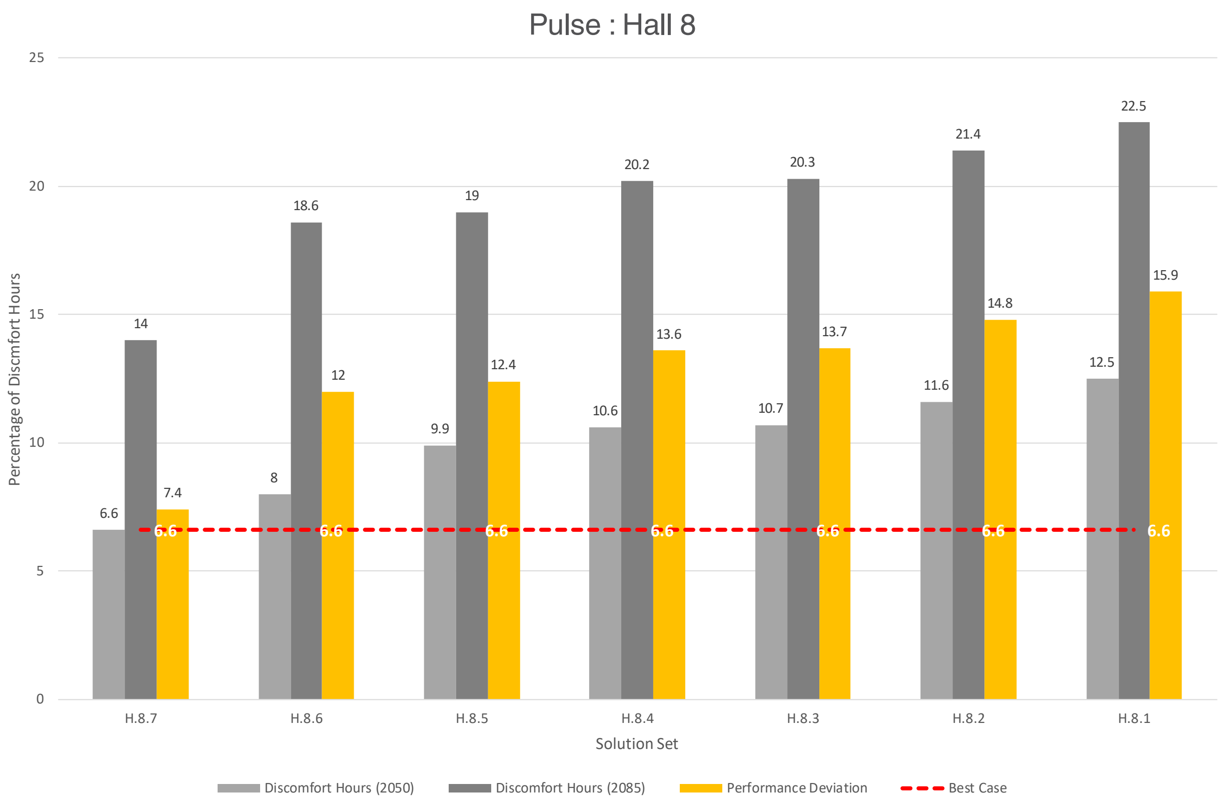
The results from the simulations were then used in the statistical model of the "best-case and worst-case" method for robustness evaluation, as proposed by Kotireddy(2019). Table 12.4 illustrates the calculation steps used. For each identified space, firstly, the design options (Cn), and their corresponding percentage of the discomfort hours in 2050 and 2085 climate scenario as their performance (Pn_{2050}, Pn_{2085}) were tabulated. The objective is to check which option could reduce the percentage of discomfort hours, therefore for each design solution, the worst performance (WC) would be the maximum percentage of discomfort hours achieved by the solution within both the climate scenario. Since the method compares the worst performance of a design solution with the best performing solution from all the solutions listed, a solution with a minimum percentage of discomfort (BC) was selected as the best performing solution. Finally, the most robust design would be the solution/s with a minimum difference between the best case of the entire design space and worst-case from each climate scenario.

Best Case -Worst Case Method					
Design code	**Climate Scenario**		**Worst-Case Performance (WC)**	**Best-Case Performance (BC)**	**Performance Deviation (WC-BC)**
	2050	2085			
C1	$P1_{2050}$	$P1_{2085}$	$max(P1_{2050},P1_{2085})$		WC1 - BC1
C 2	$P2_{2050}$	$P2_{2085}$	$max(P2_{2050},P2_{2085})$		WC2 - BC2
C 3	$P3_{2050}$	$P3_{2085}$	$max(P3_{2050},P3_{2085})$	$min(P1_{2050},P1_{2085}, P2_{2050},P2_{2085},P3_{2050},P3_{2085},...Pn_{2050},Pn_{2085})$	WC3 - BC3
...	...	...	...		....
C n	Pn_{2050}	Pn_{2085}	$max(Pn_{2050},Pn_{2085})$		WCn - BCn
				Robust Design	**min (WC-BC)**

Table 12.4: "Best-Case and Worst-Case" Statistical model for evaluating robustness. Source: Adapted from the works of Kotireddy et al,2019

12.5 Discussion of Results

The robustness assessment was conducted for each of the identified room from both the case studies. The results were tabulated and presented in the graphs. From Graph 12.11, which represents the results from Hall 8 of the Pulse building, we can observe that the best performing case in the entire design sample is design option H.8.7, with the minimum percentage of discomfort hours. The design option H.8.7 corresponds to reducing the window to wall ratio to 70% from 100% with the opaque elements with an R-value of 3m^{2}K/W. The U-Value of the internal windows were also reduced to 1 W/m^{2}K with a g value of 0.4. To use the albedo effect in reducing the external surface temperature of the roof, white ceramic tiles were proposed. For ventilation, mixed-mode strategy was proposed to increase the heat removal actively. PCM Panels were also combined to the internal partition walls. For mixed-mode, free cooling and opening of ventilators were simulated. For selecting the most robust design, the performance difference between the

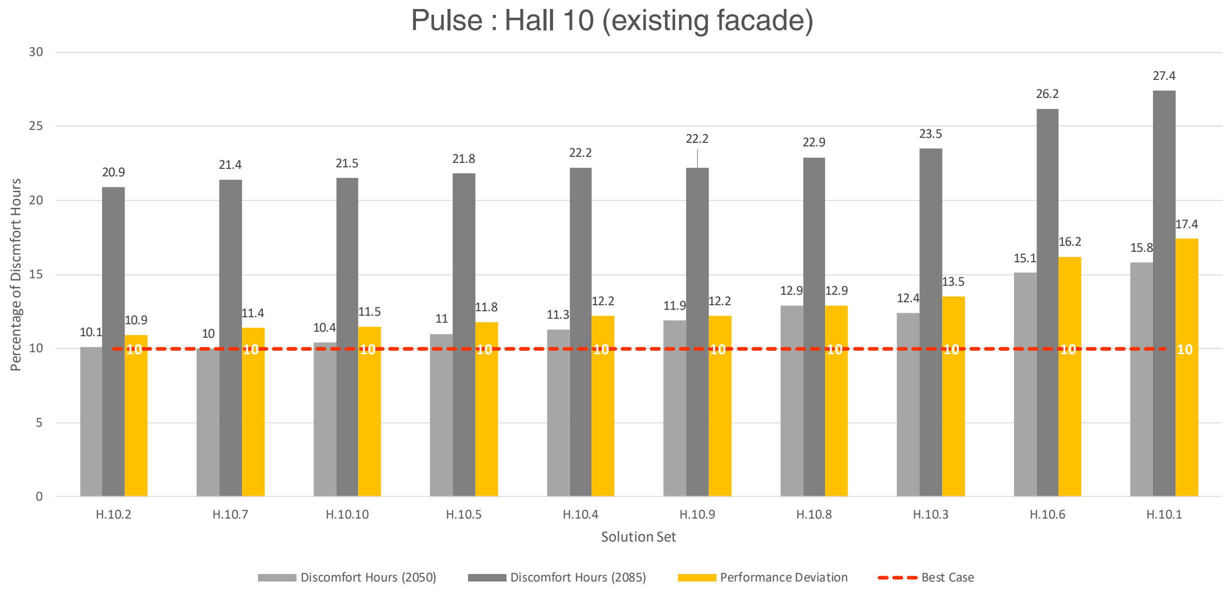


Graph 12.7: Robustness evaluation of different design strategies for Hall 8 in Pulse Building.

best-case H.8.7 and worst performance of all other design strategies out of the two-climate scenario 2050 and 2085 was calculated. Based on that design solution H.8.7 has the minimum performance deviation; thus, it was considered a robust solution for Hall 8.

For hall 10, eighteen different sets of solutions were simulated. These solutions were prepared to consider the effect of other strategies with or without changing the WWR. Therefore, to analyse the robustness of the design solutions, the strategies applied to the existing façade, and the strategies applied to the façade with WWR of 50% were done separately. Graph 12.8 illustrates the robustness assessment of strategies applied to the existing façade.

For Hall 10, the best performing design is H.10.7, with maximum reduction in percentage discomfort hours as compared to the base case. The design solution H.10.7 corresponds to the application of white ceramic tiles on the roof and facade to increase the albedo effect. As for shading strategy, external blinds were simulated, and for ventilation strategy, mixed-mode was used. To consider the effect of night ventilation with thermal mass, PCM panels were simulated towards the interior layer of the opaque part of the façade. In graph 12.7 for hall 8, it was observed that the robust design solution is the best performing design solution out of the entire sample solution. Although for hall 10, it was observed that the design solution with the minimum performance deviation was design solution H.10.2. The only difference between H.10.2 and H.10.7 is the exclusion of mixed-mode strategy in H.10.2. To analyse this discrepancy, the actual performance of the design solutions were also considered. Therefore, from the entire design



Graph 12.8: Robustness evaluation of different design strategies applied on the existing facade for Hall 10 in Pulse Building.

solution set, a solution with a minimum percentage of discomfort hours was checked in 2050 and 2085 individually.

The design solution which performed best in the 2050 climate scenario was indeed H.10.7 and H.10.2, while the solution which performs best in 2085 was H.10.2. Since the difference between both the strategies is only the use of mixed-mode system, which uses outdoor ventilation whenever possible, it was theorised that it might be possible that in the future, the outdoor air temperature is high, which could contribute towards overheating. To confirm this hypothesis, the wind rose diagrams (fig 12.3 & 12.4) were plotted for 2050 and 2085 for occupied hours and night hours. The occupied hours were taken as 9:00 – 17:00, and night hours were taken as 22:00 – 6:00, according to ISSO 32. From the wind rose diagrams, it was confirmed that the temperature of outdoor air would be high in the latter part of the century. Therefore, using ventilation would not be effective in 2085.

A similar analysis was done for the strategies which are applied to the façade with WWR 50%. On comparing the design solution H.10.1 and H.10.11, it was observed that reducing the WWR amplifies the use of white surfaces to reduce overheating by increasing the albedo effect. From graph 12.9, it can be observed that solution H.10.16 and H.10.18 are the best performing design. Along with application of white surfaces on the building envelope these solutions uses mixed mode system coupled with PCM panels. The only difference between them is the type of solar shading. From robustness evaluation the design solutions H.10.13 and H.10.14 found to be most robust. Both the solutions use ceramic tiles on the building envelope with a difference between shading strategies, where H.10.13 uses overhang and side fins, while H.10.14 uses shutters.

According to the previous discussion, the actual performance of design solutions in 2050 and

Analysis Period : May - September
Daytime : 9:00 - 17:00
One Octagonal Polyline : 33 hours

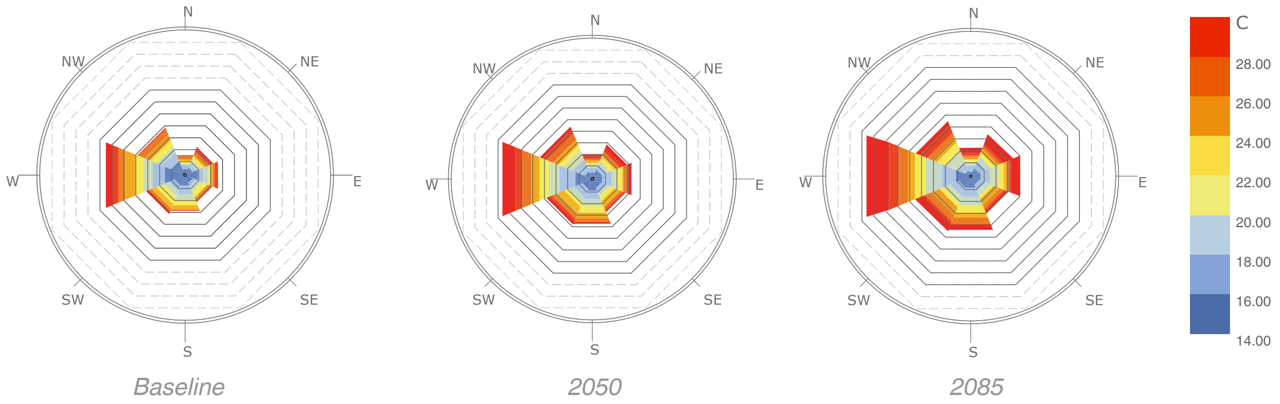


Fig 12.3: Wind rose diagrams representing outdoor air temperature for baseline,2050 and 2085 climate scenarios during daytime.

Analysis Period : May - September
Night-time : 22:00 - 6:00
One Octagonal Polyline : 33 hours

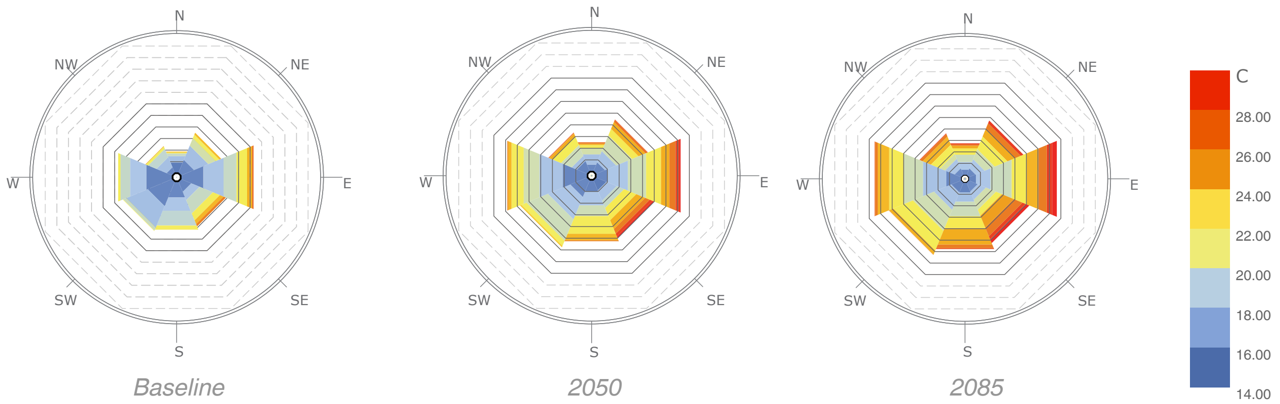
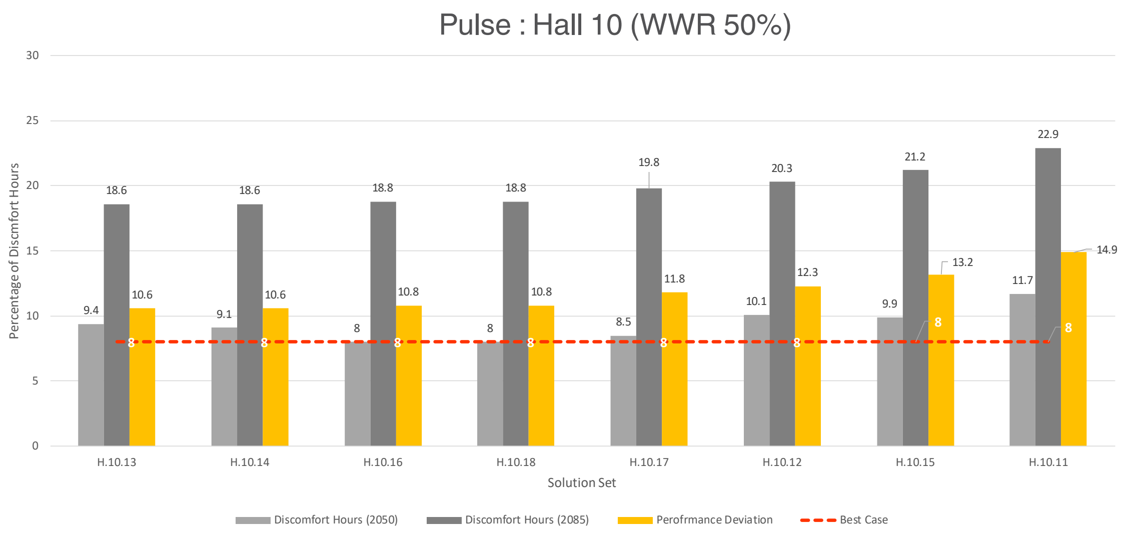


Fig 12.4: Wind rose diagrams representing outdoor air temperature for baseline,2050 and 2085 climate scenarios during night-time.



Graph 12.9: Robustness evaluation of different design strategies applied with WWR 50% Hall 10 in Pulse Building.

2085 was also considered. In 2050, design solutions H.10.16 and H.10.18 performs the best, while in 2085, design solutions H.10.13 and H.10.14 performs the best.

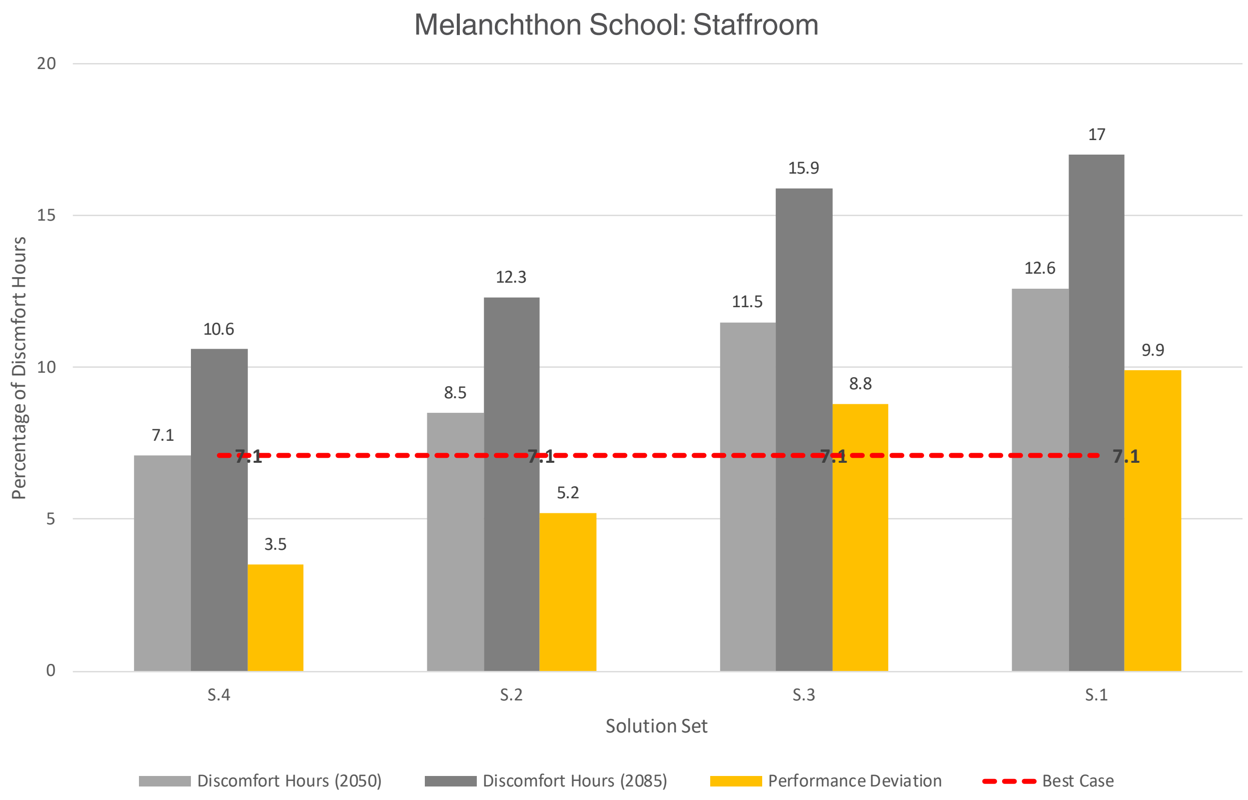
Since the window to wall ratio is reduced to 50%, the effective opening area for ventilation was also reduced. In the simulations, only two windows were considered operable; the effectiveness of more than two openable windows was not considered to limit the design options.

Upon comparing both sets of solutions, it can be concluded that reducing the window to wall ratio to 50% has the biggest impact on the reduction of overheating hours. The combined effect of both fixed or moveable shading strategies with white surfaces on the building envelope can further reduce the percentage of discomfort hours. Although a WWR of 50% will certainly impact the daylighting, which must be considered before implementing such strategies.

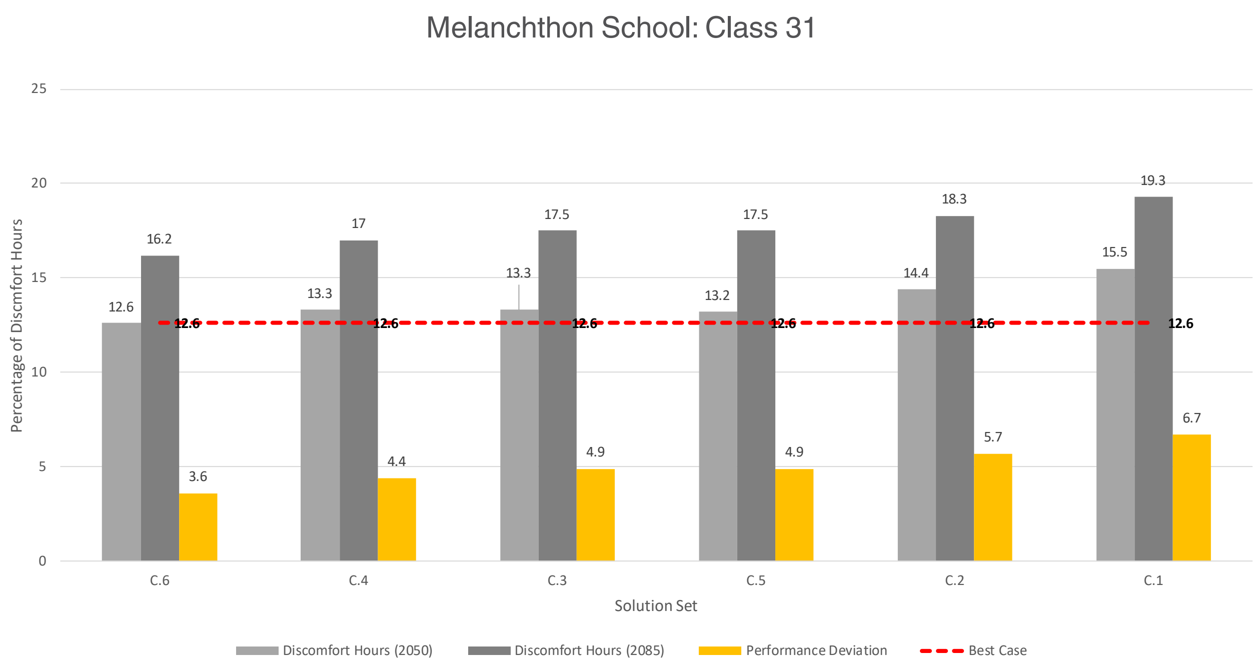
While for WWR of 75%, which is the original case of Pulse building, applying shading strategies with mixed-mode ventilation systems can certainly reduce the overheating. However, ventilation would have limited application in 2085, where the outdoor temperature would be too high to be used for ventilative cooling. This gives a fair indication that in the latter part of the century, an active cooling system would be required for maintaining thermal comfort.

The school building has an integration of numerous passive design strategies such as moveable and fixed shading strategies, highly insulated glass, summer bypass with night ventilation. Due to the availability of such strategies, the percentage of discomfort hours in future climate is quite less as compared to the Pulse building. However, few strategies were still proposed to increase the robustness of the school building.Graph12.10 represents robustness evaluation for the staffroom. The design solution S.4 is both the best performing and most robust in reducing the percentage of discomfort hours in the future. The solution S.4 constitutes of white surfaces on building envelope to increase the albedo effect and use of PCM panels as thermal mass to improve night ventilation with a pergola of 2m width to reduce further the risk of overheating. The pergola acting as a fixed shading device can be proposed as an extension of the existing pergola on the ground floor in the south orientation. The pergola, when combined with green walls, can be effective in altering the microclimate of the space.

Similarly, for class 31, design solution C6, which is similar to S4, is the most robust design (graph 12.11). The only difference is the use of a combination of openings to facilitate cross-ventilation. However, the effectiveness of ventilative cooling is limited in 2085, and spaces might require pre-cooling of the air.



Graph 12.10: Robustness evaluation of different design strategies for staffroom in Melanchthon School.



Graph 12.11: Robustness evaluation of different design strategies for class 31 in Melanchthon School.

12.6 Conclusions

For assessing the robustness of design solutions, the first step was to select strategies depending on the context of the case study buildings. To reduce the number of strategies, the analytical method was used. However, due to the limitations in considering the dynamic effects of environmental variables, the dynamic simulations were employed.

During the evaluation of different strategies for Pulse and School building, it was found that out of all four identified spaces, Hall 10 provides maximum opportunity for including different strategies. Therefore, individual assessment of different design strategies was performed by taking the case of Hall 10 only. The conclusions from the individual assessment of strategies in reducing the percentage of discomfort hours were used to prepare solutions set for other identified spaces.

From dynamic simulations, only one strategy was applied to the base case and was simulated for 2050 and 2085 climate year, for comparing the reduction in percentage discomfort hours as compared to the base case. The results were tabulated in Graph 12.3-12.5. From the analysis, it was found that among heat protection measures reducing WWR, occupancy, and equipment loads have a considerable effect on the reduction of percentage discomfort hours. Furthermore, among different shading strategies shutters, a combination of overhangs and side fins and external blinds had the most impact. For heat control and removal, a mixed-mode ventilation strategy was found to be effective. As discussed before application of PCM as thermal mass alone was not effective until unless it used with night ventilation. Another observation was made for the use of white surfaces to increase the albedo effect. It did not show any considerable effect in overheating reduction, but when the external surface temperature was compared with and without white surfaces in graph 12.6, it was found that white surfaces can indeed reduce the external temperature. It was concluded that the strategy was not effective in the base case because of less availability of the façade surface. Hence, the benefits of the albedo effect can help when WWR is reduced to 50%. Based on this analysis, different design solution sets were prepared, as described in table 12.3.

The solution set prepared according to table 12.3 were then subjected to robustness evaluation using the steps illustrated in fig 12.2. One of the essential conclusions drawn was related to the robustness assessment itself. It was concluded that the actual performance of the solutions in 2050 and the 2085 climate scenario should also be considered along with the results from the statistical model.

From the robustness evaluation, it was found that for Pulse hall 8, the combined effect of increasing WWR, increasing the insulation of opaque and transparent parts of the partition wall, application of PCM along with mixed-mode ventilation was found to be most robust in all climate scenarios.

For hall 10, almost similar sets were applied on the existing façade and the façade with a WWR of 50%. With the existing façade, the design solution H.10.2, with the combined effect of external blinds as shading devices with white surfaces applied on building envelope, were found to have the highest reduction in percentage discomfort hours, in both the climate scenarios. When the actual performance of the design solutions was checked, it was found that strategies with mixed-mode ventilation performed better in 2050, but in 2085 due to high outdoor temperature, the ventilative cooling will have limited application.

From the robustness evaluation, the application of WWR of 50% was more effective in reducing overheating then the existing facade. The design solution H.10.13 and H.10.14 were found to be most robust. Both the solutions have white surfaces on building envelope the only difference is of shading strategies where H.10.13 uses overhangs and side fins, while H.10.14 uses shutters. Although the WWR of 50 would have a considerable effect on the daylighting, therefore, a detailed daylighting analysis must be included in the robustness assessment in future research.

Upon analysing the robustness of different solutions for the school building, it can be concluded that the school building demonstrates an exemplary case of passive design strategies integrated at every level of design. The building outperforms the Pulse building in terms of percentage of discomfort hours. Although, it should not be ignored that the Pulse building has higher occupancy loads to satisfy as compared to the school building.

For both staffroom and class 31, use of albedo effect, application of PCM panels along with night ventilation can reduce overheating. However, an application of a 2m wide pergola can further reduce the risk of overheating in the future. This pergola can be used as green walls, which further improve the microclimate of the building. Class 31 can be improved further by using a combination of openings along with the above strategies. The combination of high and low openings can facilitate cross ventilation for ventilative cooling. However, the possibility of ventilative cooling will reduce due to high outdoor temperatures. Therefore, in the latter part of the century, pre cooling of air using low energy systems would become a necessity.

Part 6

D.O.T.T.

Design Orientated Transformation tool

13. Tool for Designers

Robustness is not a novel concept. Vitruvius has mentioned in "The Ten Books in Architecture" about the fundamental principles of Architecture, which translate to firmness, utility, and aesthetics (Collins & Ackerman, 2019). With his first point on an exquisite architecture to have "firmitas" or firmness, he meant about the robustness of the structure. In the present scenario, the development in the building technologies has led the buildings to become robust in terms of structural aspects. However, the concept of robustness must be extended towards the idea of indoor comfort as well.

As discussed in earlier chapters that climate change would have a detrimental impact on indoor comfort, and only a few strategies are robust enough to handle such uncertainties. It becomes essential for the architects and designers to be informed about the impact of their design choices on summer comfort and robustness of their design in a future context. Therefore, to facilitate the process, an excel based tool was developed, which could enable the designers to understand the performance of their design.

The following chapter will discuss the tool developed, its concept and how the tool can help architects to evaluate their robustness based on summer comfort.

13.1 Concept

The main purpose of the tool is to inform the designers about the impact of their design choices on the summer comfort. Along with that, the tool should also be able to perform a comparative analysis among the many design options and provide an indication of the most robust design.

Currently, there are many building simulations tools available which can provide detailed studies for the same. However, according to a study conducted by Paryudi (2015), it was found that architects and designers found such tools counter-productive for their design process. Paryudi (2015) also concluded that though advance simulation tools provide precise analysis, it is difficult for the architect to provide detail inputs during the early design stage. The designers in the early stages of design would not be interested in the precise calculation but rather at the impact of the design. Therefore, simple static calculations are considered better for designers to quickly analysis numerous design options.

The development of the tool considered these shortcomings and was developed so that it could facilitate the design process. The tool was developed based on the TOjuly method developed earlier and uses a one-room model scenario to calculate the summer comfort for July. For robustness analysis, the tool again uses the statistical method of "Best-Case and Worst-Case scenario" to compare various design options and indicate the most robust design. Because the tool is design-based and can enable its user to transform their design based on robustness, it was named as design-oriented transformative tool or d.o.t.t.

13.2 Graphical User Interface (GUI)

As mentioned earlier, the tool is being designed to enable the user to enter limited data to analyse the summer comfort. Also, the tool must provide iterative opportunities for the user to compare many design options and find the most robust option. For the same, the data input is divided into eight sections. These sections will be discussed further, along with the GUI designed for each section.

13.2.1 Tabs

Since it is an excel based tool, the GUI is integrated with the tabs. The tabs are divided into four sections (fig 13.1). These sections are based on the hierarchy of the user's interest in utilising the tool.

The **Yellow tabs** will allow you to understand the tool, use the tool and generate graphs for analysis.

The **Blue tabs** are data loggers which periodically records your data and can be used to make custom graphs or info graphics.

The **Red tabs** are for developers who would want to use the equations behind the software and improve it further.

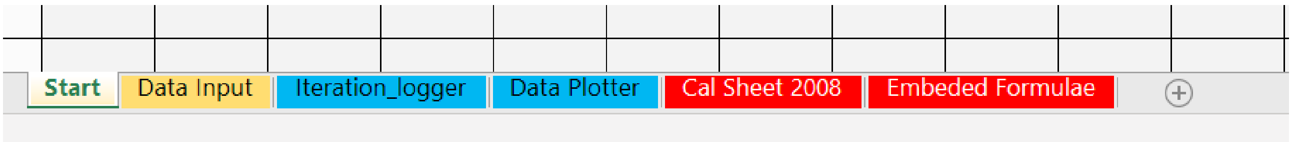


Fig 13.1: Four colour coded tabs in Excel GUI.

13.2.2 Input Parameters

The "Data Input" tab allows the user to input parameters for analysis. The data input is divided into eight easy to understand sections with relevant graphics to guide a user about what they need to enter. These sections are explained further.

Section 1: Project Details

In this section, the user is required to enter project details such as

- **Project Name:** The name of the project.
- **Room Details:** the name of the space you want to analyse (e.g., Bedroom, Classroom, etc.)
- **Date:** The date of your analysis.

- **Design Option:** This is an important entry as this is used to put label during your analysis. Here the user is required to enter a code for the design option which is ***required to be alphanumeric*** (e.g. DO1, A1, Z_S_1) (fig 13.2).

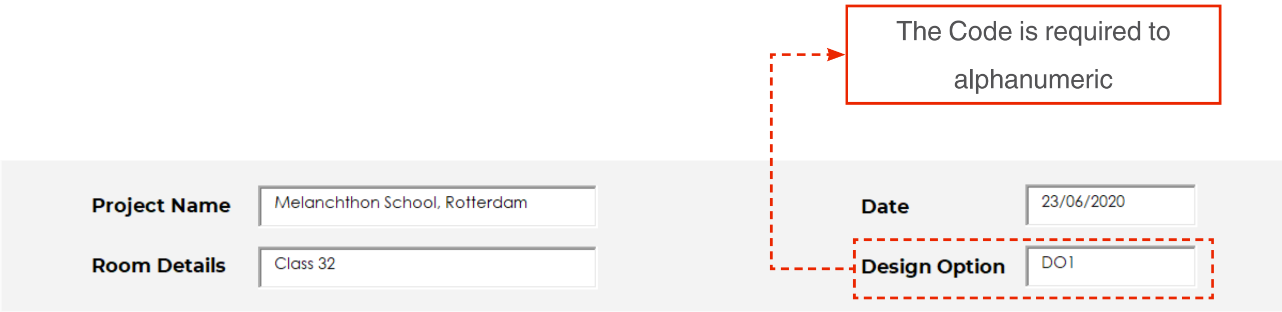


Fig 13.2: GUI for section 1(Project Details) of input parameter. The code of the design option is required to be alphanumeric.

Section 2: Spatial Details

This section corresponds to the location, type of construction and number of occupants in the space (fig 13.3a).

- **Type of Space:** What is the type of space the user wants to analyse (e.g. Residential, hospital, school, etc.)
- **Location of Space:** Where the space is situated in the building? The ground floor and top floor are floors directly on the ground and right beneath the roof, respectively. For rest, the middle floor must be selected.
- **Façade Orientation:** This regards to the direction the façade of the space is facing. Please Note: the tool currently cannot calculate corner spaces.
- **Construction Type:** The user can select from the drop-down menu regarding the particular construction style of the space. The definition of construction styles can be accessed by clicking the icon button (fig 13.3b). These definitions are taken directly from NTA 8800.
- **Number of occupants:** A data must be given regarding the capacity of the space. This value is used to calculate the minimum ventilation required for the analysed space.

Section 3: Dimensional Properties

In this section (fig 13.4), the user is required to enter the physical dimensions of the space.

- **Floor Area:** The area of the floor plate of the space excluding any walls.
- **Perimeter:** The perimeter of the floor plate of the space.
- **Wall Area:** The area of the external wall or façade, including any openings or glazing.

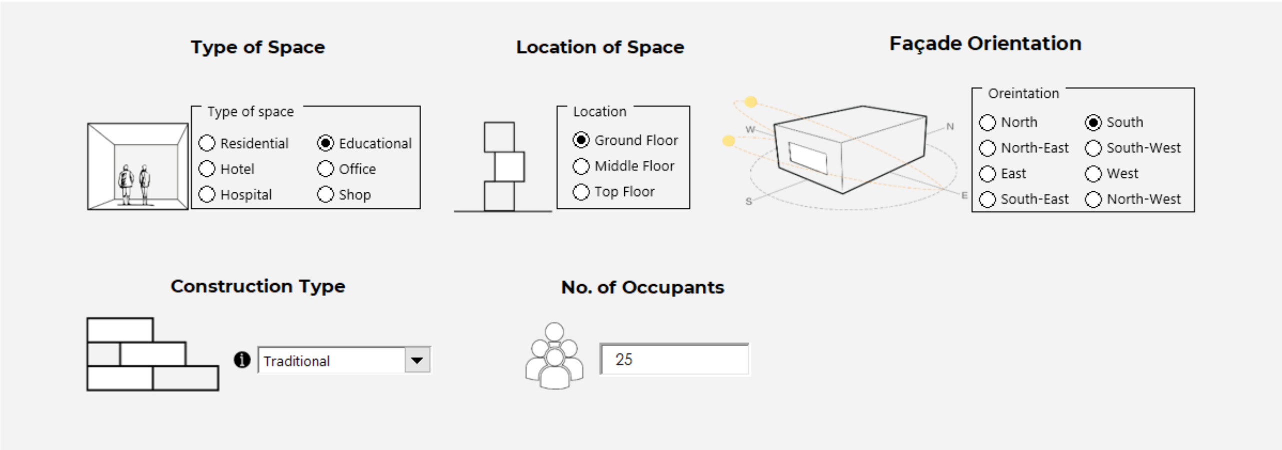


Fig 13.3a: GUI for section 2 (Spatial Details) of input parameter.

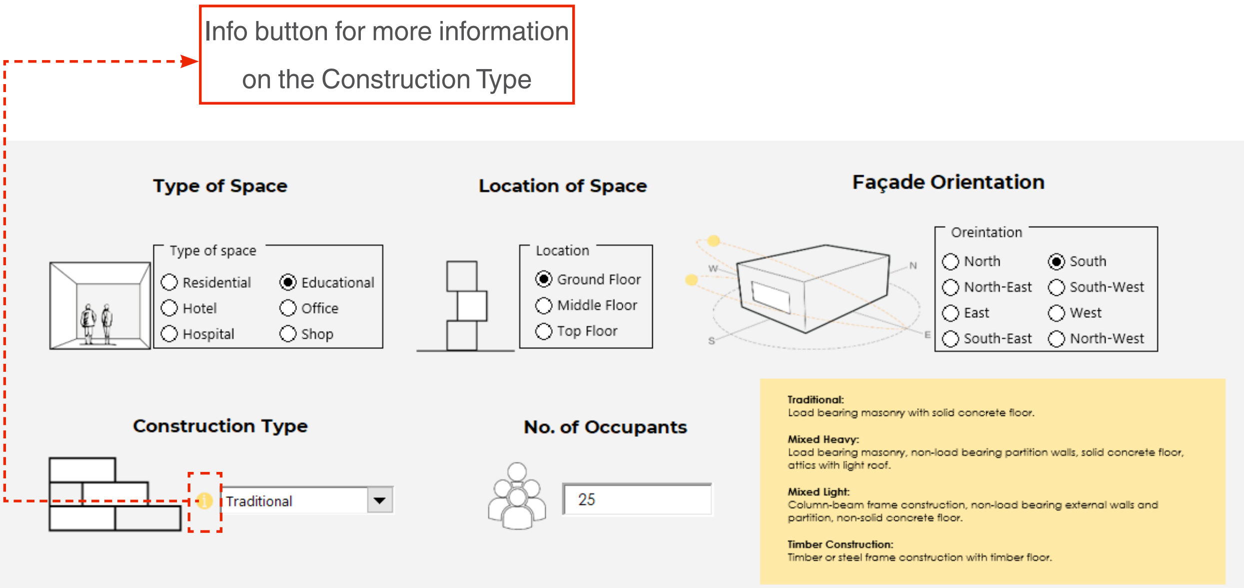


Fig 13.3b: Using Info buttons for definitions of construction types from NTA 8800.

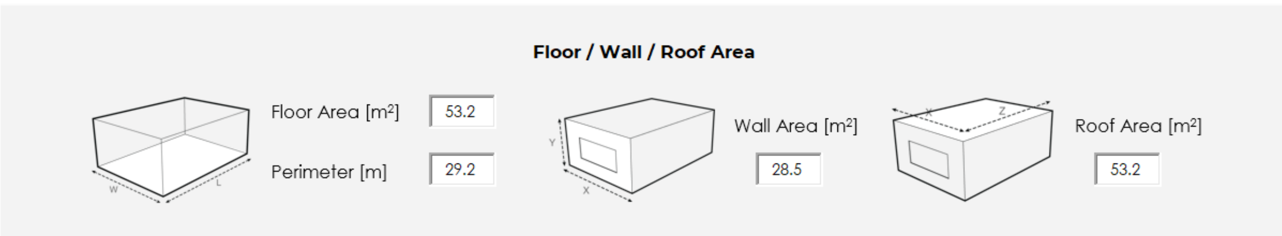


Fig 13.4: GUI for section 3 (dimensional properties) of input parameter.

- Roof Area: The area of the roof directly above the space, excluding walls. This parameter can be skipped if space is on the middle floor.

Section 4: Glazing Properties

In this section(Fig 13.5), the user is required to specify the window to wall ratio and glazing type.

- **Window-Wall Ratio:** The ratio of window (glazed) area and the overall wall area.
- **Type of Glass:** The type of glass such as single glazing, Double glazing unit (DGU), DGU with low E coating, Triple Glazing Unit (TGU) and TGU with Low E coating.
- **U-Value:** The insulation value of the type of glass chosen. The values will change according to the type of glass selected. The values are taken from NTA 8800.
- **g-Value:** The amount of solar radiation that can enter from the type of glass chosen. The values will change according to the type of glass selected. The values are taken from NTA 8800.

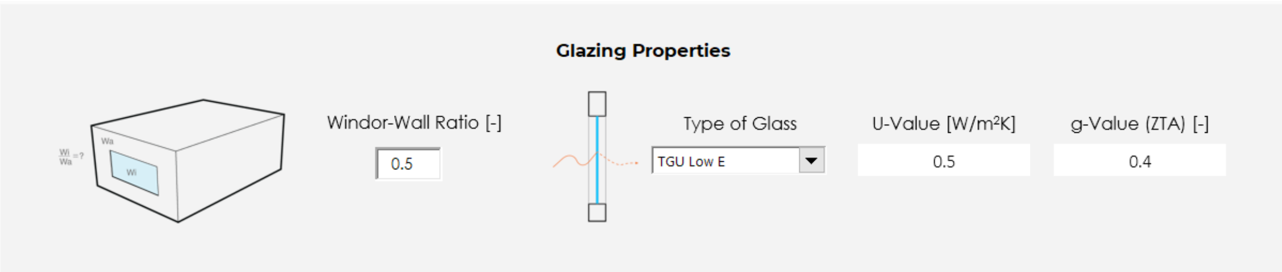


Fig 13.5: GUI for section 4 (glazing properties) of input parameter.

Section 5: Thermal Insulation Properties

In the section (fig 13.6a), the user has to specify the insulation values for the opaque parts of the building envelope.

- **External Wall (R-Value):** The insulation values as R-value of the opaque part of the façade or external wall. If the R-value is unknown, the user can use the info button to access the pre-defined R-values for external walls according to the construction year (fig 13.6b). These values are according to NTA 8800.
- **Roof (R-Value):** The insulation values as R-value of the roof. If the R-value is unknown, the user can use the info button to access the pre-defined R-values for roof according to the construction year (fig 13.6b). These values are according to NTA 8800.
- **Floor (R-Value):** The insulation values as R-value of the external floor or floor at the ground level. If the R-value is unknown, the user can use the info button to access the pre-defined R-values for the floor according to the construction year(fig 13.6b). These values are according to NTA 8800.

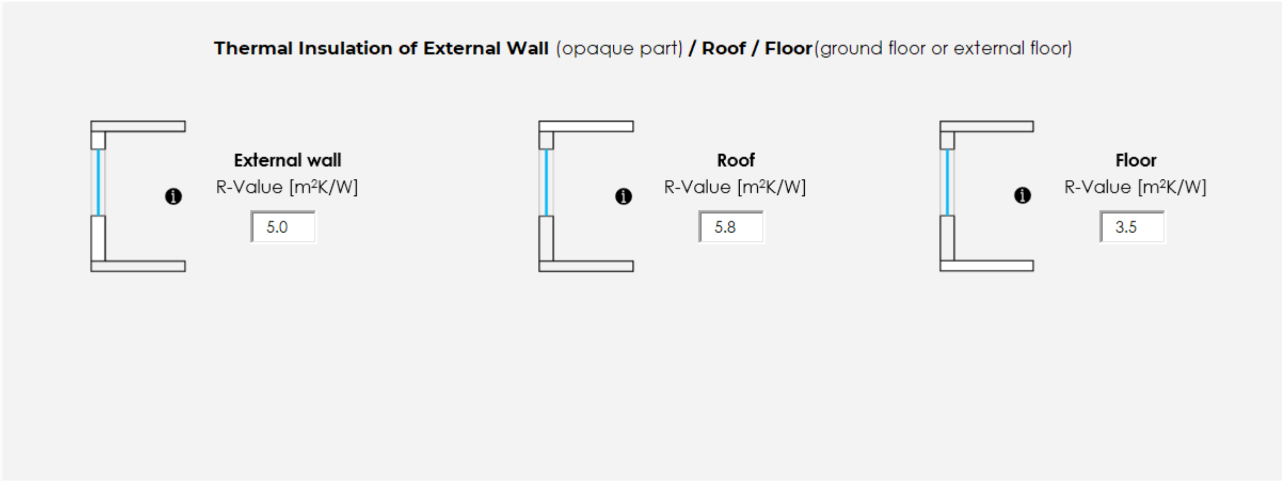


Fig 13.6a: GUI for section 5 (thermal insulation properties) of input parameter.

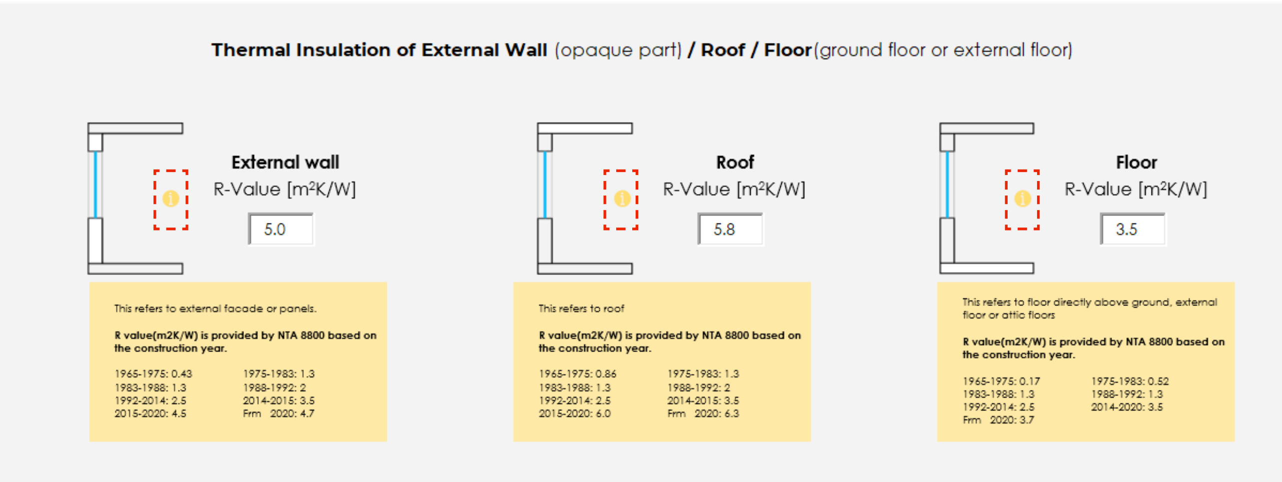


Fig 13.6b: Using Info buttons for insulation values of wall/roof/floor based on construction year. These values are taken from NTA 8800.

Section 6: Shading Properties

This section corresponds to the shading strategies for the windows in the façade.

- **% of the sky blocked by nearby context:** The amount of sky blocked by nearby context such as buildings, trees etc. expressed in percentage. From drop-down menu Heavy means more then 80% of the sky is blocked, while very little means less then 20% of the sky is blocked.
- **Overhangs:** The overhangs are expressed as a ratio between the depth of the overhang and the height of the window. For example, with a window height of 1m and overhang depth of .6m will correspond to a D/H ratio of 0.6. If the D/H ratio lies between two options from the list, a higher value must be chosen.

- **Curtains/Blinds/Shutters:** From the drop-down list, the user can select if the window has any window shading devices like curtains, blinds or shutters. From the options, only shutters are applicable outside, while all others are applied inside. To help the designer understand better, the graphic changes depending on the option the user chooses.

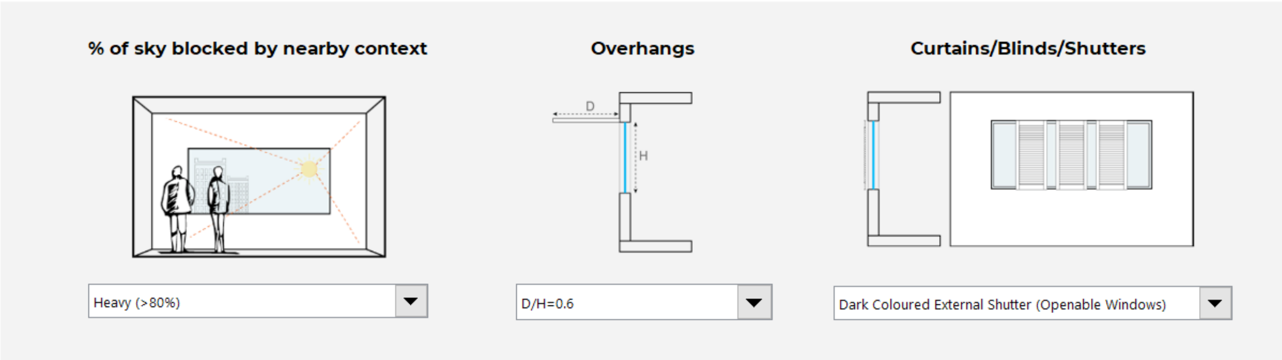


Fig 13.6: GUI for section 7 (shading properties) of input parameter.

Section 7: Ventilation Properties

This section is corresponding to the calculation of minimum ventilation required and the ventilation rate calculated from the windows.

- **Min. Ventilation Rate:** A value of minimum ventilation rate per person is required. If it is not known, the info button can be used to know minimum ventilation rates per person as specified by dutch building decree(fig 13.8a). The parameter is required to calculate the minimum ventilation required for the analysed space.
- **Ventilation through window openings:** The parameters are used to calculate how much ventilation the windows can provide. The value calculated is then compared with the minimum ventilation rate required to prompt if the windows are sufficient or not (fig 13.8b).
- **Ventilation strategy:** Check if the design allows single-sided ventilation or cross-ventilation.
- **Eff. Opening Area 1 or 2:** A total sum of the effective opening area of all the windows must be input. Example: If a room has four windows with an effective opening area x1,x2,x3,x4 respectively. The total effective opening area will be x1+x2+x3+x4.
- **Height:** This refers to the height of the opening area.

Note: Enter the value of Eff. Openings Area 2 only when cross-ventilation option is checked to avoid irrational results.

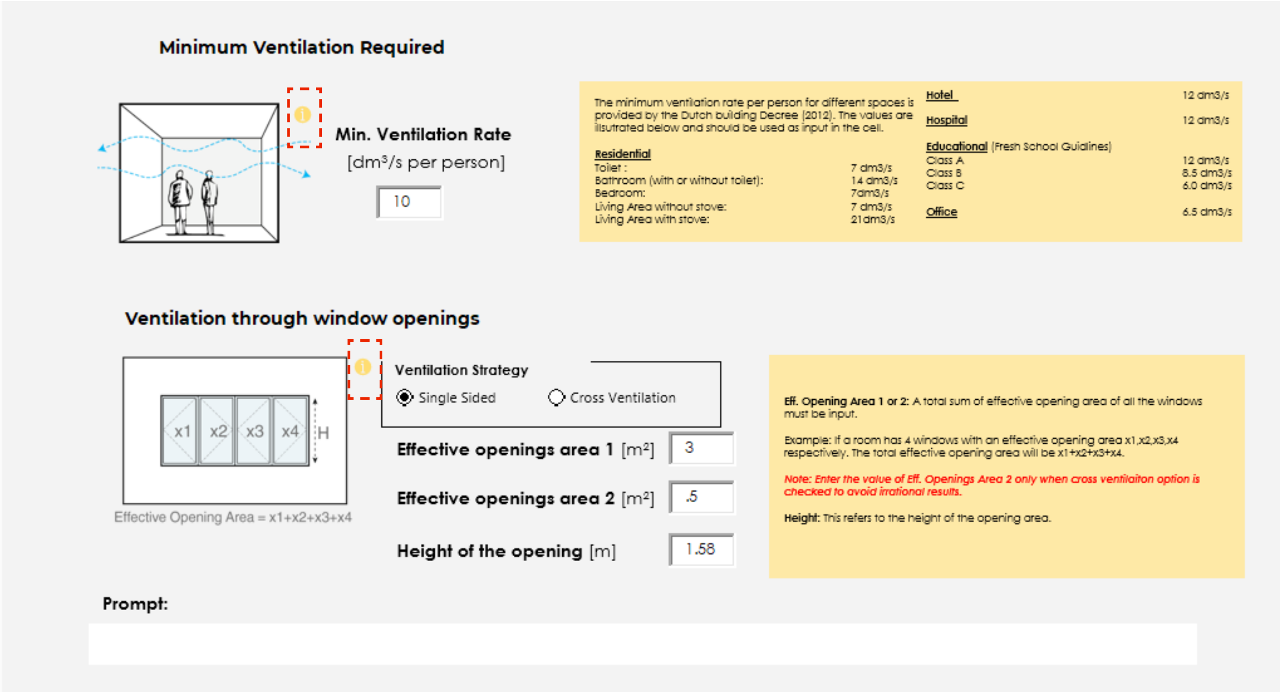


Fig 13.8a: GUI for section 7 (Ventilation properties) of input parameter. The info buttons indicated can be used by the user to know more information about the values to be input.

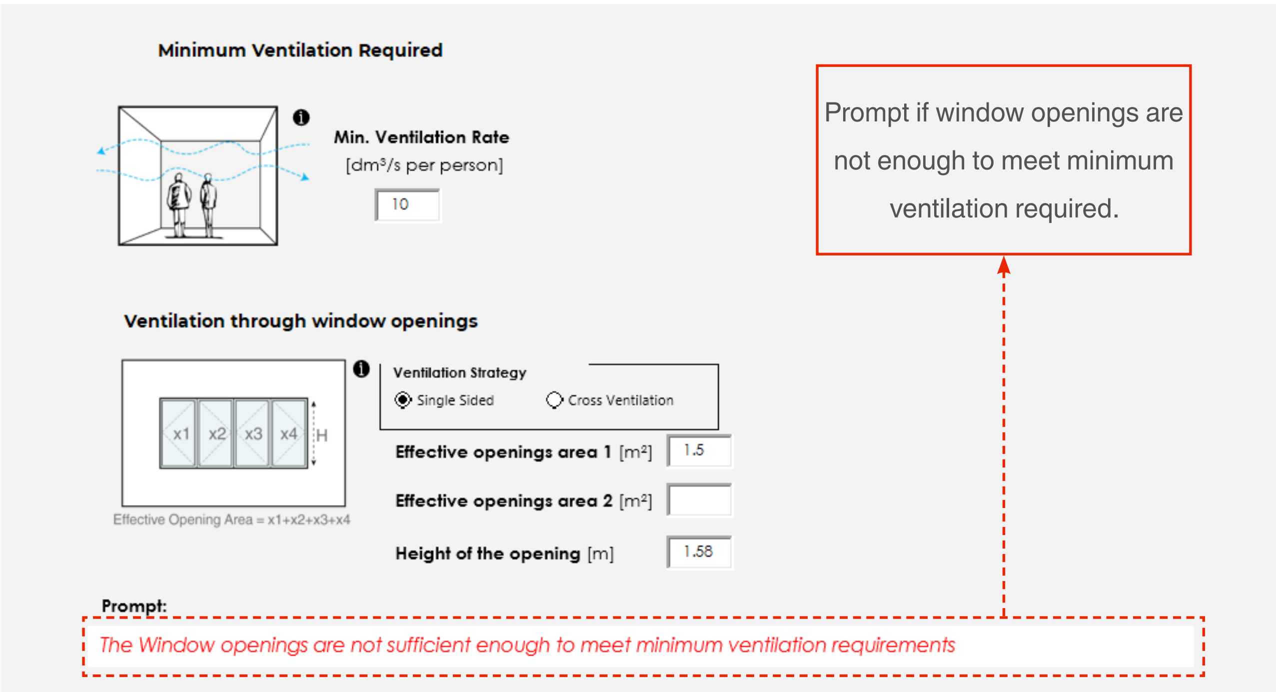


Fig 13.8b: The prompt section indicates if the window opening size is insufficient to provide minimum ventilation to space

Section 8: Internal Loads

In this section, the user is required to specify the internal heat loads.

- **Occupant Load:** The internal heat load generated by the occupants. If not known, the info button can be used to take values according to NTA 8800 (fig 13.9).
- **Equipment Load:** The internal heat load generated by the types of equipment used. If not known, the info button can be used to take values according to NTA 8800 (fig 13.9).
- **Lighting Load:** The internal heat load generated by lighting. If not known, the info button can be used to take values according to NTA 8800 (fig 13.9).

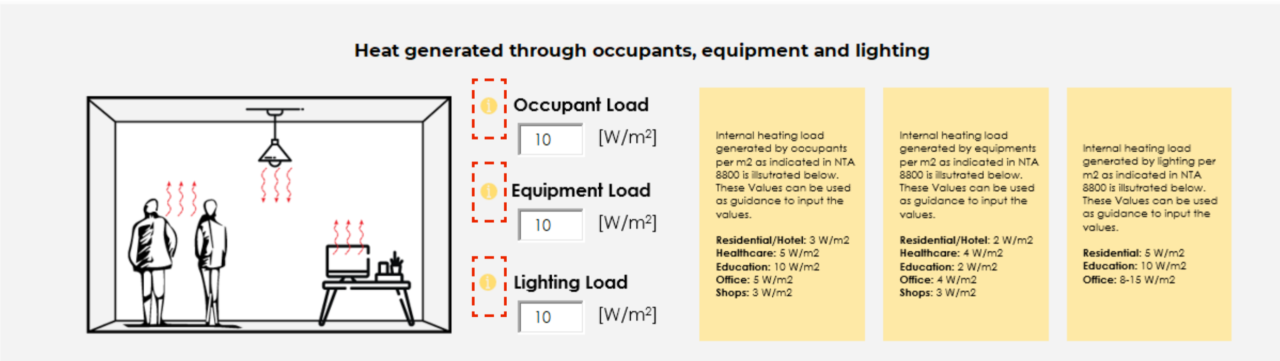


Fig 13.9: GUI for section 8 (Internal loads) of input parameter. The info buttons indicated can be used by the user to know more information about the values to be input. The values are taken from NTA 8800.

13.3 Analysis of Design Options

The analyse of the summer comfort is a two step process.

First, the user must add the design options by using the "***Add Design Option***" button. Secondly, then analyse the summer comfort and robustness by clicking the "***Calculate***" button (fig 13.10)

Note: Please add at least two design options before you calculate.

After using the ***"calculate"*** button, a graph will be plotted, indicating the TOjuly values for the 2008 baseline and 2050 climate scenario (fig 13.10). Lower the TOjuly values mean a lower risk of overheating.

Along with the bar graphs, the line graphs represent the performance deviation calculated among all the design options added (Fig 13.10). The performance deviation value changes as the user add design options. For robustness analysis, the design option which will have the lowest performance deviation will be the most robust for present and future climate. If the performance deviation of two design options is the same, then the design with least TOjuly values out of the two options will be the most robust.

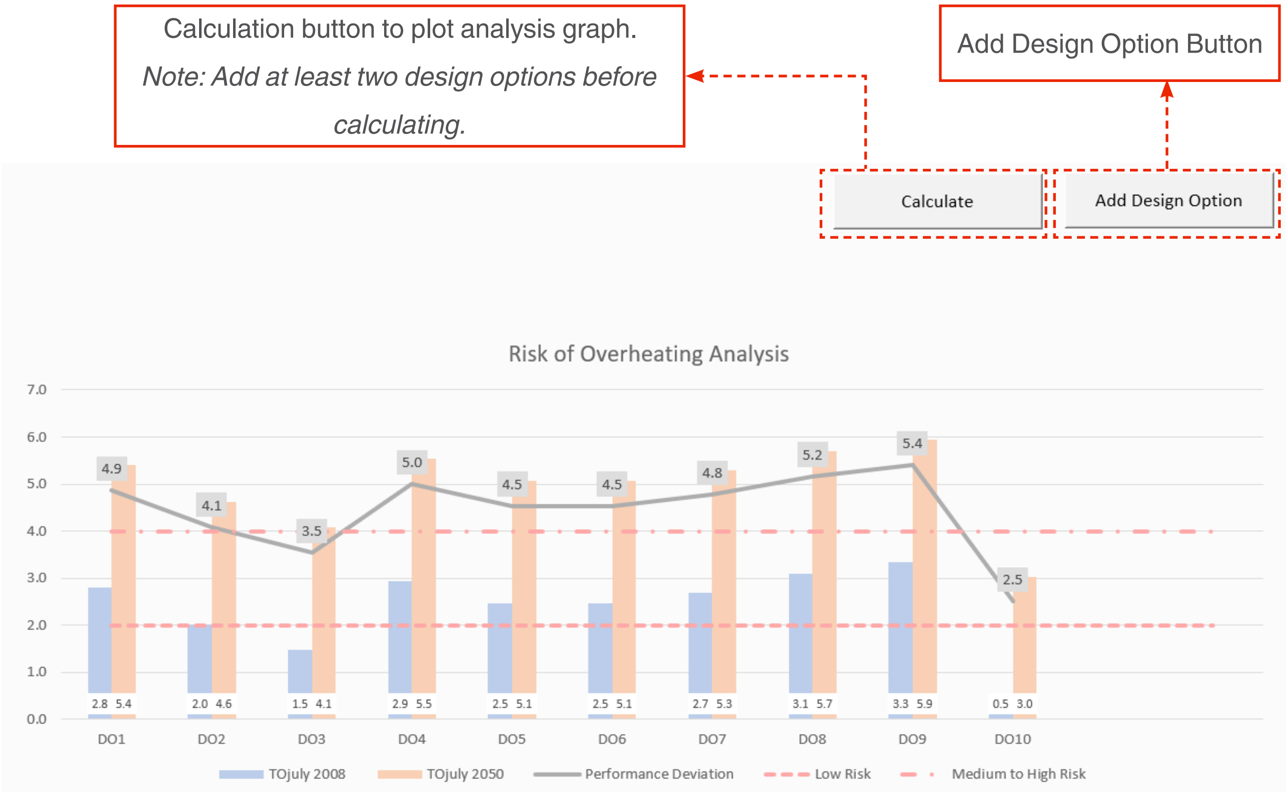


Fig 13.10: Graph generated by the tool to indicate the TOjuly values for 2008 baseline and 2050 climate. The graph also indicates performance deviation as the measure of robustness.

It can be noticed from the graph in figure 13.10, that design option DO10 has lowest TOjuly values in both climate scenarios and has the least performance deviation among all the design options. Therefore, design option DO10 is the most robust.

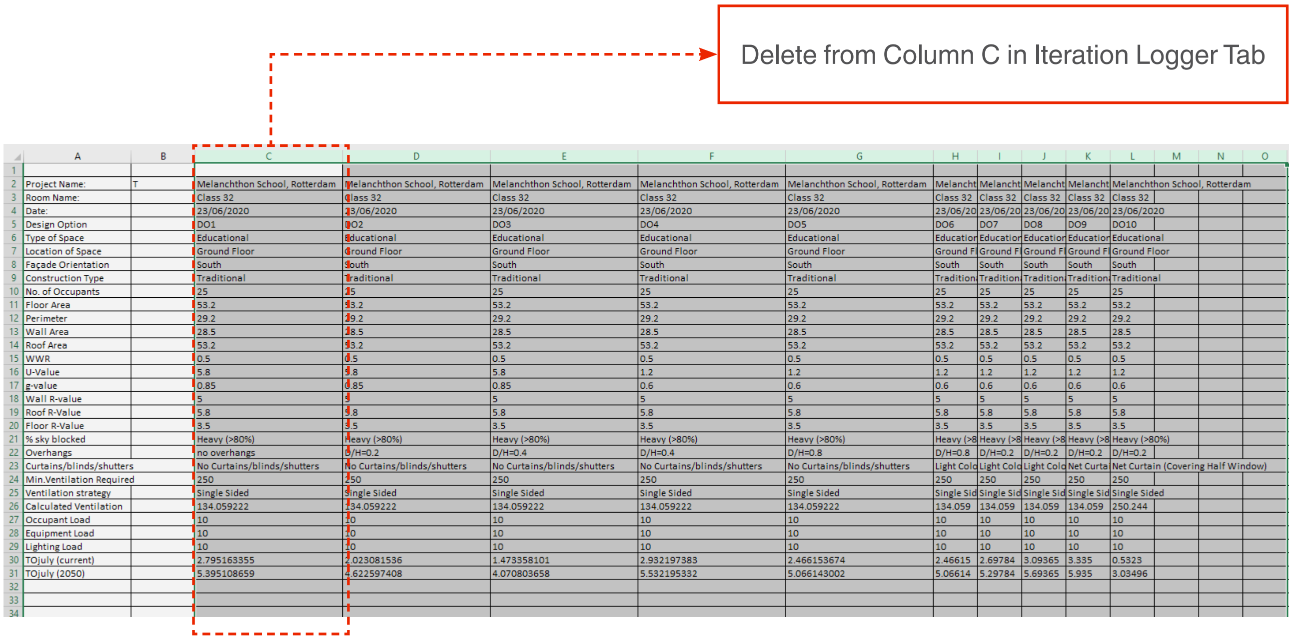
13.4 Deleting the records

In the current version, the user has to delete the records manually.

The records must be deleted using the ***"blue"*** tabs. Again it is a two-step process.

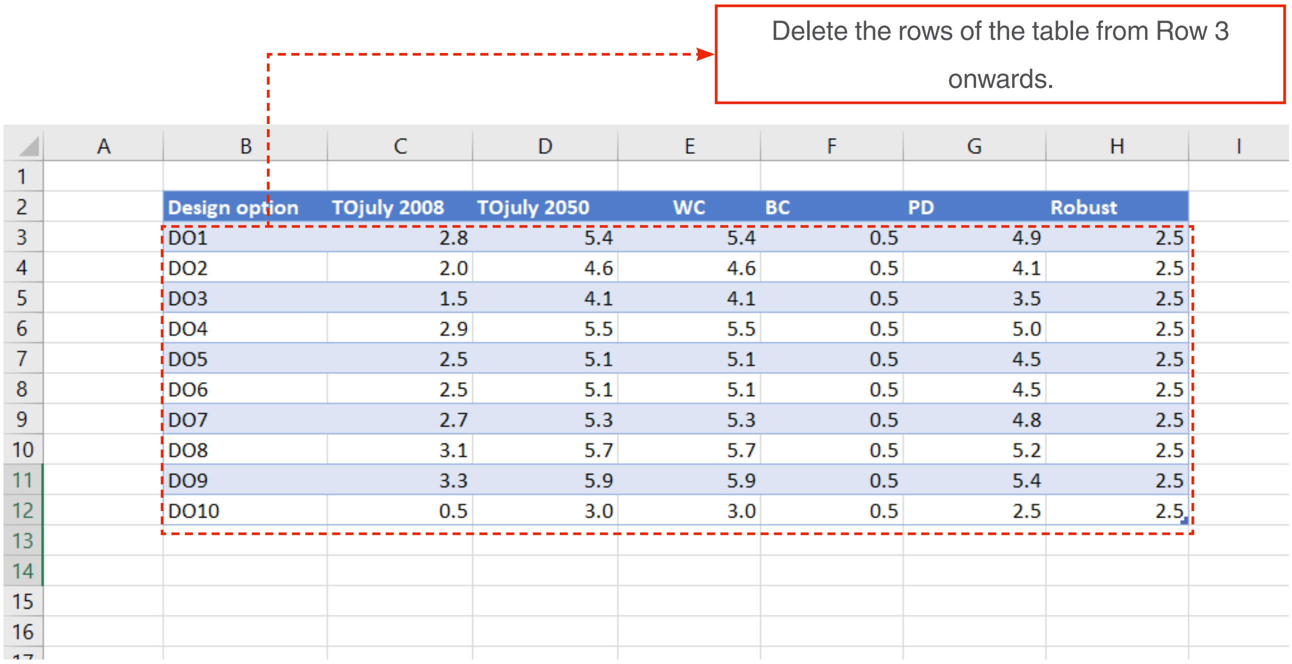
In the tab ***"Iteration logger"*** the data is recorded for all the design options. For deleting the records, the user has to delete from Column C (fig 13.11a). If the columns A and B are deleted, the tool will not function as expected.

The next step is to delete the rows of the table from row 3 onwards in the ***"Data Plotter"*** Tab (13.11b). The user must select the Rows of the table only and delete them instead of deleting the data.



	A	B	C	D	E	F	G	H	I	J	K	L
2	Project Name:	T	Melanchthon School, Rotterdam	Melanchthon School, Rotterdam	Melanchthon School, Rotterdam	Melanchthon School, Rotterdam	Melanchthon School, Rotterdam	Melancht	Melancht	Melancht	Melancht	Melanchthon School, Rotterdam
3	Room Name:		Class 32	Class 32	Class 32	Class 32	Class 32	Class 32	Class 32	Class 32	Class 32	Class 32
4	Date:		23/06/2020	23/06/2020	23/06/2020	23/06/2020	23/06/2020	23/06/20	23/06/20	23/06/20	23/06/20	23/06/2020
5	Design Option		DO1	DO2	DO3	DO4	DO5	DO6	DO7	DO8	DO9	DO10
6	Type of Space		Educational	Educational	Educational	Educational	Educational	Education	Education	Education	Education	Educational
7	Location of Space		Ground Floor	Ground Floor	Ground Floor	Ground Floor	Ground Floor	Ground Fl	Ground Fl	Ground Fl	Ground Fl	Ground Floor
8	Façade Orientation		South	South	South	South	South	South	South	South	South	South
9	Construction Type		Traditional	Traditional	Traditional	Traditional	Traditional	Tradition	Tradition	Tradition	Tradition	Traditional
10	No. of Occupants		25	25	25	25	25	25	25	25	25	25
11	Floor Area		53.2	53.2	53.2	53.2	53.2	53.2	53.2	53.2	53.2	53.2
12	Perimeter		29.2	29.2	29.2	29.2	29.2	29.2	29.2	29.2	29.2	29.2
13	Wall Area		28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5
14	Roof Area		53.2	53.2	53.2	53.2	53.2	53.2	53.2	53.2	53.2	53.2
15	WWR		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
16	U-Value		5.8	5.8	5.8	1.2	1.2	1.2	1.2	1.2	1.2	1.2
17	g-value		0.85	0.85	0.85	0.6	0.6	0.6	0.6	0.6	0.6	0.6
18	Wall R-value		5	5	5	5	5	5	5	5	5	5
19	Roof R-Value		5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8
20	Floor R-Value		3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
21	% sky blocked		Heavy (>80%)	Heavy (>80%)	Heavy (>80%)	Heavy (>80%)	Heavy (>80%)	Heavy (>8	Heavy (>8	Heavy (>8	Heavy (>8	Heavy (>80%)
22	Overhangs		no overhangs	D/H=0.2	D/H=0.4	D/H=0.4	D/H=0.8	D/H=0.8	D/H=0.2	D/H=0.2	D/H=0.2	D/H=0.2
23	Curtains/blinds/shutters		No Curtains/blinds/shutters	No Curtains/blinds/shutters	No Curtains/blinds/shutters	No Curtains/blinds/shutters	No Curtains/blinds/shutters	Light Colo	Light Colo	Light Colo	Net Curtai	Net Curtain (Covering Half Window)
24	Min.Ventilation Required		250	250	250	250	250	250	250	250	250	250
25	Ventilation strategy		Single Sided	Single Sided	Single Sided	Single Sided	Single Sided	Single Sid	Single Sid	Single Sid	Single Sid	Single Sided
26	Calculated Ventilation		134.059222	134.059222	134.059222	134.059222	134.059222	134.059	134.059	134.059	134.059	250.244
27	Occupant Load		10	10	10	10	10	10	10	10	10	10
28	Equipment Load		10	10	10	10	10	10	10	10	10	10
29	Lighting Load		10	10	10	10	10	10	10	10	10	10
30	TOjuly (current)		2.795163355	2.023081536	1.473358101	2.932197383	2.466153674	2.46615	2.69784	3.09365	3.335	0.5323
31	TOjuly (2050)		5.395108659	4.622597408	4.070803658	5.532195332	5.066143002	5.06614	5.29784	5.69365	5.935	3.03496

Fig 13.11a: Deleting records step 1: Delete the columns from "Column C" onwards in "Iteration Logger" Tab.



Design option	TOjuly 2008	TOjuly 2050	WC	BC	PD	Robust
DO1	2.8	5.4	5.4	0.5	4.9	2.5
DO2	2.0	4.6	4.6	0.5	4.1	2.5
DO3	1.5	4.1	4.1	0.5	3.5	2.5
DO4	2.9	5.5	5.5	0.5	5.0	2.5
DO5	2.5	5.1	5.1	0.5	4.5	2.5
DO6	2.5	5.1	5.1	0.5	4.5	2.5
DO7	2.7	5.3	5.3	0.5	4.8	2.5
DO8	3.1	5.7	5.7	0.5	5.2	2.5
DO9	3.3	5.9	5.9	0.5	5.4	2.5
DO10	0.5	3.0	3.0	0.5	2.5	2.5

Fig 13.11b: Deleting records step 2: Delete the rows of the table from "Row 3" onwards in "Data Plotter" Tab.

13.5 Further Development

The tool developed shows promising results in communicating the summer comfort analysis and robustness among the design options. Currently, the tool is based upon static heat balance equations; hence it does not including any dynamic effects. Therefore in the future versions of the tool, the dynamic behaviour of environmental variables can be incorporated to provide better insights into summer comfort.

The next future development would also include other significant aspects of comfort and energy analysis for having a better comparison for robustness evaluation.

Currently, the design tool is excel based where in future, the tool can be developed to be integrated with 3d modelling software where the analysis can be done in parallel with geometries prepared by the designer.

Part 7

Conclusions

14. Conclusions

The primary objective of the study was to investigate the robustness of passive design strategies applicable to the building envelope in mitigating the risk of overheating in future climate scenarios. This chapter will discuss the results and conclusions of the study by answering the main research question. The results will be discussed in a hierarchy where first, the key questions will be responded for providing answers to the sub research questions, and finally, the main research question will be addressed.

14.1 Answering research questions

1. What are the influential parameters corresponding to building envelope design?
    1.1. What is the role of building envelope in maintaining thermal comfort and energy efficiency?
    1.2. What are the energy-efficient guidelines for building envelope in the context of the Netherlands?

The building envelope, which behaves like a physical barrier between the indoor controlled environment and outdoor conditions, has a crucial role in maintaining comfort and energy-efficiency both. A poorly designed envelope can result in uncontrolled heat gain or loss, resulting in high energy demands to maintain the thermal comfort of the space. Whereas, an efficient envelope design can reduce as much as 60% of the heating and cooling demands depending on the context (International Energy Agency (IEA), 2013).

The interaction of the building envelope with the outdoor environment results in heat exchanges through conduction, convection, and radiation. The functional property of the envelope is to control these heat transfer mechanisms and regulate the heat gain or heat loss through its components without using any energy. Based on the function of envelope components in limiting the outdoor environment into the inside, the components can be divided as opaque or transparent components. The opaque components constitute the roof, external wall, floor, while the transparent components constitute the windows, doors, skylights (Al-saadi, 2006).

To enhance the efficiency of the building envelope components, the Dutch government has prescribed minimum functional requirements of insulation, ventilation, and infiltration. According to the Dutch regulations NTA 8800, the minimum insulation R-values for the roof, external wall, and the external floor is specified as 6.3 m^2.K/W, 4.7 m^2.K/W and 3.7 m^2.K/W respectively, whereas the heat transfer from the windows must be limited to the maximum U-Value of 1.65 W/m^2.K including glazing and frame. Ventilation through building envelope provides optimum indoor air quality by regulating the CO^2 generated by the occupants. It also controls the indoor climate by providing a medium for heating and cooling. The ventilation strategy can be incorporated in the building envelope either by natural means or mechanical means. According to Bouwblesuit 2012, for an education building, a minimum of 8.5 l/s per person must be used in designing ventilation openings or mechanical systems.

In conclusion, the most influential parameters for an energy efficient building envelope design corresponds to the insulation levels and ventilation requirements for both opaque, transparent components in regulating heat gain or loss through transmission, solar radiation, infiltration, and ventilation.

2. What are the different parameters that contribute to the overheating of space?

2.1. What is overheating

2.2. What are the sources of overheating?

Overheating can be defined as the accumulation of heat inside a building to such an extent that it creates thermal distress among the occupants. According to literature, 25°C is general the temperature limit at which occupant feels discomfort due to overheating and thermally uncomfortable at 28°c.

As discussed in chapter 5, the primary sources of overheating during summers are the heat gain from solar radiations and internal loads along with inadequate ventilation system to remove excess heat. These heat gains, when coupled with other factors like urban heat island effect, insufficient thermal mass, airtightness, increases the risk of overheating in any space.

For highly energy-efficient buildings, the building envelope design focuses on high glazing ratio, high insulation, and airtightness of the components to reduce heat loss in winters. However, in summer, the indoor spaces behave much like greenhouses, which results in overheating of the spaces. With the increase in the outdoor air temperature, the risk of overheating is likely to increase, and since the building envelope is the primary factor of overheating, the strategies must focus on improving and proposing building envelopes for future scenarios.

3. What are the potential spaces which may overheat in case study buildings?

3.1. What are the thermal comfort guidelines for educational buildings in the Netherlands?

3.2. What are the overheating thresholds in the Netherlands?

3.3. What are the precedence studies for the overheating problem in educational buildings?

3.4. How to identify the spaces which may overheating in the case study buildings?

Thermal comfort is regarded as the satisfaction of the state of mind concerning the thermal environment around the occupant. There are various researches, comfort models and metrics developed to determine the thermal comfort. These metrics, however, can be classified broadly into steady-state models and adaptive models.

According to Dutch Guidelines, the thermal comfort of a space is assessed using the temperature exceedance model. Various evaluation methods such as TO, GTO, and ATG were developed to assess the temperature exceedance in both summer and winter. However, for this study, the ATG method is used to assess the thermal comfort of a space.

The ATG method is based on an adaptive model of thermal comfort and was revised in 2014, according to European standard EN 15251. The ATG method is often considered as a hybrid method since it can be applied for both mechanically cooled (Beta Type) and free-running buildings (Alpha type). The Dutch guidelines ISSO 74 specifies “Class B” as the minimum requirement for new buildings. Therefore, educational buildings must satisfy Class B requirements.

The ATG method is useful in determining the overheating of a space. Earlier methods like TO and GTO were used to indicate overheating with thresholds like 100 hours or 150 hours, respectively. However, the ATG method instead of considering hours, it uses the percentage of discomfort hours as the indicator of overheating, which is directly connected to the thermal comfort assessment of Class B. As specified in ISSO 74, a particular space qualifies for Class B if the percentage of discomfort hours are limited to 10% of the total occupied hours, which is taken as the threshold for overheating analysis.

From chapter 10.2, it was found that generally, learning spaces like the classroom and lecture halls are more susceptible to thermal comfort problems due to large occupant loads for a longer time. It was also observed that the spaces on South, South-East, North West and North East orientation are the most likely to overheat. Lastly, the spaces on the top floors are susceptible to overheating in summers due to solar gains from the façade and the roof.

However, the studies are very much dependent on the context of the building. Therefore, to understand the impact of context in blocking the summer sun, a solar radiation analysis was performed on the case studies. The case studies were modelled in Rhino with a nearby context, and solar radiation analysis was done using the ladybug tool for grasshopper (fig

10.2a, 10.2b , 10.4). From the analysis, it was observed that the spaces on the northeast , northwest, and south indeed receive high solar radiation. Therefore, the spaces located in these directions were identified from both the case studies.

In Pulse building, seven spaces were identified (fig 10.3) . Hall 1 and Hall 2 though on the ground floor, may have a risk of overheating due to solar gain from the roof and high occupancy load. Hall 4 on the intermediate floor, Hall 5 on the first floor, Hall 9, and Hall 10 on the second floor are located on the northeast side of the building. Another compelling case was considered for Hall 8 on the second floor. It was assumed that space might overheat due to heat gain from roof and sky-light; also, due to the glass partition wall, the hall may receive radiation from the southwest façade. Another aspect was the lower insulation values of the partition walls. Since Hall 8 is conditioned space, the partition wall should have high insulation to reduce any heat gain from the corridor spaces, which are relatively less conditioned.

In School Building, three spaces were considered for evaluation (fig 10.4). From the analysis, the classrooms facing south and on the top floor might have a risk of overheating. Therefore, staffroom, class 31, and class 32 were chosen for further analysis.

4. What is the potential risk of overheating in educational buildings in the present and future climate scenarios?

    4.1. What are the future scenarios to be considered for evaluation?

    4.2. How to identify the risk of overheating using analytical calculations?

    4.3. How to validate the analytical tool for identifying and measuring the overheating in educational buildings?

    4.4. How to use a dynamic simulation tool to identify the risk of overheating?

The Dutch meteorological institute provides four climate change scenarios based on the change in air circulation and average global temperature. For the study, the worst-case scenario of Wh, which represents the warm temperature with the high change in air circulation, was taken. The climate change scenarios are also provided for two specific future time horizon that is 2050 and 2085.

To incorporate future weather into the assessment of overheating and thermal comfort, the hourly weather files are prepared based on the test reference years mentioned by NEN 5060:2008. The online transformation tool from KNMI was used to prepare three weather files, namely baseline 2008 1%, 5060 1%, and 2085 1%, where 1% is the probability of actual temperature overshoot then specified in the reference months. These three weather files were used further for the analysis of overheating in the case study buildings.

From the conclusion of preliminary analysis, a total of ten spaces (seven in Pulse, three in

School) were identified, which may have a risk of overheating. Ideally, these spaces would now be analysed using dynamic simulation to look for the real risk of overheating. However, dynamic simulation for ten spaces would require much time. Therefore, an analytical method was used to narrow down the ten spaces to the most typical cases. For the same, the TOjuly method proposed by NTA8800 was used.

The TOjuly method is a static heat balance calculation model that indicates the probability of excess temperature in July. Therefore, the higher the TOjuly value, the higher the risk of overheating. To understand the risk of overheating from the TOjuly value, the value between 0-2 is considered to be a minimum risk. A value between 2-4 is considered as moderate risk, and a value higher then 4 indicates a high risk of overheating (Lente Akkord, 2019).

The TOjuly method is validated for only residential use but not for educational buildings. Therefore, the method was validated by calculating TOjuly from dynamic simulations. Since TOjuly uses 24°C as a limit for calculating excess temperature. A difference between average simulated air temperature in July and 24°C was taken. The method was validated as the difference between calculated and simulated TOjuly value was under 20%. However, it was concluded that the TOjuly value could not be used for assessing corner spaces.

From TOjuly calculation, the ten identified spaces from each case study were narrowed down to Hall 8 and Hall 10 in the Pulse building, while classroom 31 from the school building. In the school building, the corner staffroom was also selected for dynamic simulations since the results from calculated TOjuly were inconclusive.

The Design Builder tool was used for dynamic simulations. For analysing the risk of overheating in the identified spaces in 2050 and 2085, a workflow was designed, as illustrated in Fig 11.1. From the workflow, ATG graphs were prepared for all the spaces in the present and future climate scenarios, and the percentage of discomfort hours were compared (graph 11.2).

From the comparison of the results, it was concluded that the Pulse building is subjected to overheating in future climate scenarios. To maintain comfort in the future, the spaces would require higher cooling loads, which will lead to an increase in energy demands. Therefore, it is imperative to analyse the impact of passive design strategies into the building envelope to limit the discomfort hours to 10%, even in the future climate.

The Melanchthon school, which is a free-running building, also performs within the comfort Class B in baseline climate. The Melanchthon school exhibits a good example of integrated passive design strategies on all levels of design. Although, it would be interesting to observe how far the passive design strategies can help in reducing overheating risk.

5. What are the adaptive design strategies in temperate climate available for building envelope?

   5.1. What are the different passive design strategies in temperate climate available, which could reduce the risk of overheating?

   5.2. Which among the passive strategies found in key question 5.2 is applicable for building envelope?

   5.3. When in the building lifespan, these strategies should be incorporated?

Adaptive strategies can be understood as the strategies which interact with the external environment and adapt to provide indoor comfort by utilising the full potential of natural conditions. In response to summer comfort, the main agenda is to provide cooling. Therefore, as an initial strategy to reduce the cooling demands, passive design and cooling principles which are climate responsive must be employed (Looman, 2017; Prieto, Knaack, Auer, & Klein, 2018).

The energy-efficient building design in a temperate climate during winters makes use of passive solar heating strategies involving external and internal heat gain. However, as discussed in chapter 5, these heat gains must be controlled in summer for reducing the risk of overheating. The high insulation and airtightness in winters reduce the heat loss, but in summers, the heat accumulated inside due to high insulation must be removed via ventilation. Thus, to reduce overheating, the strategies must focus on heat protection, heat control, and heat removal (Table 7.1).

From various literature, it was also found that the effectiveness of passive strategies to reduce overheating can be enhanced through integrated design. The integration of passive design can be achieved in three stages of design. Firstly by designing the building itself (Pre-Design Stage) by considering the site, orientation, microclimate, solar shading. Secondly, by focusing on the climate design (Concept design stage), through integrating strategies such as thermal mass, window to wall ratio, window locations over the building envelope and finally using low energy cooling strategies (system design) like radiant system, evaporative cooling, wind towers.

Fig 7.1 provides a non-exhaustive overview of different passive design strategies at three stages of design, namely pre-design, concept design, and system design. In each design stage, the strategies are arranged on the objective of the passive design strategy that is passive cooling, ventilation, heating, and daylighting. While selecting the appropriate passive measures, it is also essential to consider the level of application like the site, building, spatial, and component to facilitate the utmost integration of strategies.

Since building envelope is one of the primary factors for overheating of the buildings, literature research was conducted for various types of buildings, and the strategies used to reduce overheating. Based on the conclusions from the literature research done in section

7.4, strategies applicable to building envelope were extracted from the general overview of strategies. Figure 7.5-7.7 illustrates the passive design strategies which can be applied to the building envelope. The strategies are again arranged as the objective of the passive cooling strategy that is heat avoidance, control, and removal. Further, the strategies were arranged based on the control parameter and "where" in the design stage it can be integrated. As mentioned earlier, climate change is a moving target; therefore, a progressive approach to upgrade the building envelope can benefit in reducing the risk of overheating in future scenarios (CIBSE, 2005). Therefore, another dimension of "when" to apply these strategies was also added to the illustrations.

6. How to evaluate the robustness of different design solutions in mitigating overheating problems in the present and future climate scenarios?

   6.1. What is robustness in the context of energy efficient buildings?

   6.2. What are the assessment methods available in the literature to evaluate the robustness of a design?

   6.3. What are the different parameters needed to evaluate the robustness of a design?

As discussed in chapter 8, the evaluation of robustness is generally more prevalent in the product design industry, although the concept is equally valid for the performance of the building design. The concept of robustness refers to the minimum performance variation of design as compared to the predicted one in the presence of any uncertainties. Therefore, an energy-efficient design can be called robust if the building continues to provide comfort and maintain its energy efficiencies in the presence of uncertainties due to occupancy behaviours and outdoor climate. From the literature, it was concluded that the impact of uncertainties from climate change is high on the performance of energy-efficient design. The risk of overheating in energy efficient buildings is already present, and with the increasing outdoor temperature due to climate change, the problem will only be aggravated. From the study, it was also concluded that the building envelope is the primary factor for controlling overheating, and passive design strategies could help reduce the risk of overheating. Therefore, for the context of the study, the passive strategies which are capable of controlling overheating even in the worst-case scenario of climate change would be regarded as a robust design solution.

As discussed in chapter 8, three statistical methods were identified to evaluate robustness, namely "min-max method," "worst-case & best case method," and "min-max regret method,"out of which the "best-case and worst-case scenario" method was used. In this method, the design solutions were compared with each other across all climate scenarios through performance deviation. The performance deviation was calculated as the difference between the best performance of the entire design space and the worst performance of design across considered scenarios. The robust solutions were the ones with minimum performance deviation. For analysing the robustness, three parameters were used; first, the design solution sets prepared for each identified space for both the case studies. These solution sets are illustrated in table 12.3. Second, future climate scenarios of 2050 and 2085 and finally the percentage of discomfort hours as the performance indicator. The workflow prepared to analyse the robustness of the design solutions is illustrated in fig 12.2.

7. How robust are different passive design building envelope solutions?

In the context of the study, a robust design solution would be the solution set, which reduces the percentage of discomfort hours in future climate scenarios as compared to the performance of the base case. Upon comparing the robustness evaluation for the case studies, it can be concluded that the combined effect of relevant strategies is more effective than individual application. A combination of reduced WWR and application of white surfaces on building envelope could reduce up to 40% of percentage discomfort hours in 2050 and up to 30-35% in 2085. The effectiveness can further be enhanced by using strategies where in terms of fixed shading, combination of overhangs and side fins and for moveable shading, external blinds and shutters are more robust. The summer bypass combined with mixed-mode ventilation strategy and PCM can reduce up to 50-60% of overheating in the 2050 climate scenario, but in 2085 the effect of ventilative cooling is much lower. Hence, it can be concluded that a combination of white surfaces on the building envelope, reduction in WWR, careful application of shading strategies, and limited application of mixed-mode ventilation till 2050 are the most robust solutions applicable to the building envelope. Although, in 2085, we cannot avoid the use of active cooling to support these strategies.

8. How to incorporate robustness in the design process for architects and designers ?

As discussed in chapter 13, the robustness of design is an essential factor which needs to be considered during the early stages of the design. However, robustness is an abstract concept for designers. Therefore, a tool was developed, keeping the architects and designers in mind which can quantify this abstract concept and inform design decisions.

From the research, it was found that generally, architects and designers find the advance simulation software counter-productive for their design process. The primary reason is the excessive data input and lack of user-friendly interface. To reduce these shortcomings, the tool was developed in such a way that the user can navigate itself and provide as minimum inputs as possible. For incorporating the tool into the design process, multiple design iterations can be analysed quickly to indicate the summer comfort and the most robust design option among the entire design sample space.

Currently, the tool is limited to static heat balance equations; however, the tool can be developed to consider the dynamic effects of the environmental variables. Furthermore, other aspects of comfort like visual, acoustic, along with energy consumption, can be incorporated to provide a holistic analysis of the most robust design solution.

*What are the **adaptive strategies** in a temperate climate, applicable to **building envelope** facilitating **robustness** of **energy efficient educational buildings** by reducing the risk of **overheating** in **future climate** change scenario?*

The study aimed at investigating the adaptive design strategies which could enhance the robustness of energy efficient educational buildings in mitigating the risk of overheating in future climate scenarios.

The building envelope of highly energy efficient buildings intends to conserve heating loads in winter by making a highly insulated and airtight building envelope. However, the same strategy converts the space into a greenhouse in summers resulting in overheating. In the worst-case scenario of climate change, there will be a significant rise in the outdoor temperature, which could reduce the number of heating days; thus, the risk of summer overheating will even be more serious. Therefore, it is imperative to look into the current building design and evaluate the robustness of the design strategies at building envelope for its performance in future scenarios.

The study employed both analytical and dynamic simulation methods to evaluate the robustness of strategies in the context of the selected case study of educational buildings. The analytical method of TOjuly, which is used for only residential buildings, was adapted and simplified for use in educational buildings. The method was validated using dynamic simulations; but, the method cannot be applied for corner spaces. However, the method is simplified enough to be used for overheating analysis for the early design stage.

The study also developed various workflows for analysing the risk of overheating future climate using the ATG methods. The case study selected was the Pulse building in TU delft campus, which is a mechanically cooled building and Melanchthon school in Rotterdam, which is a free-running building. The ATG method was used to evaluate the overheating because of its applicability to both mechanically cooled and free-running buildings. The workflow developed could very well inform designers and architects with a non-technical background to analyse the thermal comfort and overheating in buildings.

From the identification of risk of overheating in the present and future climate scenario, it was found that the Pulse building, has a higher risk of overheating in the future as compared to the school building. The school building has well-integrated passive design measures which reduce the risk of overheating greatly. This conclusion also falls in line with the research done by Sarah et al. (2011) on the robustness of building profiles. Their study also concluded that the climate influenced building profiles are much robust then climate ignoring.

For reducing the overheating, the study conducted an in-depth literature review of the various strategies applicable to the temperate climate. The study also presents illustrations for the various strategies applicable to building envelope for reducing overheating. The illustrations were designed for building designers, architects, and non-technical professionals to provide a visual representation of the various design strategies.

From robustness evaluation, it was concluded that along with the statistical evaluation method, the actual performance of the design solution must also be compared. Upon comparing the robust solution and the design solution with the best performance in 2050 and 2085, it was found that the ventilative cooling is only effective until 2050. In 2085 due to the elevated outdoor temperature, the ventilative cooling would have limited effect.

From the overall study, it was concluded that a combination of reduced WWR, white surface on building envelope, and careful application of shading devices on building envelopes could very well make a building robust for a future scenario. However, in 2085 active cooling systems would be a necessity. Thus, the study suggests on development of low energy cooling in the latter part of the century, which could complement the passive strategies, thus developing a synergy between active and passive strategies.

14.2 Future Research directions

At present, the study focused on the robustness of passive strategies in the context of summer comfort in energy-efficient design. The outcomes of the study are very well dictated by only comfort aspects. Therefore, it would be interesting to add another parameter of energy efficiency into the robustness analysis.

Since the study took only the case of educational buildings, the research must be validated by the application of the workflows to other types of building stock like residences, hospitals, office.

During the research, many workflows were prepared to evaluate robustness, dynamic simulations and plotting ATG graphs. However, these workflows are stand-alone and still not integrated into one holistic process. Therefore, another research direction is to embed the workflow using parametric design to prepare dynamic tools for simulating the performance of a design and robustness evaluation.

Part 8

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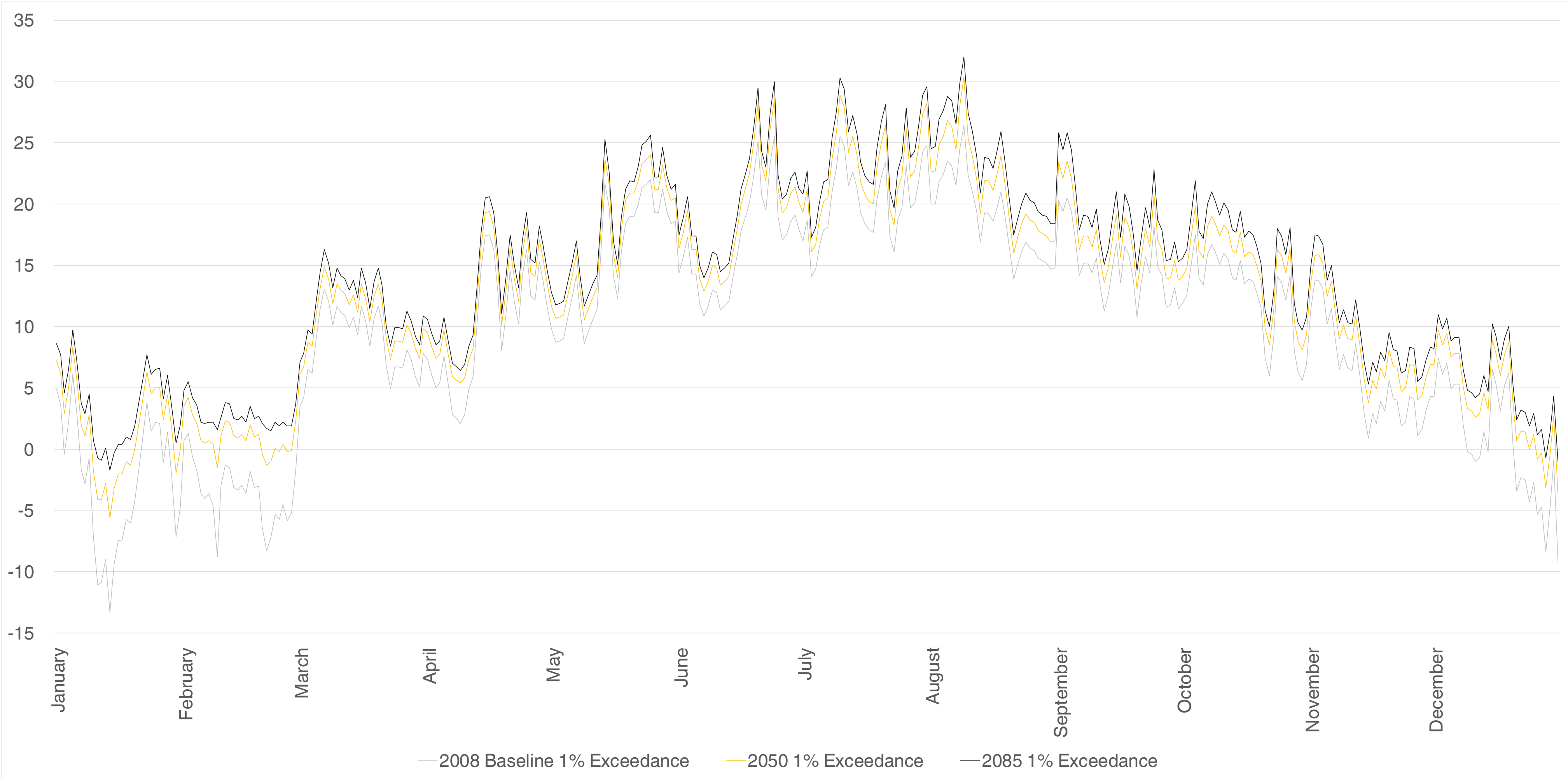
Part 9

Appendices

Appendix A

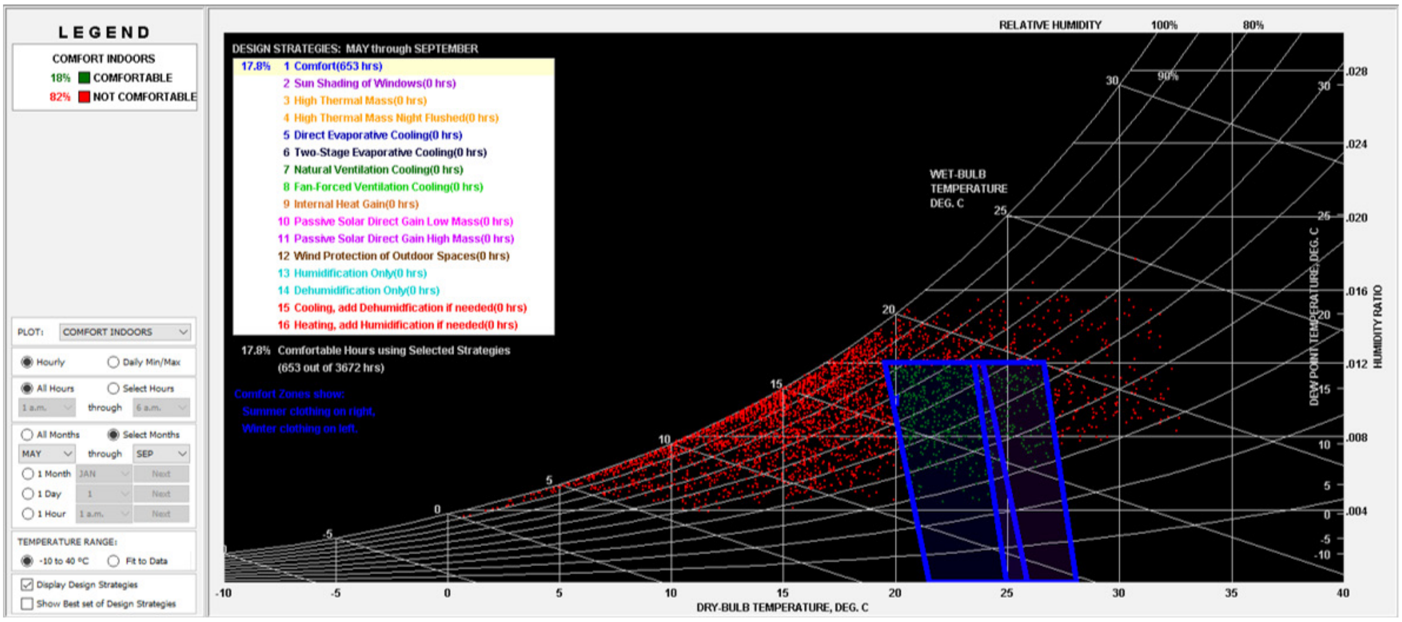
Comparison of Transformed weather files from baseline 2008, 2050 and 2085



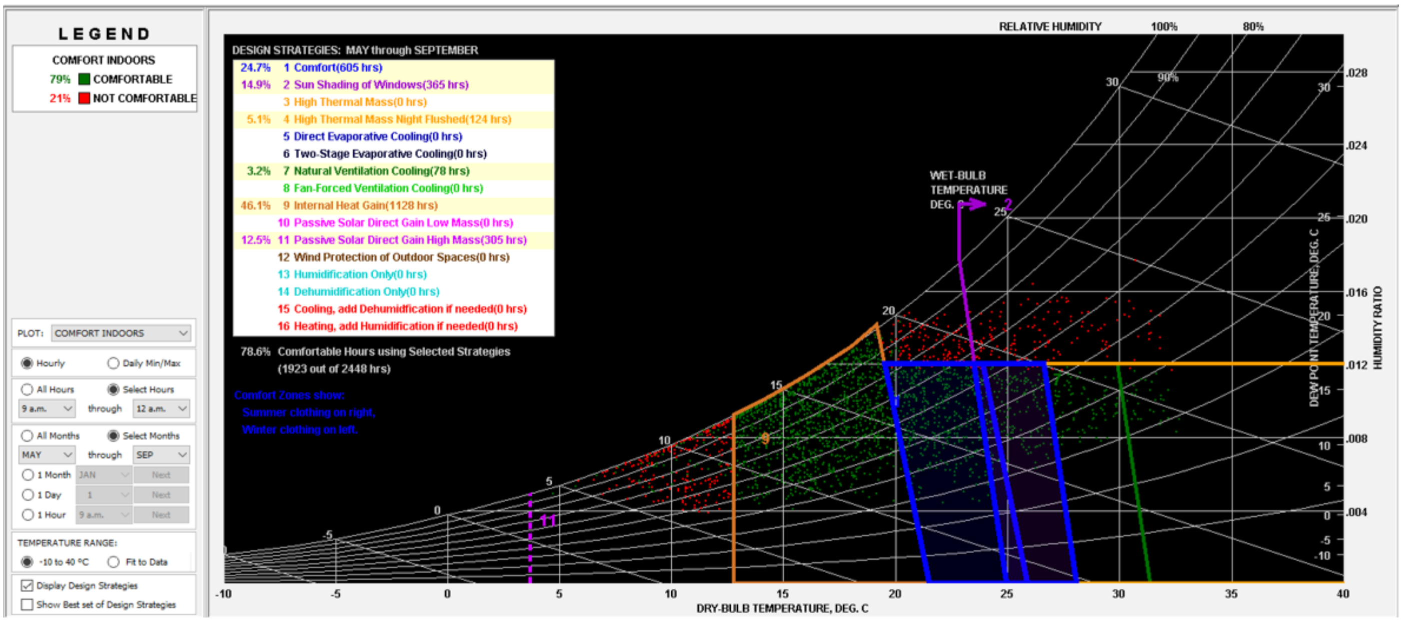
Appendix B

Psychrometric Charts

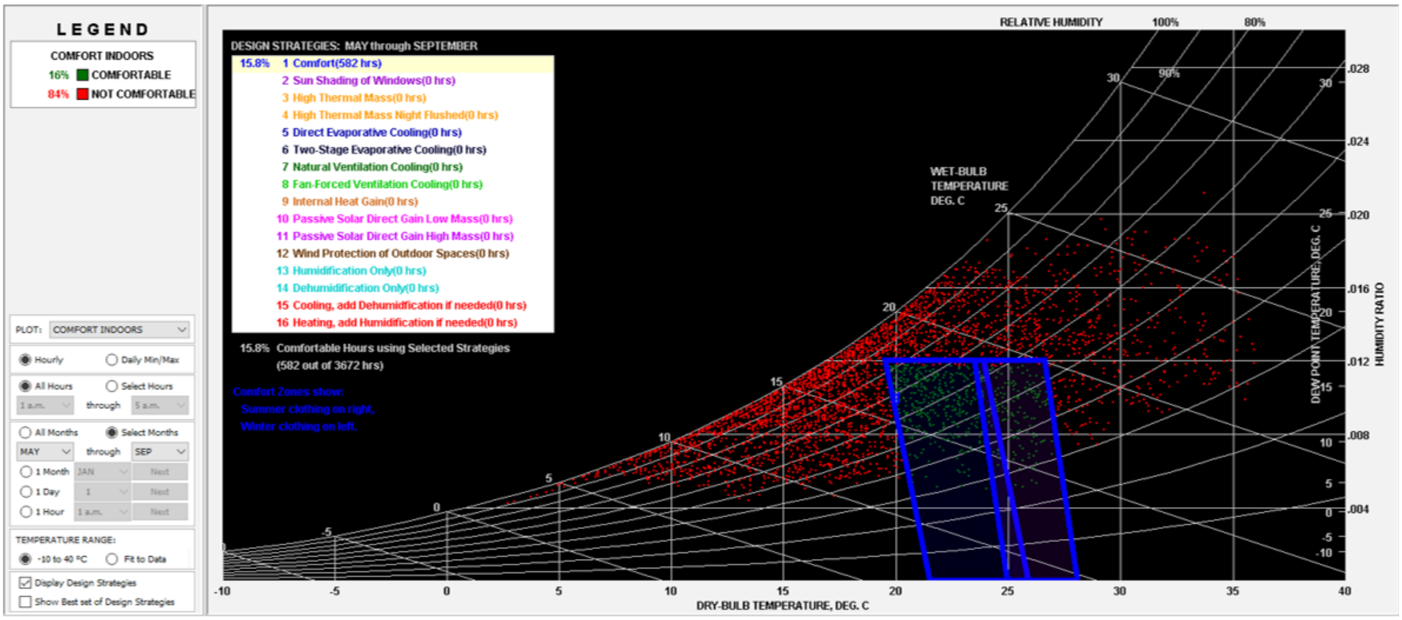
Psychrometric Charts : Baseline 2008



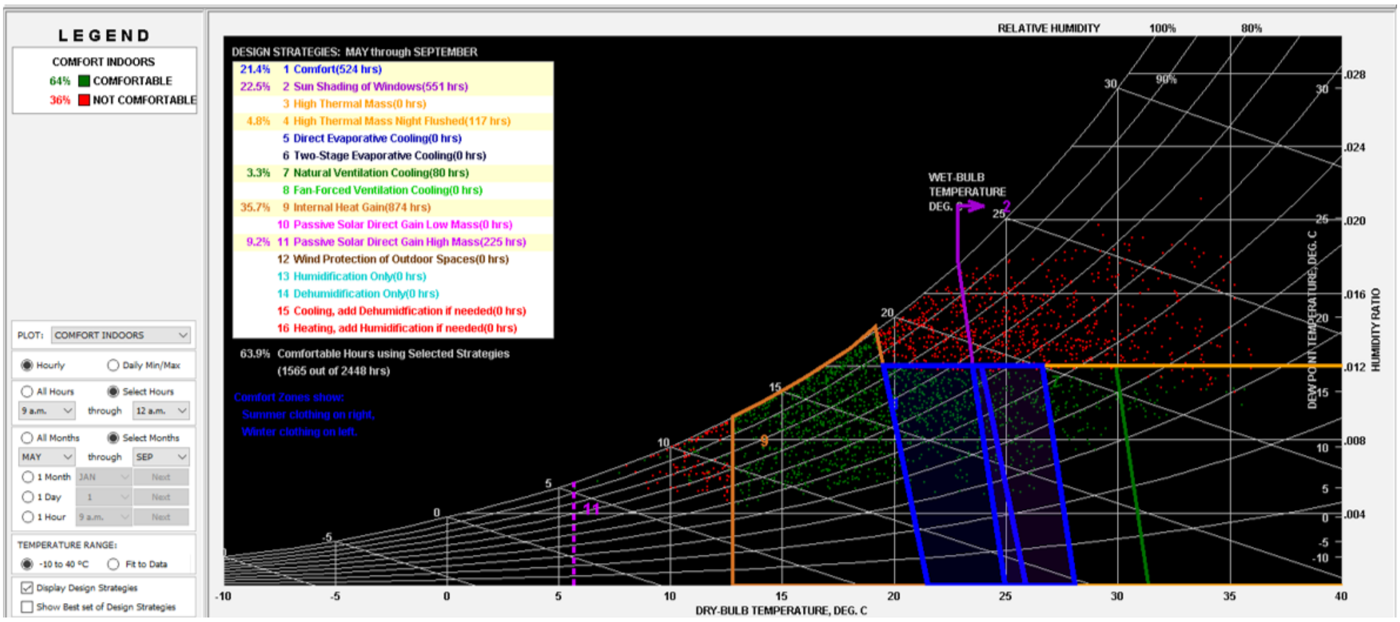
Passive design strategies for Baseline 2008



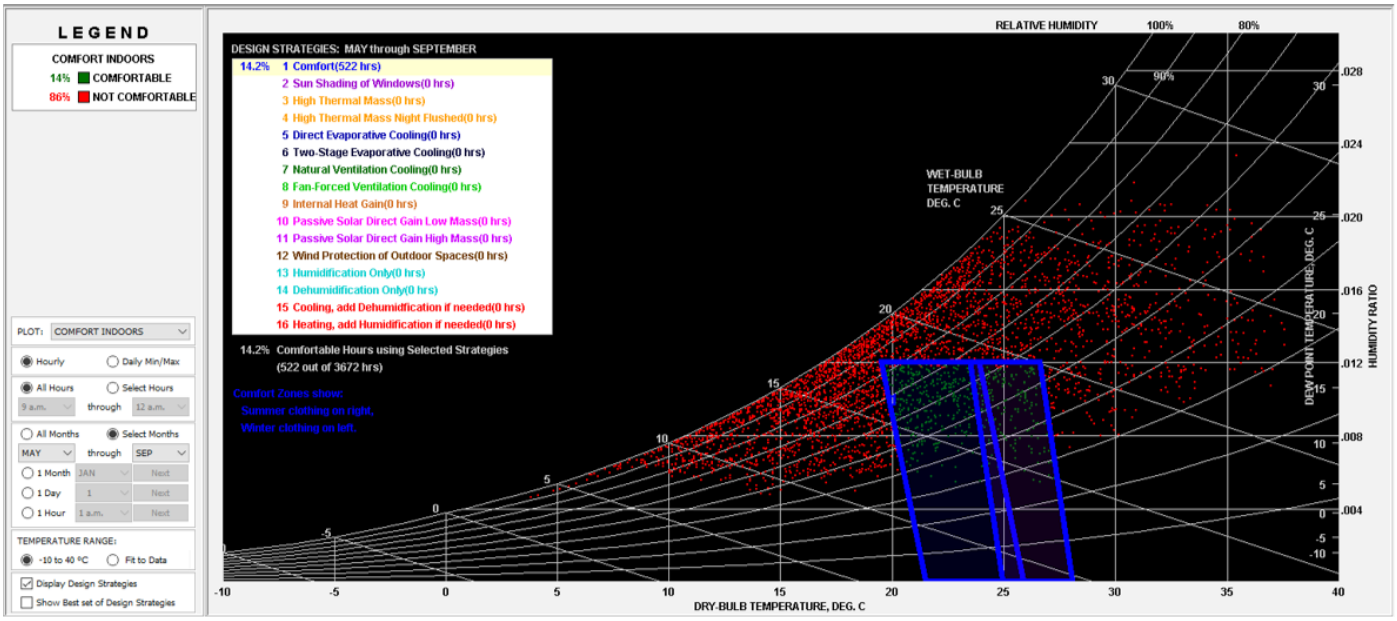
Psychrometric Charts : 2050



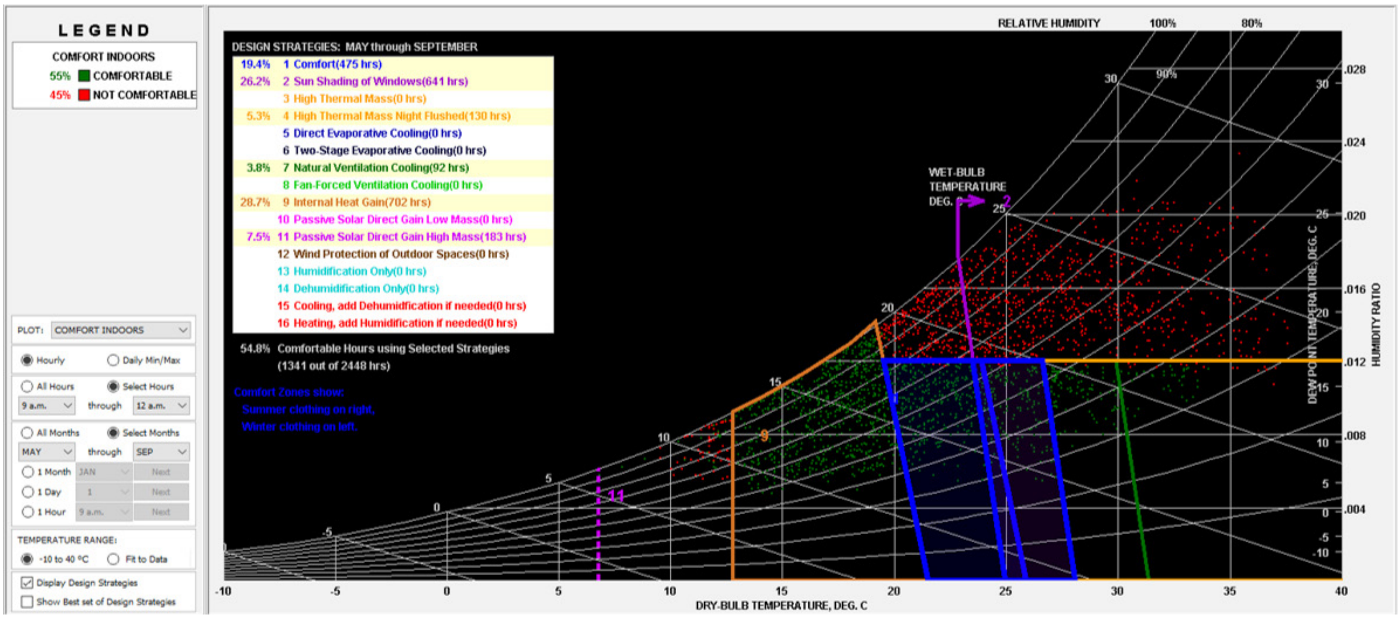
Passive design strategies for 2050



Psychrometric Charts : 2085



Passive design strategies for 2085



Appendix C

Validation of Simplified TOjuly Method (In Collaboration with Hamidreza Shahriari)

The TOjuly method developed for the study is a simplified method adapted from NTA 8800, NEN 7120 and NEN 5128. The TOjuly is already calculated by a "UNIEC 2" software developed by the Dutch government. Therefore, to validate the simplified method, TOjuly values for a simple apartment was calculated using the 'UNIEC 2" and the developed method. Fig C.1 illustrates the essential parameters used for a sample apartment and the TOjuly values calculated from the simplified method.

Zone area [m2]	40
Roof area [m2]	0
Zone parameter [m]	0
Di [specific effectic thermal capacity] [Kj/m2K]	350
Wall area [m2]	16.9
WWR [-]	0.3
U-value of glass [w/m2k]	1.5
g-value of glass [-]	0.6
U-value of roof	0
U-value of opaque [w/m2k]	0.22
U-value of floor [w/m2k]	0
R (shading factor)	1
Ihorizontal [W/m2]	191
Isol [W/m2]	112.5
gsol [Mj/m2]	301.32
qv [dm3/s]	48
qv;natural [dm3/s]	48
qv;mechanical [dm3/s]	0
HD [W/k]	13.132145
Hg [W/k]	0
Hu [W/k]	0
HA [W/k]	0
ηb;koinde;I [-]	0.595434434
Qtotal heat loss [Mj]	833.5754995
Qtotal heat gain [Mj]	1399.023738
ɣI [-]	1.678340761
Qbeh;koude;juli;I [Mj]	565.9968309
Ht;koude;I [W/k]	13.132145
Hv;Koude;I [W/k]	57.6
Tojuli	2.987595074

Only if these spaces are on the ground

Δu	0.17305
Surcharge formula	0.17305

West

Natural supply and natural distcharge

Qsolar gain [Mj]	756.207738
Qinternal [Mj]	642.816

If (ɣI)=1	ηb;koinde;I [-]	0.92537735
If (ɣI)≠1	ηb;koinde;I [-]	0.595434434

Cthermal capacity [Kj/k]	14000
Tkoude	197.9298097
akoude	12.40075704

Fig C.1: TO july calculation with simplified model for West orientation. In collaboration with Hamidreza Shahriari.

Similar properties were used to calculate TOjuly from UNEIC 2. To validate the simplified method, statistical validation methods like CV(RMSE), NMBE and R2 were employed. The simplified method can be considered validated upon achieving a lower NMBE, CV(RMSE)<0.15 and R2 value. Fig C.2 and Fig C.3 indicate the data sets used for statistical validation and the results from the evaluation . From fig C.3, it was concluded that the simplified model is accurate enough to represent the complex TOjuly calculations.

			Uniec2	Simplified method
Glass h++- 0.35 g-value- 1.21 U-value	30% WWR	South	1.75	1.6
		North	1.00	0.7
		West	1.64	1.45
		East	1.80	1.64
	50% WWR	South	2.70	2.88
		North	1.39	1.3
		West	2.50	2.66
		East	2.80	2.97
	65% WWR	South	3.40	3.8
		North	1.67	1.76
		West	3.13	3.5
		East	3.50	3.9
Glass h+- 0.6 g-value- 1.5 U-value	30% WWR	South	3.06	3.22
		North	1.60	1.52
		West	2.85	2.98
		East	3.15	3.31
	50% WWR	South	4.93	5.4
		North	2.43	2.7
		West	4.56	5.03
		East	5.07	5.5
	65% WWR	South	6.23	6.89
		North	3.03	3.5
		West	5.78	6.43
		East	6.41	7.07

Fig C.2: TOjuly values according to two calculation methods. In collaboration with Hamidreza Shahriari.

NMBE	CV(RMSE)	R^2
-0.069	0.11	0.99

Fig C.3: Results of statistical validation of the simplified models. In collaboration with Hamidreza Shahriari.

Appendix D
TOjuly Calculations

D.1 Heat Loss Coefficient due to Transmission [1068:2012]

$$H_{T;koud;i} = H_D + H_g + H_U + H_A \qquad (D.1)$$

Where :

$H_{T;koud;i}$	Heat Loss coefficient due to transmission of zone i	W/K
H_D	Direct heat loss coefficient between heated inner space and outside air with flat rate linear thermal bridge	W/K
H_g	Stationary heat loss coefficient through the floor	MJ
H_U	Heat Loss coefficient via adjacent unheated spaces.	W/K
H_A	Heat Loss coefficient via adjacent heated spaces.	W/K

D.1.1 Direct Heat Loss Coefficient

$$H_D = \Sigma(A_{T;i} \, x \, (U_{C;i} + \Delta U) \qquad (D.2)$$

Where :

H_D	Direct heat loss coefficient between heated inner space and outside air with flat rate linear thermal bridge	W/K
$A_{T;i}$	Area of the flat element of the zone i (opaque part of façade, transparent part, roof, etc)	m^2
$U_{C;i}$	U- value of the flat element of the zone i (opaque part of façade, transparent part, roof, etc)	W/ m^2K
ΔU	Flat rate surcharge for calculation of linear thermal bridges	W/ m^2K

$$\Delta U = \max\left[\, 0, 0.1 - 0.25\left(\frac{\Sigma_i(A_{T;i} \, x \, U_{C;i})}{\Sigma_i(A_{T;i})} - 0.4\,\right)\right] \qquad (D.3)$$

Where :

$A_{T;i}$	Area of the flat element of the zone i (opaque part of façade, transparent part, roof,etc) which is not a floor above a crawl space, directly on a surface or a plane	m^2
$U_{C;i}$	U-Value of flat element of the zone i (opaque part of façade, transparent part, roof, etc) which is not a floor above a crawl space, directly on a surface or a plane	W/ m^2K

D.1.2 Stationary Heat Loss Coefficient due to ground

$$H_g = (A_{T;fl} \, x \, U_{C;fl}) + \; 1.2 \, x \, P) \qquad (D.4)$$

Where :

H_g	Stationary heat loss coefficient through the floor	W/K
$A_{T;fl}$	Area of the floor	m^2
$U_{C;fl}$	U- value of the floor	W/ m^2K
P	Perimeter of the Zone	m

D.1.3 Heat Loss Coefficient via adjacent heated and unheated spaces

The heat loss coefficient of adjacent heated and unheated spaces in a flat rate calculation is taken as zero.

$$H_U = 0, H_A = 0 \qquad (D.5)$$

D.2 Heat Loss Coefficient due to Ventilation [7120:2012, Simplified]

$$H_{V;koud;i} = 1.2 \, x \, q_{v;i} \qquad (D.6)$$

Where :

$H_{V;koud;i}$	Heat Loss coefficient due to ventilation of zone i	W/K
$q_{V;i}$	Air volume flow for cooling	dm^3/s

D.2.1 Air volume flow for cooling

$$q_{v;i} = q_f \;\; x \, A_g \qquad (D.7)$$

Where :

q_f	Minimum Air flow rate or Design Air flow rate (combination of natural, mechanical and infiltration) per m2	dm^3/s per m^2
A_g	Area of the zone	m^2

D.3 Heat Loss due to transmission and ventilation [5128:2003]

$$Q_H = [H_{T;koud;i} + H_{V;koud;i}] \times [\theta_{i;koud} - (\theta_e + \theta_{corr})] \times t \qquad (D.8)$$

Where :

Q_H	Total Heat loss due to Transmission and Ventilation	MJ
$H_{T;koud;i}$	Heat Loss coefficient due to transmission of zone i from C.1	W/K
$H_{V;koud;i}$	Heat Loss coefficient due to ventilation of zone i from eq C.6	W/K
$\theta_{i;koud}$	The indoor temperature averaged for a period. A value of 24 ˚C must be taken according to 5128:2003	˚C
θ_e	Average outside temperature over the period. A value of 17.5 ˚C must be taken for the month of July according to NTA8800	˚C
θ_{corr}	Correction factor for the outside temperature. A value of 2 ˚C must be taken according to 5128:2003	˚C
t	Length of the month of July. A value of 2.678 MS must be taken according to 5128:2003 and 7120:2012.	MS

D.4 Heat Gain due to Solar Radiation [5128:2003]

$$Q_{sun;i} = Q_{Trans;i} + Q_{nontrans;i} + Q_{Roof;i} \qquad (D.9)$$

Where :

$Q_{sun;i}$	Heat Gain due to striking solar radiation for zone i.	MJ
$Q_{Trans;i}$	Heat gain from the transparent part of the façade for zone i.	MJ
$Q_{nontrans;i}$	Heat Gain from the opaque part of the façade for zone i.	MJ
$Q_{Roof;i}$	Heat Gain from the roof of zone i.	MJ

D.4.1 Heat gain from the transparent part of façade.

$$Q_{Trans;i} = [f_{sh} \times ZTA \times A_r] \times 0.75 \times C_{corr} \times g_{sol} \qquad (D.10)$$

Where :

$Q_{Trans;i}$	Heat gain from the transparent part of the façade for zone i.	MJ
f_{sh}	Shading reduction factor	-
ZTA	g-value of the glass at façade for daylight opening	-
A_r	Area of the opening including frame	m^2
C_{corr}	Correction factor for solar radiation for the calculation of cooling requirement. To be taken as 1 according to 5128:2003	-
g_{sol}	Total incident solar radiation on the opening in an orientation.	MJ/m^2

D.4.1.1 Shading factor calculation (Standard Assessment Procedure, SAP:2012)

$$f_{sh} = f_{blinds} \; x \, [\, f_{acc} + f_{overhang} - 1] \qquad (D.11)$$

Where :

f_{sh}	Solar Shading Factor	-
f_{blinds}	Shading reduction factor for blinds or curtains. Values should be taken from SAP:2012, table P3.1	-
f_{acc}	Solar Access factor. Values should be taken from SAP:2012, table 6d.	-
$f_{overhangs}$	Shading factor for overhang. Values should be taken from SAP:2012, table P4 and P5	-

D.4.2 Heat gain from the transparent part of façade.

$$Q_{nontrans;i} = Q_{roof;i} = [\alpha_{sol} \; x \, R_{se} \; x \, U_C \; x \, A_t \; x \, f_{sh,nt} \; x \, I_{sol} \; x \, 0.001 \; x \, t_m] \; x \, 3.6 \qquad (D.12)$$

Where :

$Q_{nontrans;i}$ $Q_{roof;i}$	Heat Gain from the opaque part of the façade or from the roof for zone i.	MJ
α_{sol}	Dimensionless absorption coefficient for solar radiation. Should be taken as 0.6 according to NTA 8800	-
R_{se}	Heat transfer resistance of the outside air	m^2K/W
U_C	U-value of the non-transparent part of façade or roof	W/m^2K
A_t	Area of the non-transparent part of the façade or roof	m^2
$f_{sh,nt}$	Shading reduction factor for the non-transparent external façade element or roof	-
I_{sol}	Incident solar radiation on the non-transparent of the façade for an orientation. For Roof the value can be taken as 191 according to NTA 8800	W/m^2
t_m	Length of the month of July. The value should be taken as 744 according to NTA 8800	h

D.5 Heat Gain due to Internal Loads [5128:2003]

$$Q_{int;i} = (Q_{occ;i} + Q_{equip;i} + Q_{light;i}) \; x \, A_{g;i} \; x \, t \qquad (D.13)$$

Where :

$Q_{int;i}$	Heat Gain due to internal loads for zone i.	MJ
$Q_{occ;i}$	Total Occupant Load in zone i per m^2	W/m^2
$Q_{equip;i}$	Total Equipment Load in zone i per m^2	W/m^2
$Q_{light;i}$	Total Lighting Load in zone i per m^2	W/m^2
$A_{g;i}$	Area of the zone i.	m^2
t	Length of the month of July	Ms.

D.6 Total Heat Gain due to sun and internal loads [5128:2003]

$$Q_{G;i} = Q_{sun;i} + Q_{int;i} \qquad (D.14)$$

Where :

$Q_{G;i}$	Total Heat gain due to sum and internal loads for zone i.	MJ
$Q_{sun;i}$	Total heat gain due to sun from the transparent, non-transparent part of the façade and roof for zone i.	MJ
$Q_{int;i}$	Total internal heat gain due to occupants, equipment's and lighting loads for zone i.	MJ

D.7 Total Cooling Required [5128:2003]

$$Q_{beh;koud;juli;i} = (1 - \eta_{b;koud;i}) \times Q_{G;i} \qquad (D.15)$$

Where :

$Q_{beh;koud;juli;i}$	Total cooling required for zone i in the month of July.	MJ
$\eta_{b;koud;i}$	Utilisation factor for the heat gain in zone i.	-
$Q_{G;i}$	Total Heat gain due to sum and internal loads for zone i. Calculated from C.15	MJ

D.7.1 Heat Gain utilisation factor [5128:2003]

If $\gamma_l = 1$; $\eta_{b;koud;i} = \frac{a_{koud}}{1 + a_{koud}}$ (D.16)

If $\gamma_l \neq 1$; $\eta_{b;koud;i} = \frac{1 - \gamma_l^{a_{koud}}}{1 - \gamma_l^{a_{koud}+1}}$ (D.17)

Where :

$\eta_{b;koud;i}$	Utilisation factor for the heat gain in zone i.	-
	Ratio between total heat gain and total heat loss.	
γ_l	Total heat loss is calculated using eq C.8	-
	Total heat gain is calculated using eq C.14	
a_{koud}	Dimensionless numeric parameter.	-

D.7.1.1 Dimensionless numeric parameter [5128:2003]

$$a_{koud} = a_o + (\tau_{koude} \ x \ \tau_{o;koude}) \qquad (D.18)$$

Where :

a_{koud}	Dimensionless numeric parameter used in calculation of utilisation factor.	-
a_0	Dimensionless constant. According to 5128:2003 following values must be used: Residential: 1 Utility buildings: 0.8	-
τ_{koude}	Nominal time constant for calculation. According to 5128:2003 following values must be used: Residential: 0.0576 Utility Buildings: 0.252	Ms
$\tau_{0;koude}$	Time constant in a relevant heated zone.	Ks

D.7.1.2 Time constant in a relevant heating zone [5128:2003]

$$\tau_{koude} = \frac{C_i}{H_{T;koud;i} + H_{V;koud;i}} \qquad (D.19)$$

Where :

τ_{koude}	Time constant in a relevant heated zone.	Ks
$H_{T;koud;juli;i}$	Heat Loss coefficient due to transmission of zone i from C.1	W/K
$H_{V;koud;juli;i}$	Heat Loss coefficient due to ventilation of zone i from C.6	W/K
C_i	Thermal Capacity of the construction in the zone i.	KJ/K

D.7.1.3 Thermal Capacity of the construction [5128:2003]

$$C_i = D_i \ x \ A_{g;i} \qquad (D.20)$$

Where :

C_i	Thermal Capacity of the construction in the zone i.	KJ/K
D_i	Specific Effective Thermal Capacity of the construction of the zone i. The values can be taken from table 38 of 5128:2003	KJ/m^2.K
$A_{g;i}$	Area of the zone i.	m^2

Appendix E

Input Parameters for TOjuly calculations (simplified method)

Parameters	Units	G.F. Hall 1	G.F. Hall 2	I.F. Hall 4	F.F Hall 5	S. F. Hall 8	S.F. Hall 9	S.F. Hall 10
Dimensional Properties								
Zone Area	m^2	196.6	225.53	134	169	194	125.8	182
Zone Perimeter	m	56.6	64.2	0	0	0	0	0
Wall Area	m^2	0	0	70	60	130.5	46	65
Roof Area	m^2	196.6	225.53	0	0	64	125.8	182
WWR	-	0	0	0.5	0.7	0.5	0.7	0.7
Construction Properties								
Specific Effective Thermal Capacity	KJ/m^2K	450	450	450	450	450	450	450
Thermal Properties								
U-Value of Glass	W/m^2K	0	0	1.0	1.0	1.0	1.0	1.0
g-value of Glass	-	0	0	0.4	0.4	0.4	0.4	0.4
U-Value of Opaque Part	W/m^2K	0	0	0.13	0.13	0.13	0.13	0.13
U-Value of Roof	W/m^2K	0.13	0.13	0	0	0.13	0.13	0.13
U-Value of Floor	W/m^2K	0.2	0.2	0	0	0	0	0
Solar Shading Factor								
R(Shading Factor)	-	0	0	0.8	0.8	0.39	0.8	0.8
I_{sol} Roof	W/m^2	191	191	0	0	191	191	191
I_{sol} Facade	W/m^2	0	0	81.2	81.2	88.5	81.2	81.2
Internal Properties								
q_v	dm^3/s	1555.5	4500	750	1000	1000	750	1000
Internal Load	W/m^2	58	58	58	58	58	58	58
TOjuly	-	0.8	0.0	3.5	3.1	3.8	3.1	3.8

Table E.1: Input parameters for TOjuly calculations for Pulse Building.

Parameters	Units	Staffroom	Class 31	Class 32
Dimensional Properties				
Zone Area	m^2	73	53.2	67.3
Zone Perimeter	m	0	0	0
Wall Area	m^2	73	28.5	22.11
Roof Area	m^2	73	53.2	67.3
WWR	-	0.3	0.5	0.5
Construction Properties				
Specific Effective Thermal Capacity	KJ/m^2K	450	450	450
Thermal Properties				
U-Value of Glass	W/m^2K	1.1	1.1	1.1
g-value of Glass	-	0.35	0.35	0.35
U-Value of Opaque Part	W/m^2K	0.2	0.2	0.2
U-Value of Roof	W/m^2K	0.17	0.17	0.17
U-Value of Floor	W/m^2K	0	0	0
Solar Shading Factor				
R(Shading Factor)	-	0.75	0.75	0.75
I_{sol} Roof	W/m^2	191	191	191
I_{sol} Facade	W/m^2	113.4	109.7	109.7
Internal Properties				
q_v	dm^3/s	2000	450	500
Internal Load	W/m^2	55	50	50
TOjuly	-	0.4	1.3	1.2

Table E.2: Input parameters for TOjuly calculations for Melanchthon School.

Appendix F

Design Builder Model and thermal zones for the case study buildings

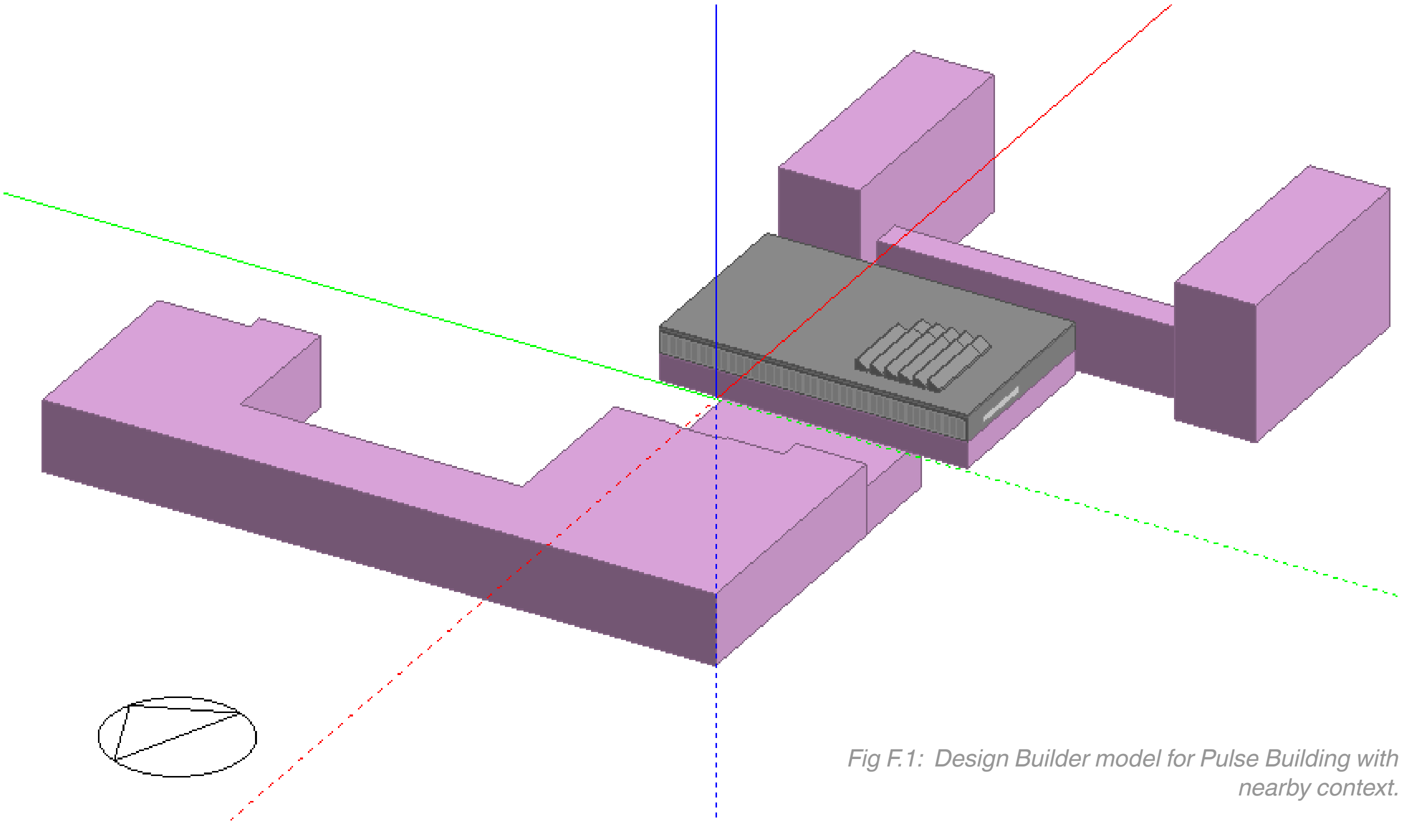


Fig F.1: Design Builder model for Pulse Building with nearby context.

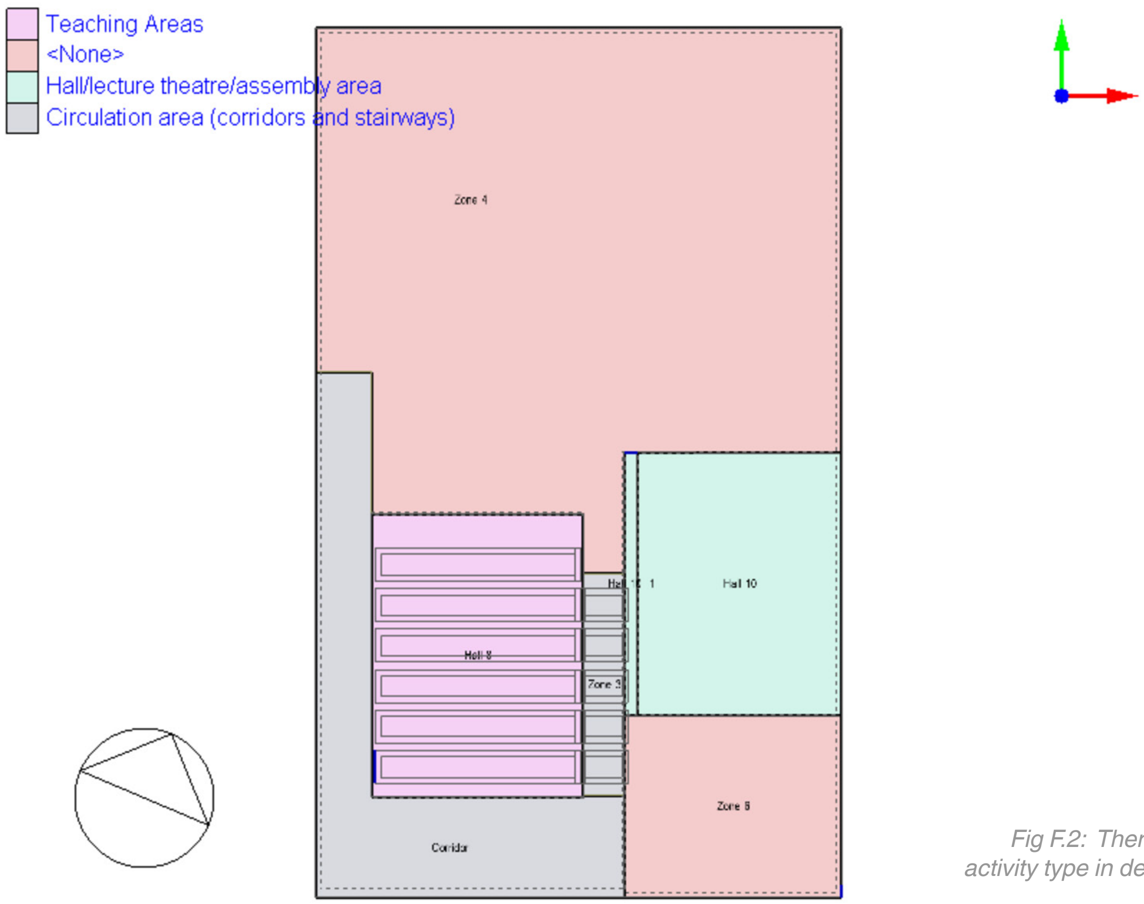


Fig F.2: Thermal zones with activity type in design builder for Pulse Building.

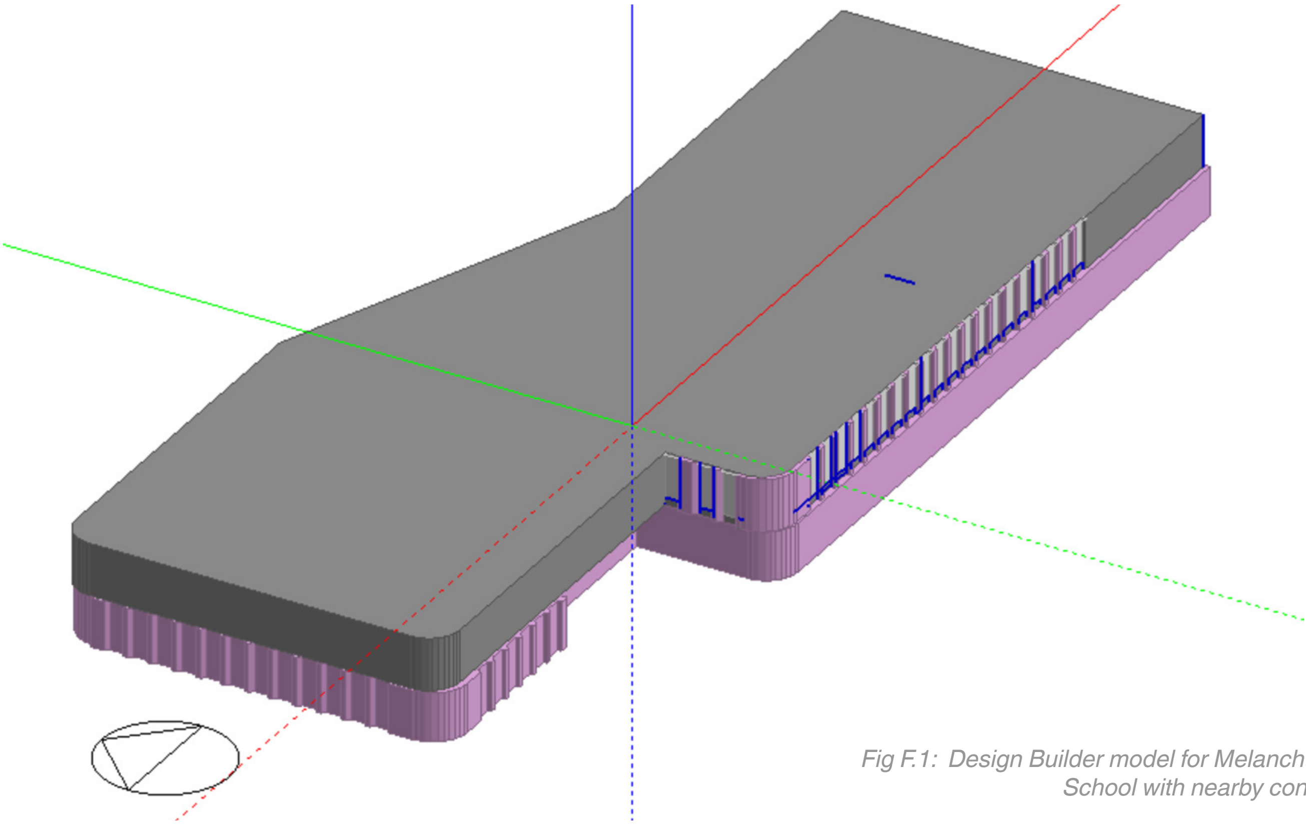


Fig F.1: Design Builder model for Melanchthon School with nearby context.

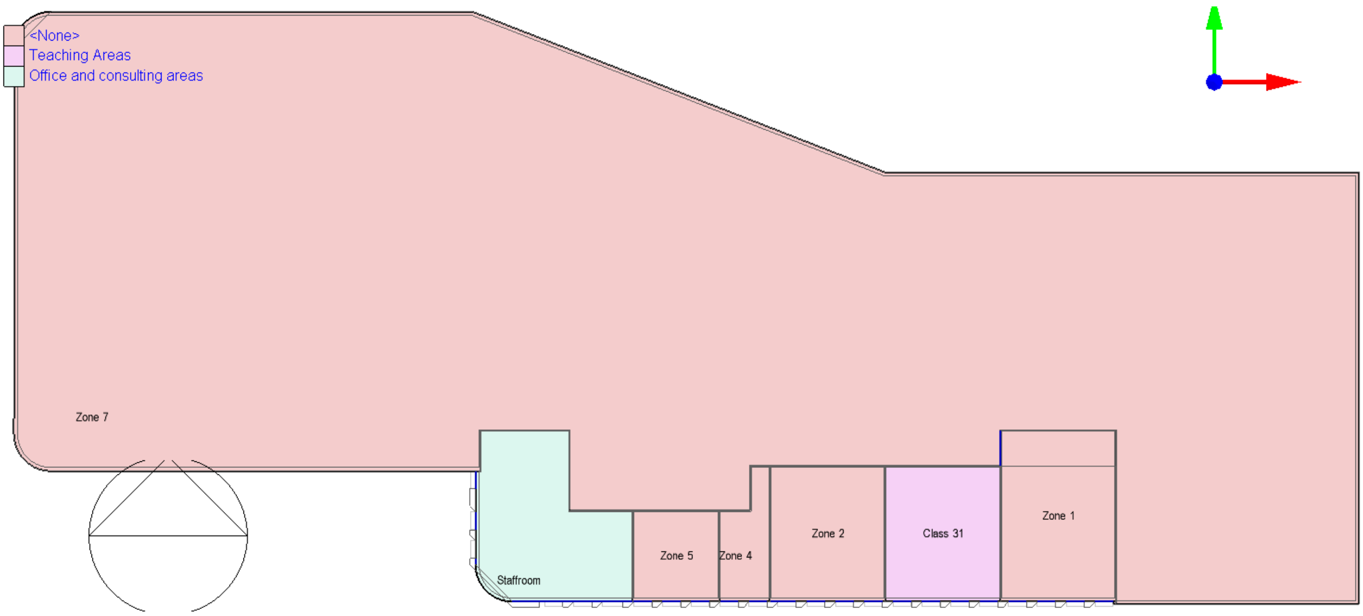


Fig F.2: Thermal zones with activity type in design builder for Melanchthon School .

Appendix G

Calibration of design builder model for Pulse Building.

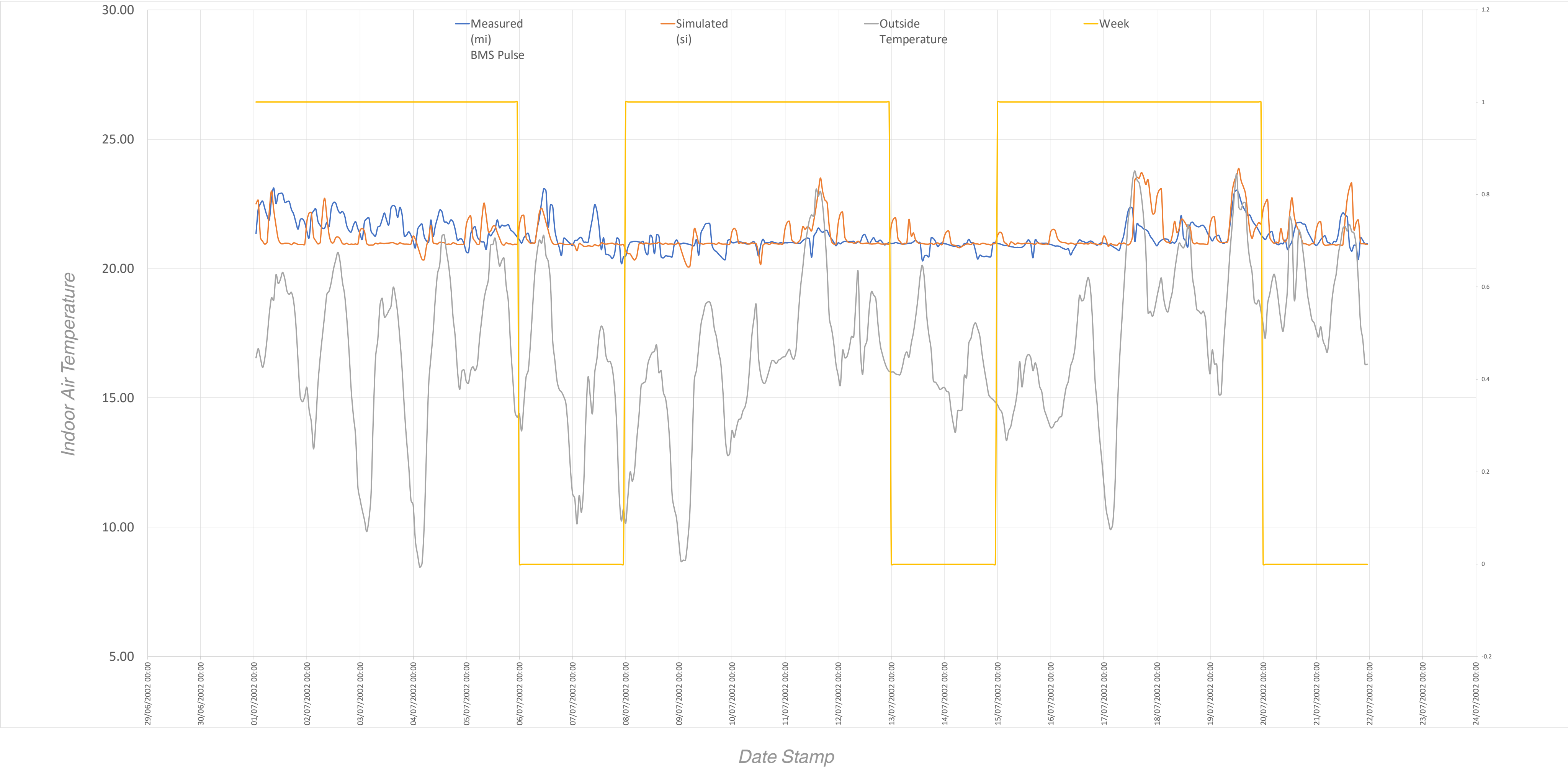


Fig G.1: Calibration for Hall 10 , Pulse Building.

Fig G.2: Calibration for Hall 8 , Pulse Building.

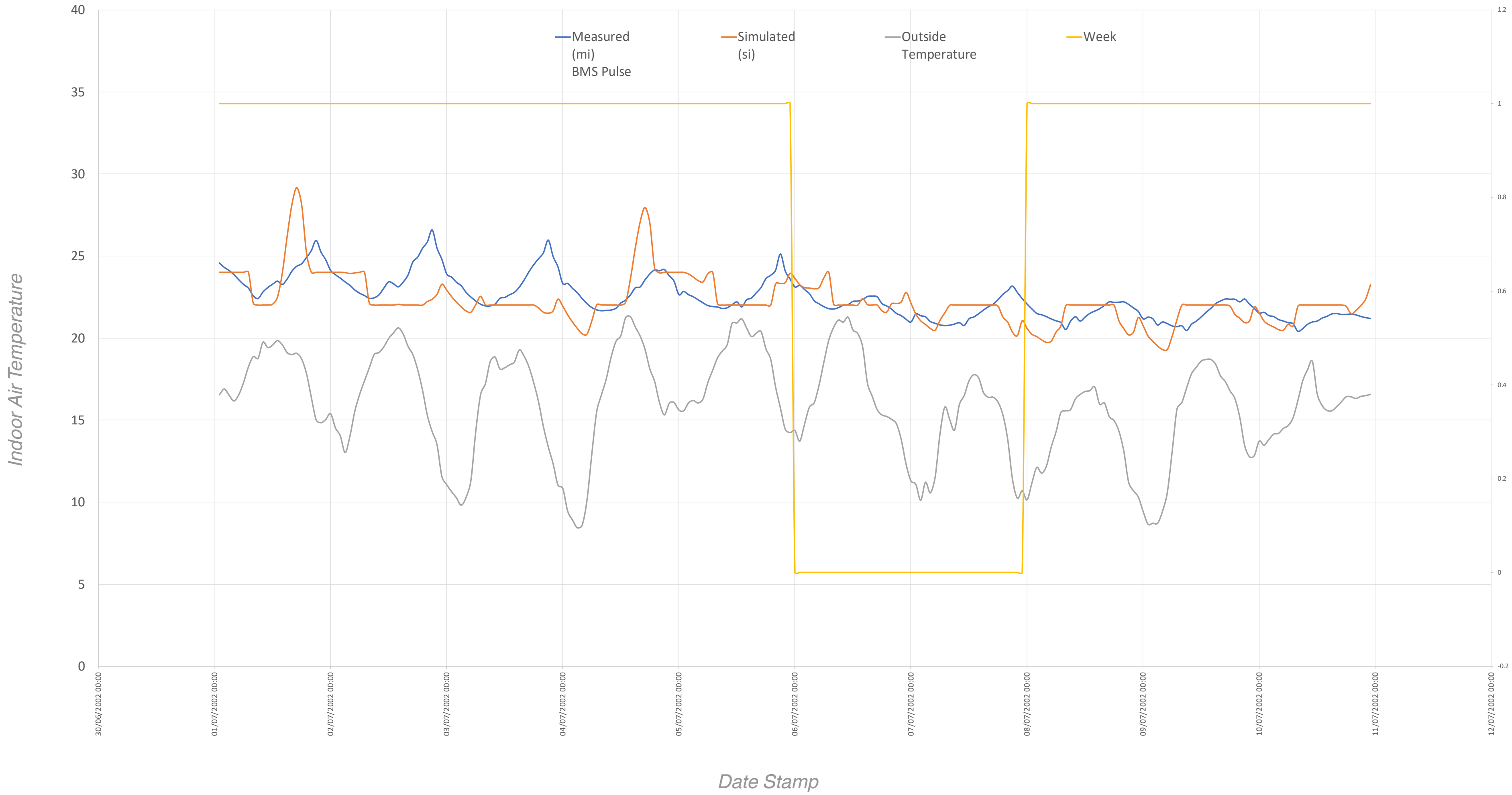
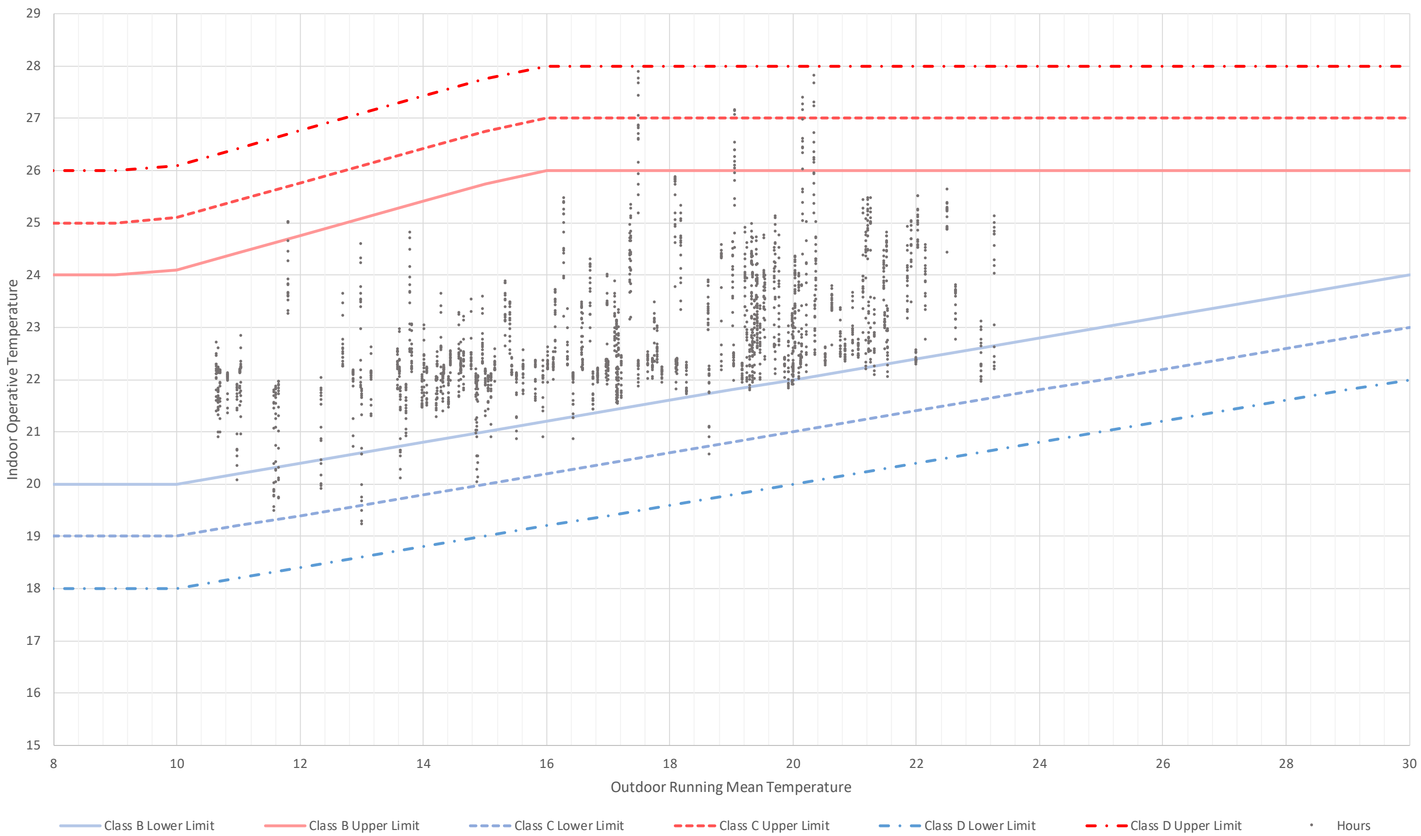


Fig G.3: Calibration for corridor , Pulse Building.

Appendix H

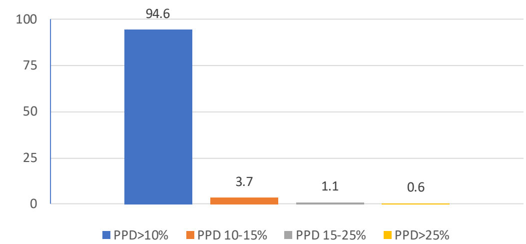
ATG Graphs

H.1 Pulse Hall 10 (TRY 2008, baseline)

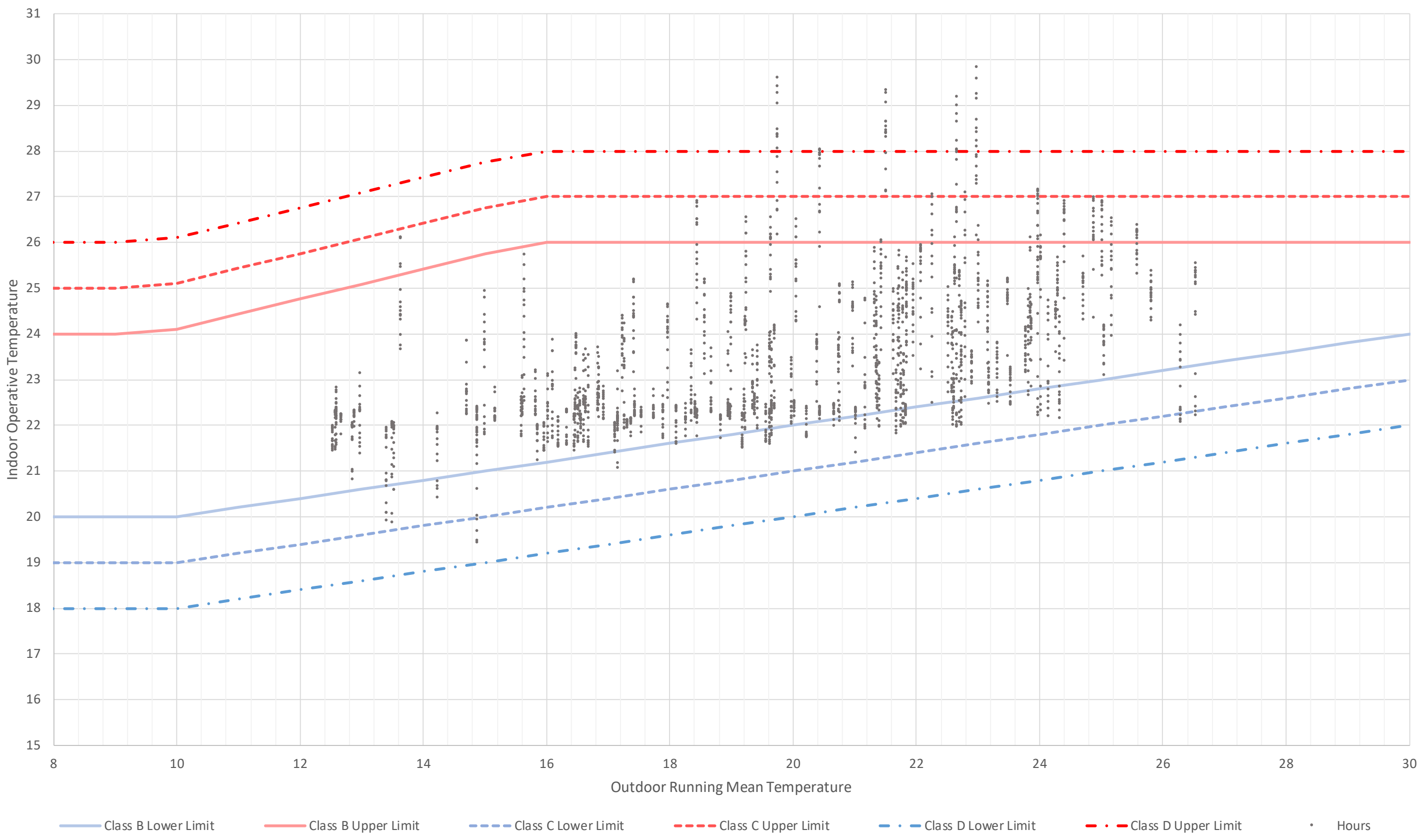


Building	**Pulse**
Room No.	Hall 10
Room Type	**Beta**
Temp. Type	Operative
Analysis Period	**May-September**
Occupied Hours	2448
Thermal Performance	**Good**
Class	Class B

Comfort Bandwidth	No. of Hours	% of Time
Class B	2316	94.6
Class C	90	3.7
Class D	90	3.7
Above Class D	15	0.6

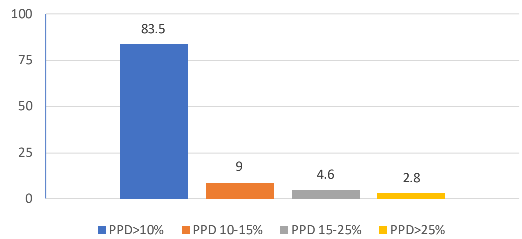


H.2 Pulse Hall 10 (TRY 2050)

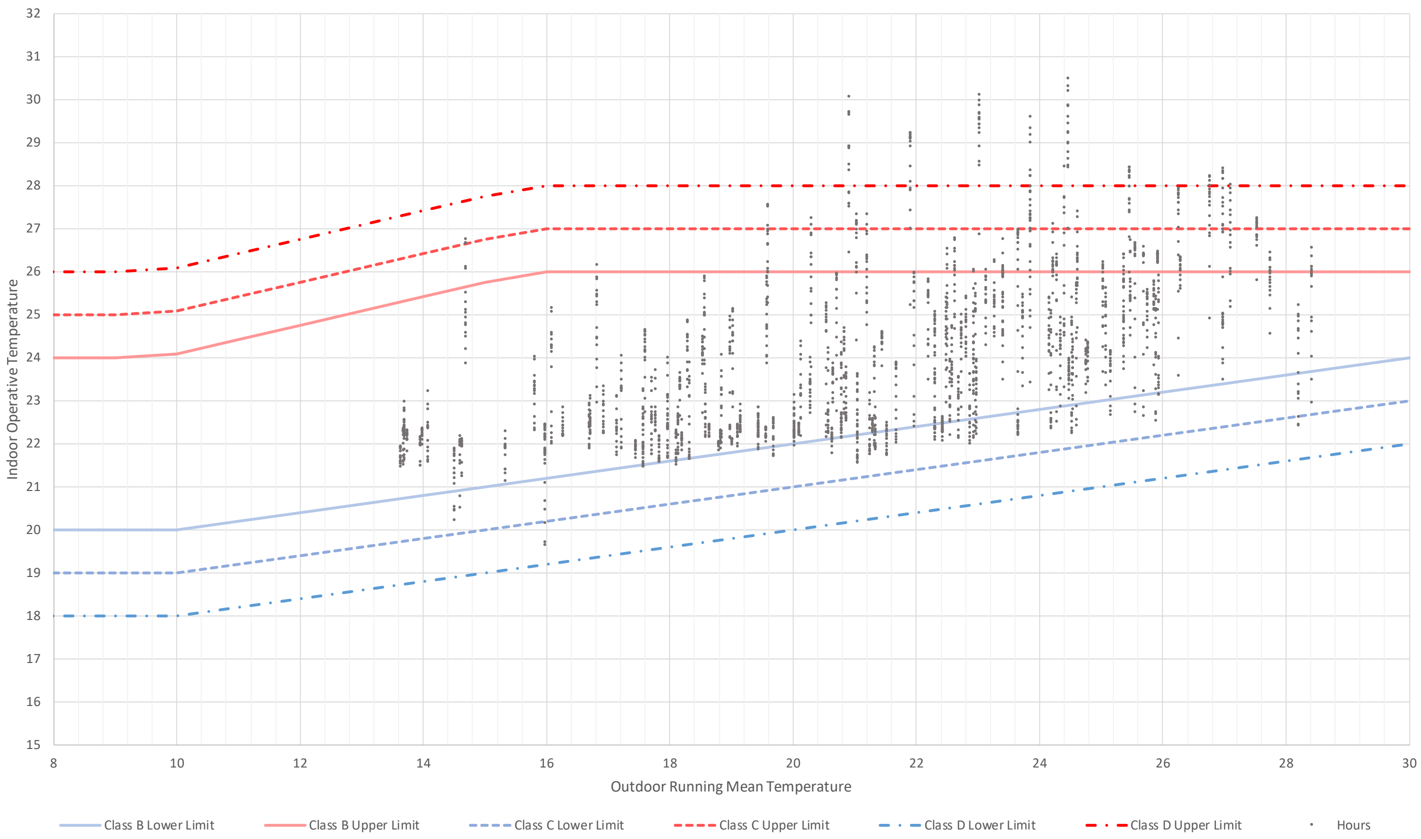


Building	**Pulse**
Room No.	Hall 10
Room Type	**Beta**
Temp. Type	Operative
Analysis Period	**May-September**
Occupied Hours	2448
Thermal Performance	**Bad**
Class	Class D

Comfort Bandwidth	No. of Hours	% of Time
Class B	2045	83.5
Class C	221	9
Class D	113	4.6
Above Class D	69	2.8

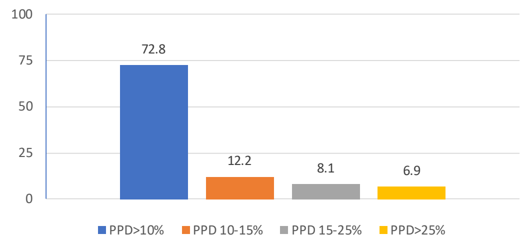


H.3 Pulse Hall 10 (TRY 2085)

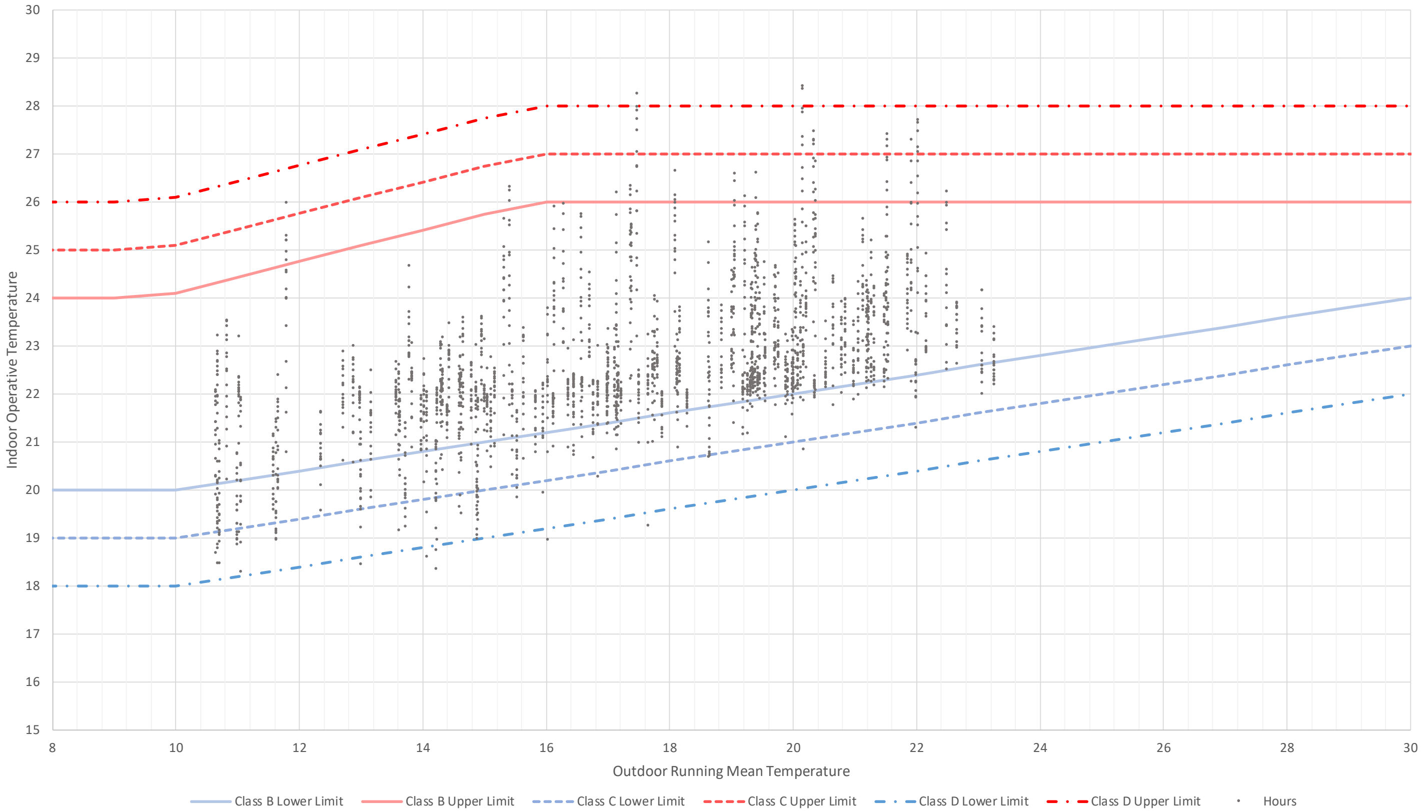


Building	**Pulse**
Room No.	Hall 10
Room Type	**Beta**
Temp. Type	Operative
Analysis Period	**May-September**
Occupied Hours	2448
Thermal Performance	**Bad**
Class	Class D

Comfort Bandwidth	No. of Hours	% of Time
Class B	1781	72.8
Class C	299	12.2
Class D	198	8.1
Above Class D	170	6.9

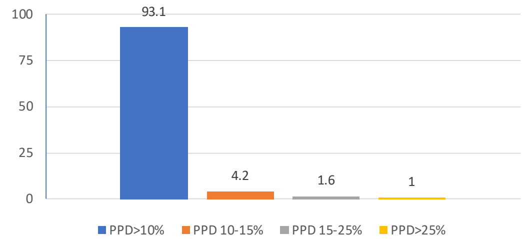


H.4 Pulse Hall 8 (TRY 2008, Baseline)

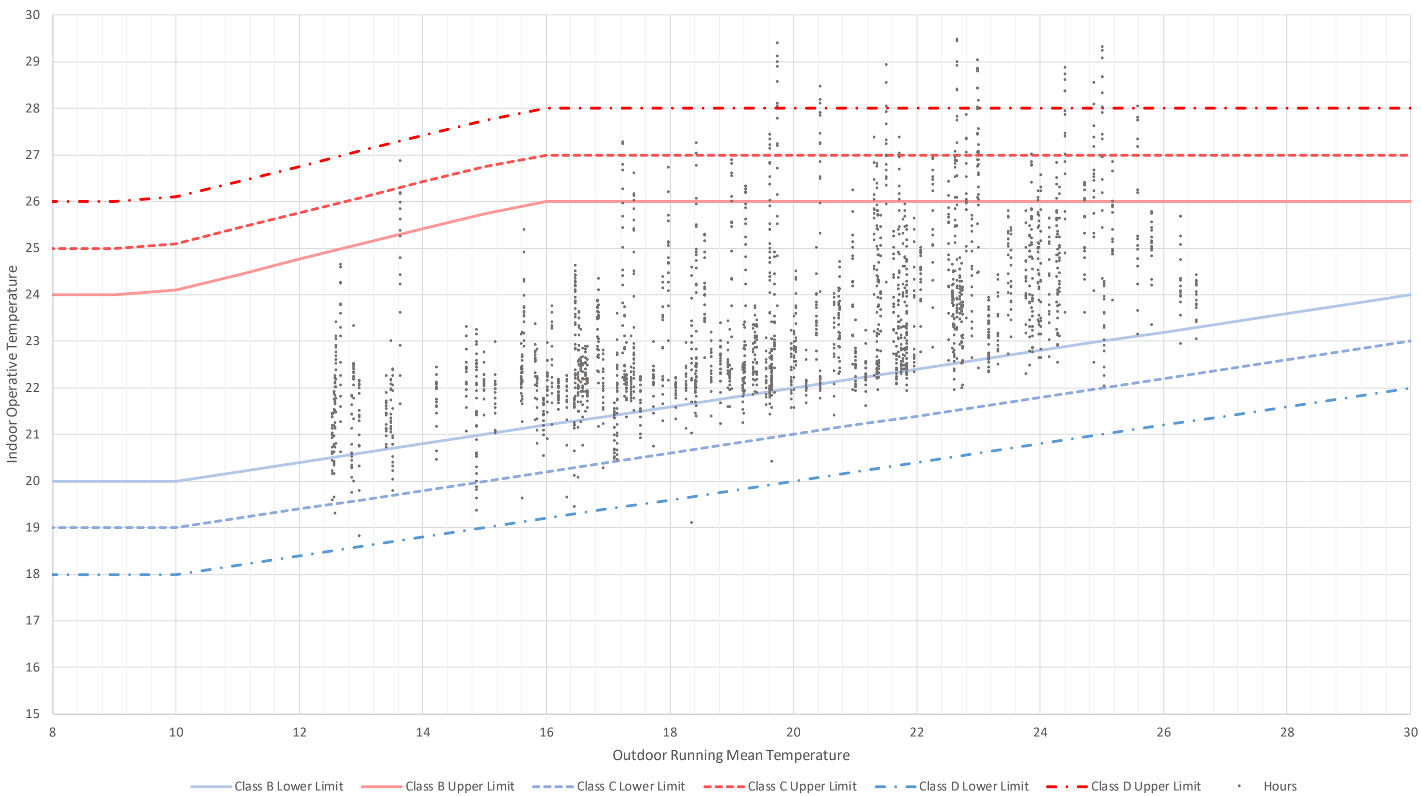


Building	**Pulse**
Room No.	Hall 8
Room Type	**Beta**
Temp. Type	Operative
Analysis Period	**May-September**
Occupied Hours	2448
Thermal Performance	**Good**
Class	Class B

Comfort Bandwidth	No. of Hours	% of Time
Class B	2280	93.1
Class C	104	4.2
Class D	39	1.6
Above Class D	25	1

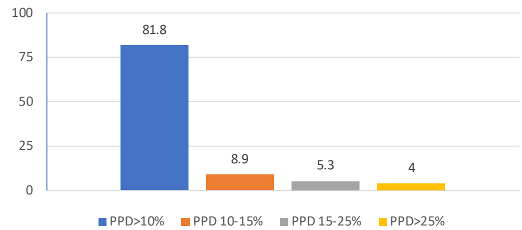


H.5 Pulse Hall 8 (TRY 2050)

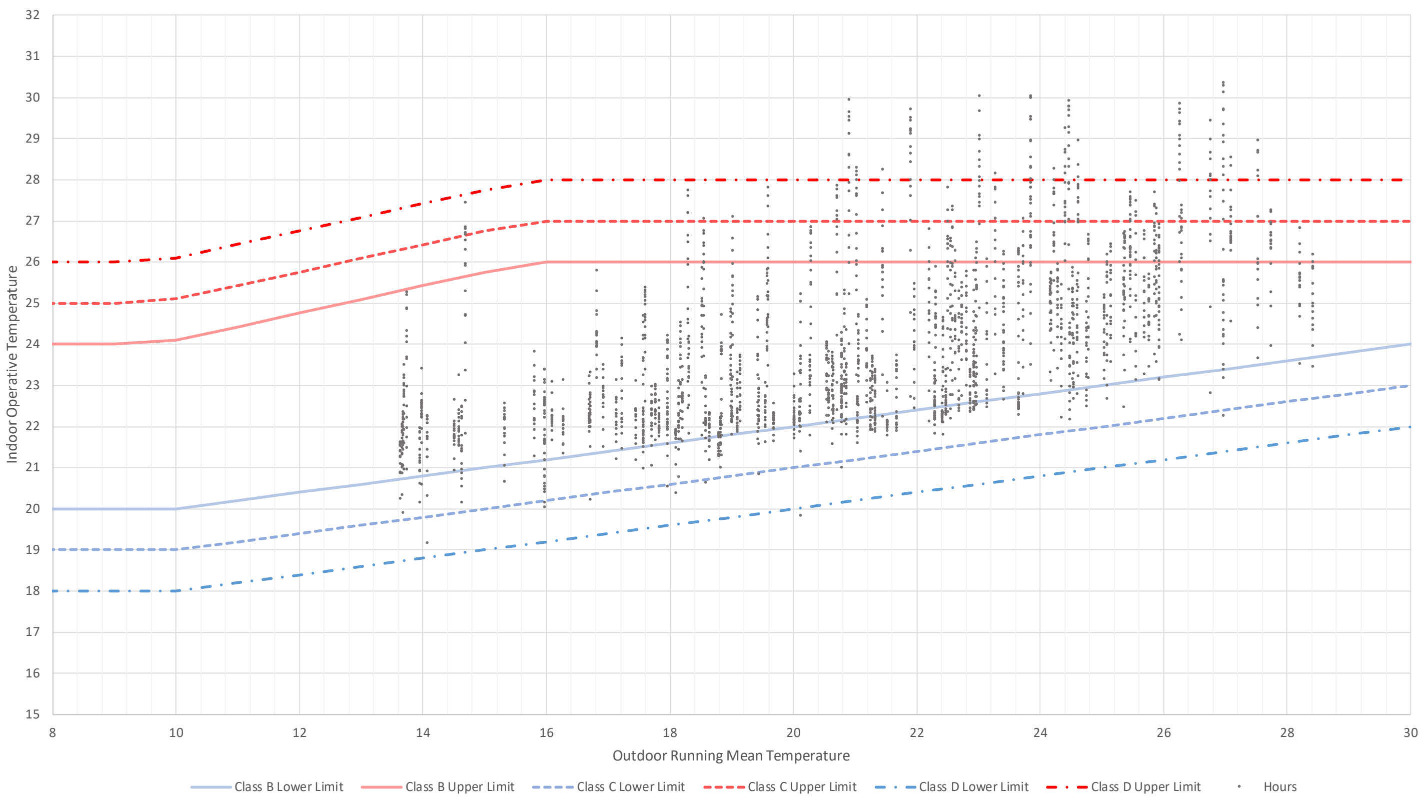


Building	**Pulse**
Room No.	Hall 8
Room Type	**Beta**
Temp. Type	Operative
Analysis Period	**May-September**
Occupied Hours	2448
Thermal Performance	**Bad**
Class	Class D

Comfort Bandwidth	No. of Hours	% of Time
Class B	2003	81.8
Class C	217	8.9
Class D	130	5.3
Above Class D	98	4

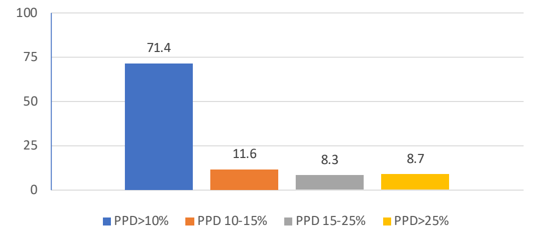


H.6 Pulse Hall 8 (TRY 2085)

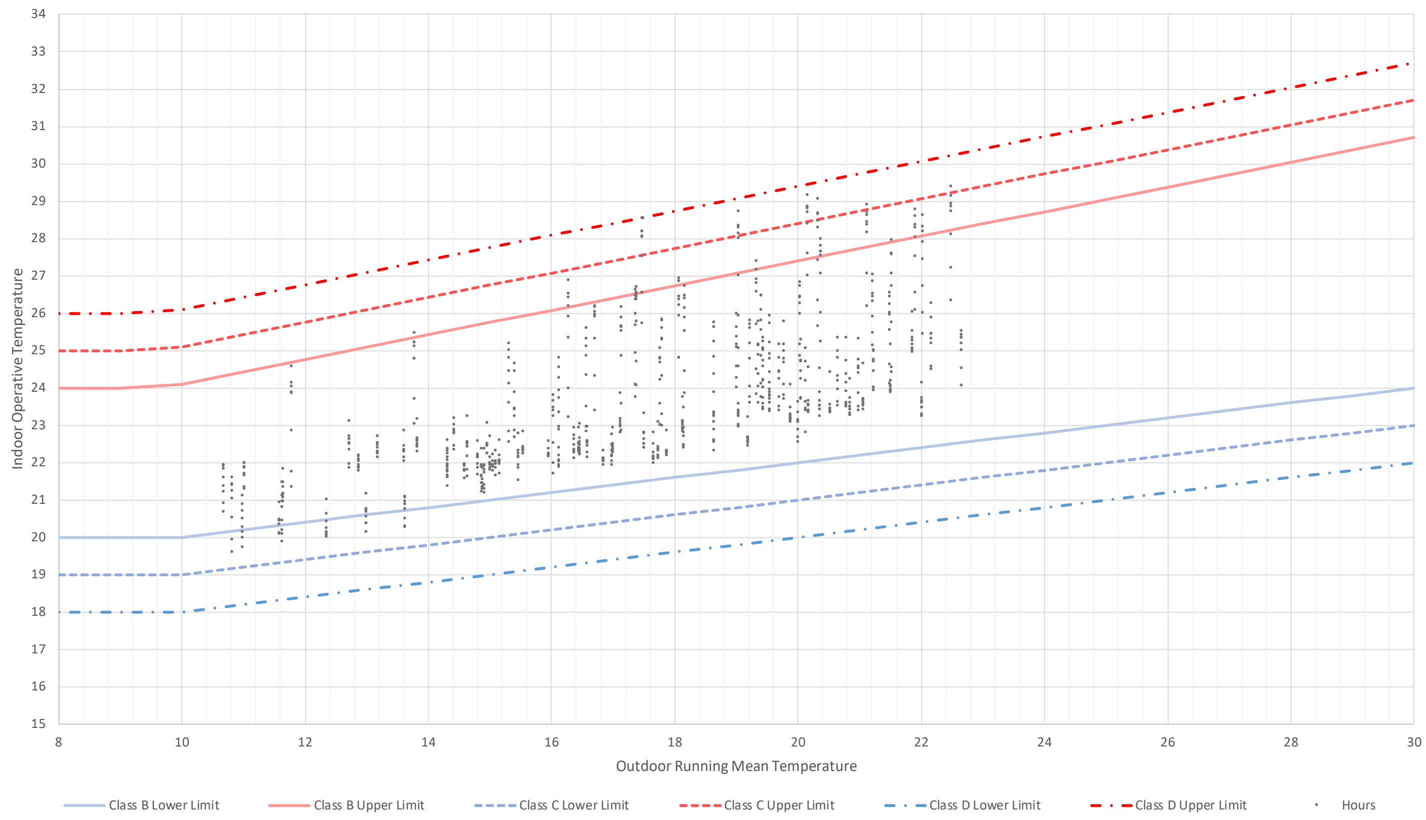


Building	**Pulse**
Room No.	Hall 8
Room Type	**Beta**
Temp. Type	Operative
Analysis Period	**May-September**
Occupied Hours	2448
Thermal Performance	**Bad**
Class	Class D

Comfort Bandwidth	No. of Hours	% of Time
Class B	1748	71.4
Class C	285	11.6
Class D	202	8.3
Above Class D	213	8.7

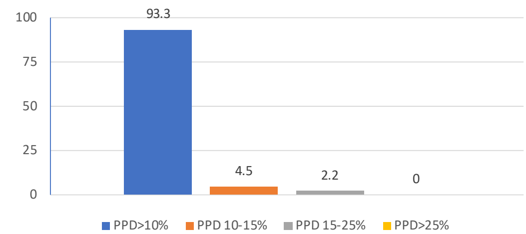


H.7 Melanchthon School Staffroom (TRY 2008, Baseline)

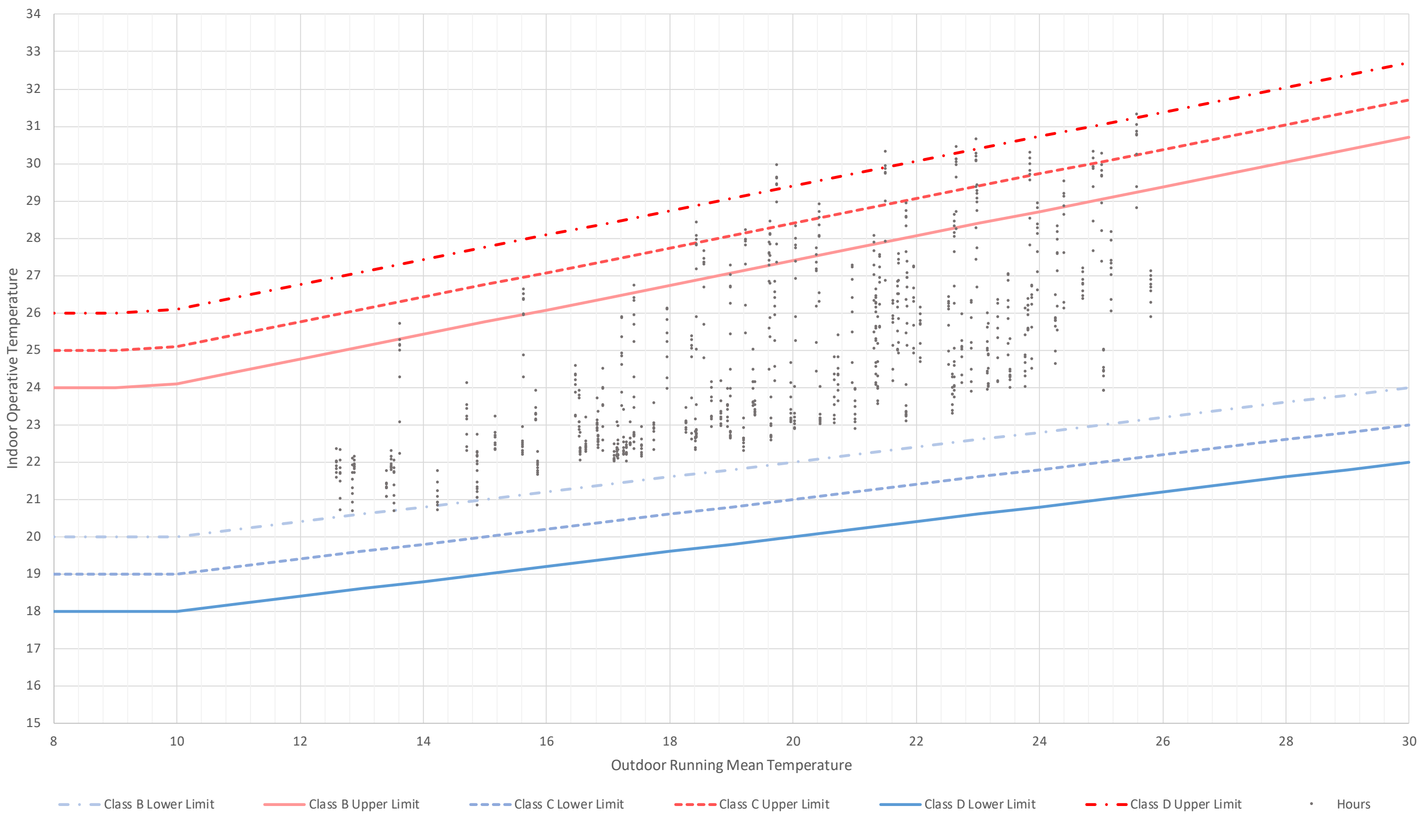


Building	**Melanchthon**
Room No.	Staffroom
Room Type	**Alpha**
Temp. Type	Operative
Analysis Period	**May-September**
Occupied Hours	872
Thermal Performance	**Good**
Class	Class B

Comfort Bandwidth	No. of Hours	% of Time
Class B	814	93.3
Class C	39	4.5
Class D	19	2.2
Above Class D	0	0

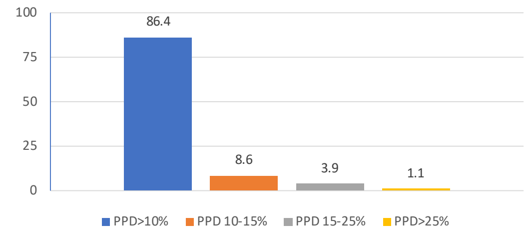


H.8 Melanchthon School Staffroom (TRY 2050)

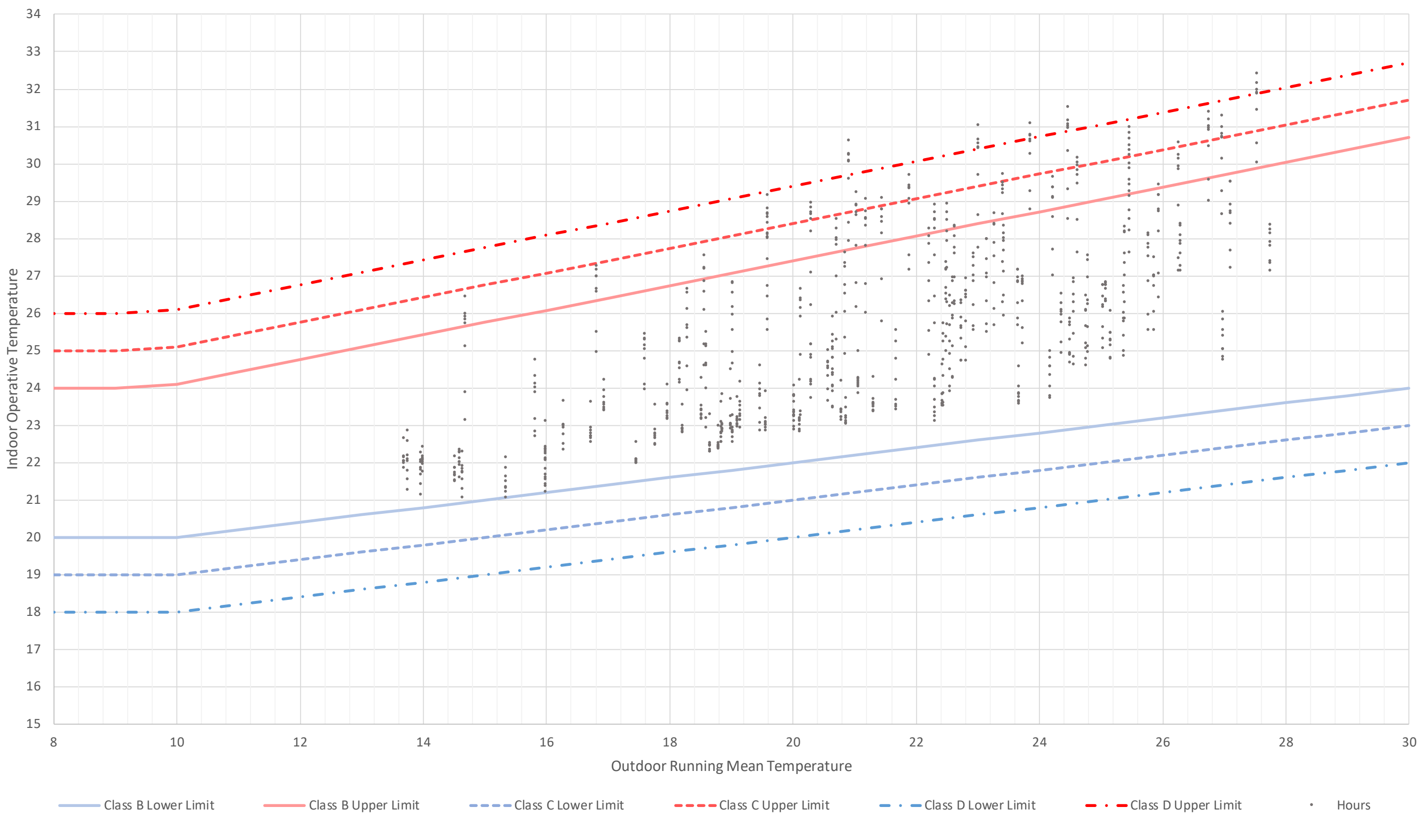


Building	**Melanchthon**
Room No.	Staffroom
Room Type	**Alpha**
Temp. Type	Operative
Analysis Period	**May-September**
Occupied Hours	872
Thermal Performance	**Acceptable**
Class	Class C

Comfort Bandwidth	No. of Hours	% of Time
Class B	753	86.4
Class C	75	8.6
Class D	34	3.9
Above Class D	10	1.1

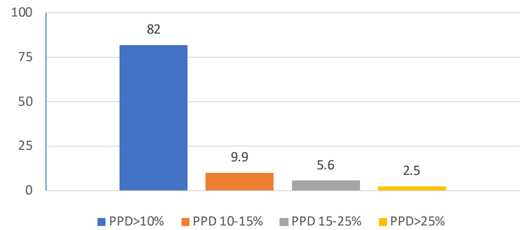


H.9 Melanchthon School Staffroom (TRY 2085)

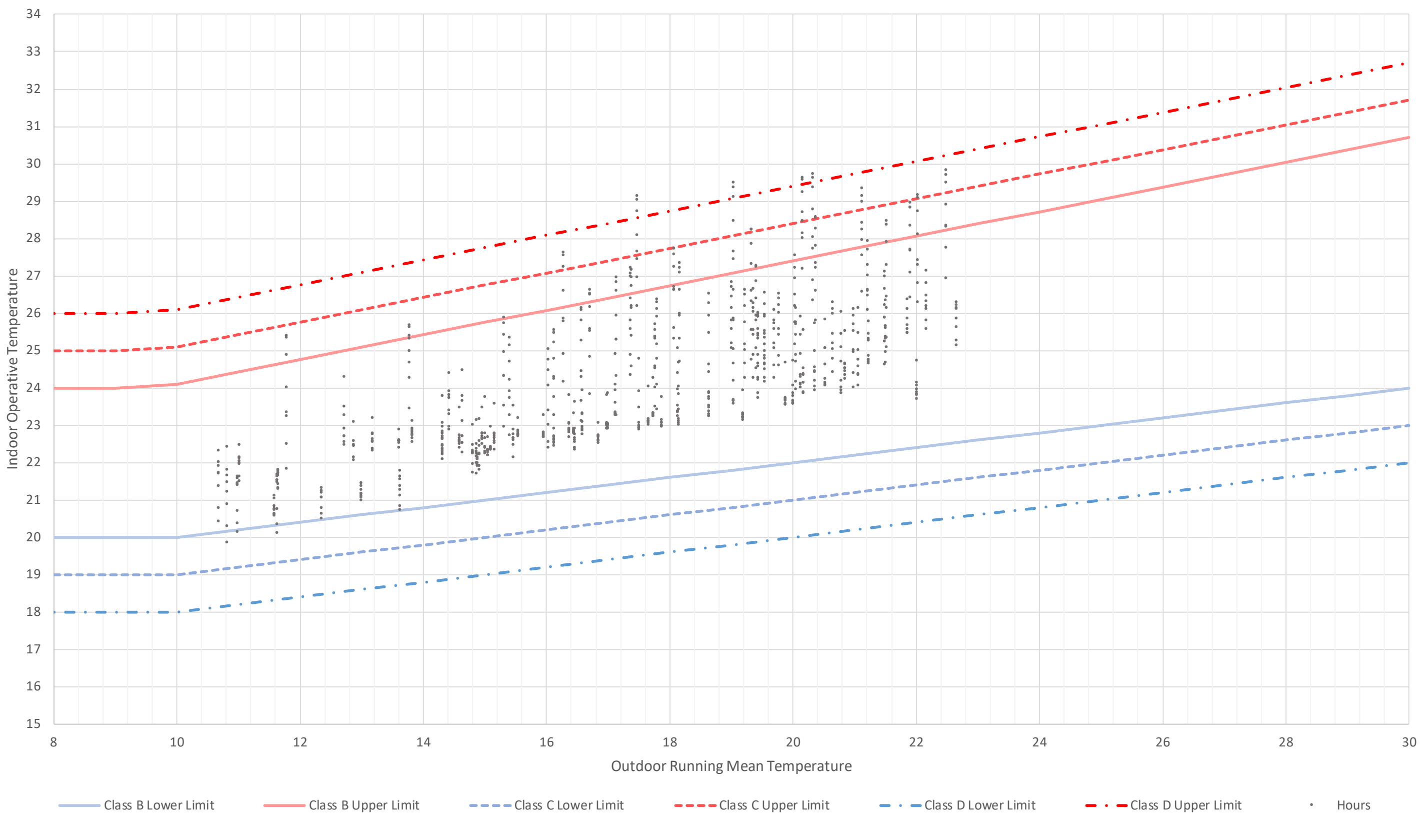


Building	**Melanchthon**
Room No.	Staffroom
Room Type	**Alpha**
Temp. Type	Operative
Analysis Period	**May-September**
Occupied Hours	872
Thermal Performance	**Bad**
Class	Class D

Comfort Bandwidth	No. of Hours	% of Time
Class B	715	82
Class C	86	9.9
Class D	49	5.6
Above Class D	22	2.5

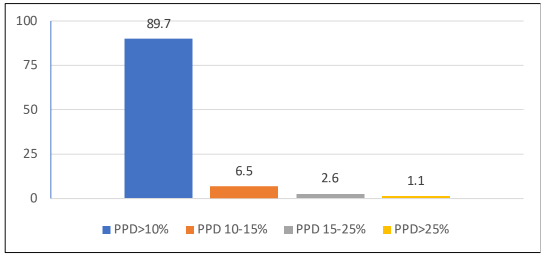


H.10 Melanchthon School Class 31 (TRY 2008, Baseline)

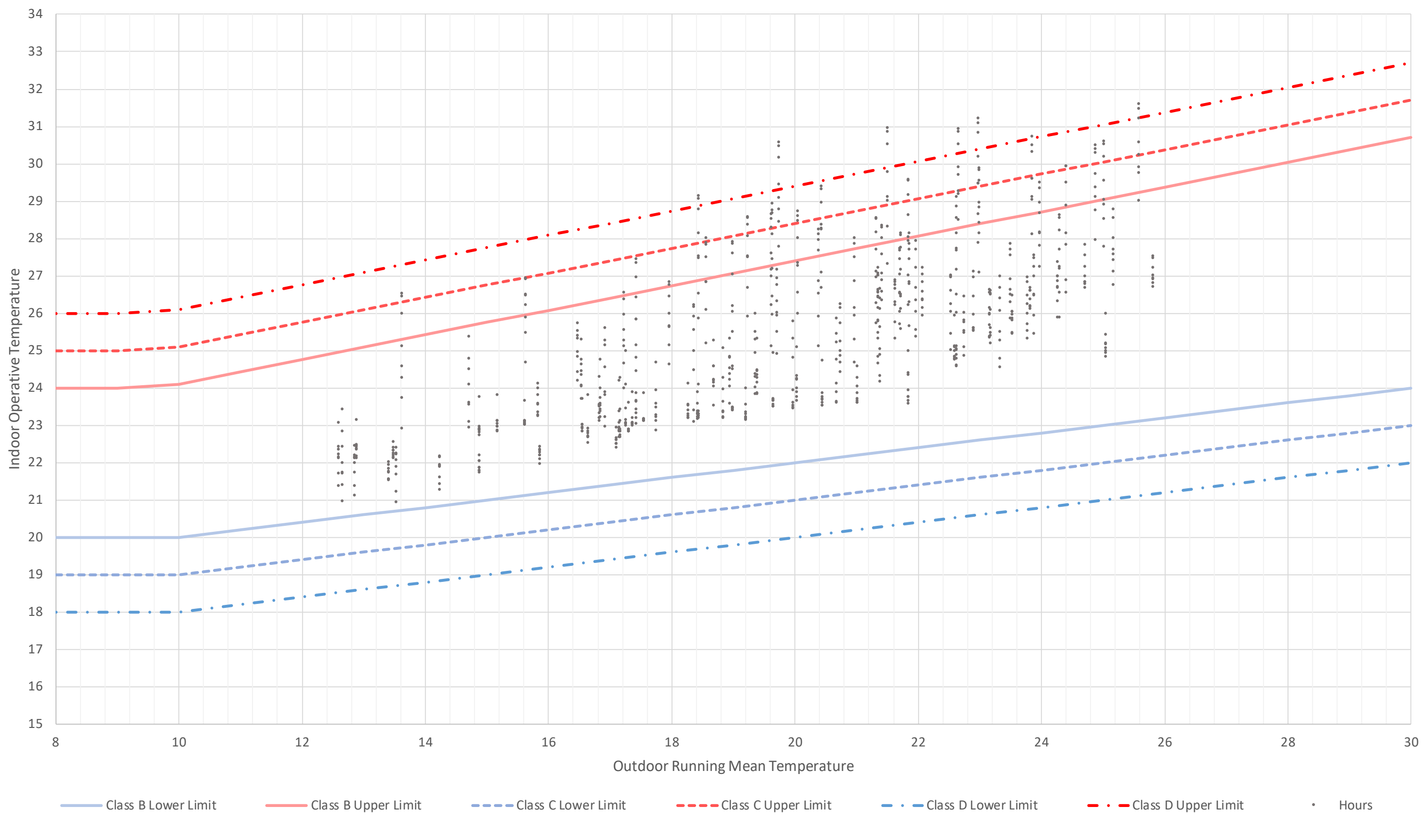


Building	**Melanchthon**
Room No.	Class 31
Room Type	**Alpha**
Temp. Type	Operative
Analysis Period	**May-September**
Occupied Hours	872
Thermal Performance	**Acceptable**
Class	Class C

Comfort Bandwidth	No. of Hours	% of Time
Class B	782	89.7
Class C	57	6.5
Class D	23	2.6
Above Class D	10	1.1

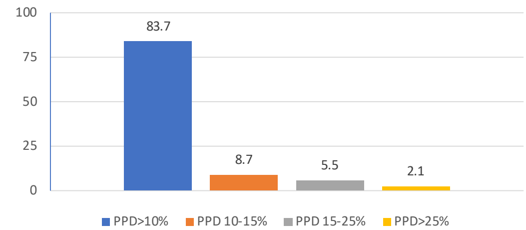


H.11 Melanchthon School Class 31 (TRY 2050)

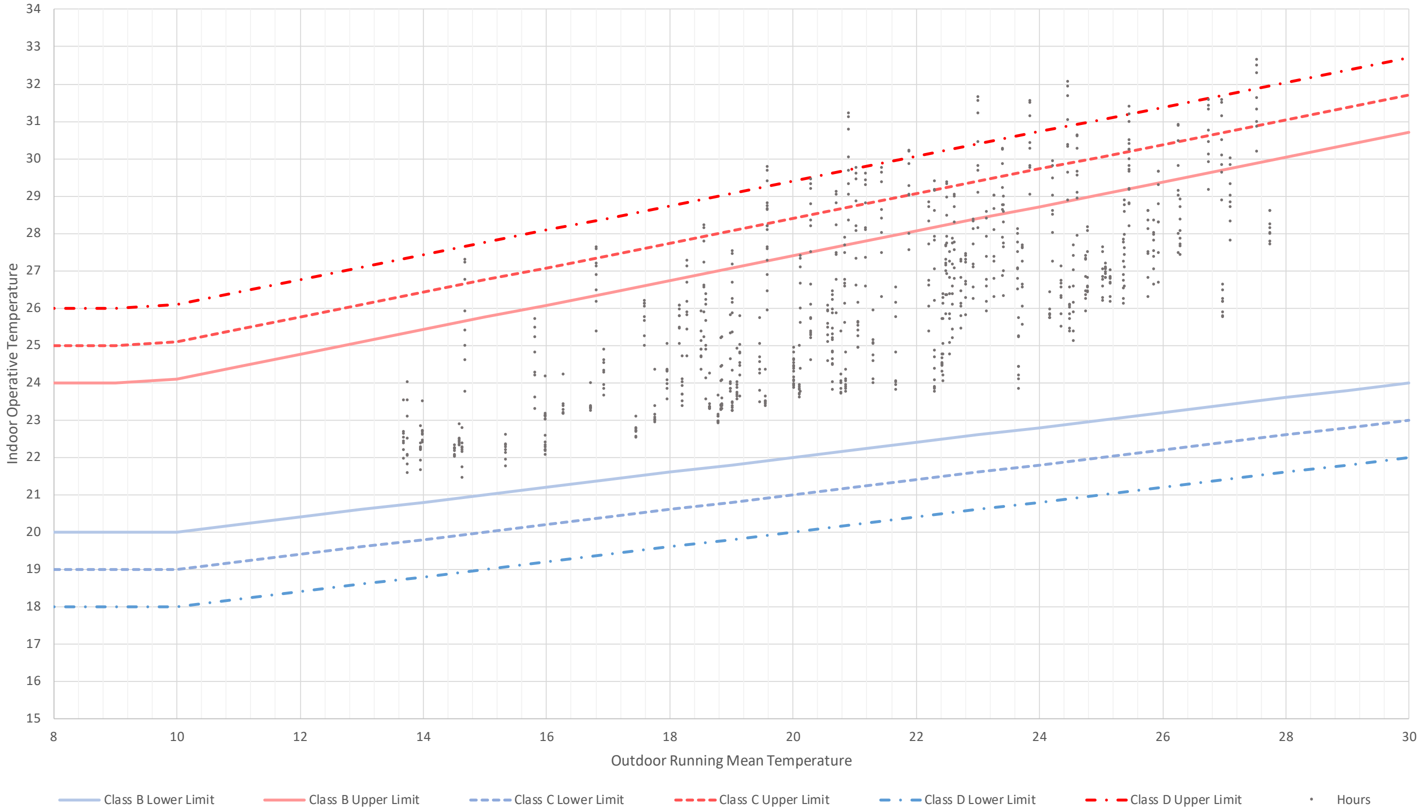


Building	**Melanchthon**
Room No.	Class 31
Room Type	**Alpha**
Temp. Type	Operative
Analysis Period	**May-September**
Occupied Hours	872
Thermal Performance	**Bad**
Class	Class D

Comfort Bandwidth	No. of Hours	% of Time
Class B	730	83.7
Class C	76	8.7
Class D	48	5.5
Above Class D	15	2.1



H.12 Melanchthon School Class 31 (TRY 2085)



Building	**Melanchthon**
Room No.	Class 31
Room Type	**Alpha**
Temp. Type	Operative
Analysis Period	**May-September**
Occupied Hours	872
Thermal Performance	**Bad**
Class	Class D

Comfort Bandwidth	No. of Hours	% of Time
Class B	695	79.7
Class C	83	9.5
Class D	69	7.9
Above Class D	25	2.9