Evaluation of overheating risks and passive cooling measures in low energy Swedish dwellings

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Master thesis in Energy-efficient and Environmental Buildings
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Lund University

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The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Abstract

Overheating in buildings is becoming a major concern and cause for various health issues. Existing research and previous studies on the issue were examined to acquire relevant information about the definition of overheating, its possible causes, and the heath impacts it could have on human health. The review included data on the current status of thermal comfort and overheating regulations in Sweden and neighbouring countries and information on the history of heatwaves and future climatic trends. Further research was conducted to gain more knowledge on passive cooling methods that could be implemented into buildings and new constructions to mitigate overheating to safer thresholds.

This study is divided into two major parts, the first part includes an analysis of overheating risks during the months of July and August of the year 2018, using data measurements for temperature and relative humidity recorded in 150 low energy detached houses located in various cities across Sweden. The measurements were analysed according to three Swedish and international standards which define overheating differently. It was concluded that overheating was occurring in most dwellings for prolonged hours particularly those located in urban areas. The results were evaluated according to CIBSE's overheating threshold which considered the annual occupancy schedule and showed higher overheating occurrences when compared to FEBY's threshold which considered overheating between April and September. Boverket's suggested threshold was associated with the highest overheating occurrences due to setting a single temperature threshold of 26° C, regardless of occupancy or the specification of a period of time. Novel parameters were also proposed to evaluate the duration of exposure to overheating.

In the second part, using building performance simulation program IDA-ICE, a simulated model of a study case based in Sundsvall, Sweden was used to investigate the possibility of incorporating passive cooling measures and determining their efficiency in mitigating indoor overheating. The final results revealed that opening windows for prolonged periods of time at night-time, as well as employing cross-ventilation can significantly reduce overheating to minimum thresholds. Lowering the g-value of the glazing and applying external shading yielded results within FEBY's threshold for some cases, whereas only relying on solar control through internal shading did not generate desirable outcomes.

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Terminology

CIBSE	Chartered Institute for Building services and Engineers
IPCC	Intergovernmental Panel on Climate Change
U-value	Thermal transmittance (W/m^2·K)
SHGC	Solar heat gain coefficient / g-value
CAV	Constant Air Volume
IDA ICE	IDA Indoor Climate and Energy simulation program
BBR	Boverket Building Regulations
SMHI	Swedish Meteorological and Hydrological Institute
FEBY	Swedish forum for energy-efficient buildings
NZEB	Near-Zero Energy Buildings
PMV	Predicted Mean Vote Index (+3 hot. +2 warm. +1 slightly warm. 0 neutral)
PPD	Predicted Percentage Dissatisfied (%)
TM59	Technical Memorandum (Predicting Overheating in Buildings)
WHO	World Health Organization
WMO	World Meteorological Organization

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1 Introduction

1.1 Background

Amongst the substantial consequences triggered by climate change is the phenomenon of global warming. As atmospheric carbon dioxide continues to rise due to the increase in global energy demand and the release of greenhouse emissions, it is inevitable that global surface temperatures will continue to rise and in turn cause irreversible damage to the earth's atmosphere and ecosystem (NOAA, 2021). According to the National Centres for Environmental Information, the years 2014-2020 ranked amongst the warmest years on record in Europe with 2020 being the warmest of the seven years despite the economic slowdown due to the global Covid-19 pandemic, where the annual temperature recorded +2.16 °C above average surpassing the previous record of 1.88 °C in 2018 (NCEI, 2020). As a result of the significant rises in temperature, it is expected that more frequent and intense heatwaves will occur (Christidis, et al., 2015). In turn, heatwaves eventually lead to overheating of dwellings, especially those lacking active cooling systems. These occurrences are associated with the disturbance of indoor thermal comfort threatening the health, wellbeing, and productivity of the occupants (Ruuhela, et al., 2021).

Extreme temperatures for prolonged periods of time can prompt several adverse reactions in the human body, including disruption of lung functions and blood flow in the body which in certain cases might lead to cardiovascular diseases and population mortality (He, et al., 2019). People aged 60 years and more, those suffering from illnesses and chronic diseases, and who are also expected to be occupying their homes during the peak hours of heat during the day, are found to be even more vulnerable to the health risks of overheating caused by heat stress (Kenny, et al., 2010).

Today, the focus is set on reducing greenhouse emissions and carbon dioxide concentrations in the atmosphere. The EU commission asserts that its main priority is to mitigate global warming by decreasing the energy use of buildings. In Sweden, the ministry of environment and energy has declared that the priority to deter climate change and global warming is even higher as it is committed to being completely fossil-free and climate-neutral by 2045. Since the building sector in Sweden accounts for about 40% of the total energy use, it is therefore deemed crucial to construct energy efficient buildings according to the NZEB concept. The global transition towards lowering carbon emissions puts massive pressure on the building sector to construct energy efficient buildings as an important step to cut building-related carbon emissions by 87% in 2050 (International Energy Agency, 2019) Hence, current constructions are being designed to be well-insulated and airtight focusing on the reduction of thermal losses, reducing heating loads and optimizing solar gains without being concerned about the long-term impacts on thermal comfort and occupant wellbeing during the summer season (Rohdin, et al., 2014). Employing more insulation and airtightness in residential dwellings has been also associated with summer overheating outcomes, where most dwellings lack any air-conditioning systems (Farahani, et al., 2021).

Weather warnings for high temperatures in Sweden are issued by the Swedish Meteorological and Hydrological Institute (SMHI) to give an opportunity to the healthcare sector and risk groups to be prepared. A heatwave is defined by SMHI as the continuous period when the maximum temperature of the day is at least 25 °C for at least 5 days in a row. One of the worst heatwaves recorded in Sweden was the summer of 2018, as the maximum average temperature was measured at 31.2 °C for the whole country. Generally, southern Swedish regions are more effected by heatwaves. The Swedish public health agency warns that prolonged exposure to heat can trigger several negative health risks such as detrimental dehydration, general impairment to more severe symptoms such as seizures and heat strokes. Recent studies indicate that heat sensitivity is increasing in Sweden and have found that children, older people, pregnant women, and people diagnosed with heart failure, diabetes or psychiatric illnesses are the most vulnerable (Folkhälsomyndigheten, 2015).

Swedish residential houses constructed to achieve passive standards/ low energy building (FEBY, 2012) are typically not equipped with active cooling systems and proper passive cooling measures therefore posing unforeseen risks and health impacts, sometimes even fatal, on their occupants due to overheating occurrences, specifically during an event of an intense heatwave where high indoor temperatures become unmanageable (Oudin Åström, et al., 2013). With unprecedented climate change linked to global warming and escalating temperatures (IPCC, 2021), overheating must be urgently addressed. The Swedish public health agency has set a maximum threshold of 26°C in residential indoor environments (Folkhälsomyndigheten, 2014) and instructs on the use of internal and external shadings to minimize solar radiation, in addition to opening windows to increase ventilation as a method to prevent heated environments. The current guidelines are seen as ambiguous and insufficient as no regard is given to the occupants' presence schedule or the function of the assessed areas in addition to the disregard of the duration and frequency of the overheating periods. To meet the existing thresholds might not be attainable even with the installation and utilization of passive cooling measures. Otherwise, air conditioning might be the sole strategy to mitigate overheating according to the current thresholds which evidently goes against low energy and low carbon policies.

1.2 Goal and scope

Energy-efficient buildings are becoming the standard for new buildings that have generally been known to exhibit overheating problems in warmer seasons. It is essential that a healthy indoor environment is also maintained all-year round in conjunction with the low carbon benefits of the new constructions. The main goal of this study is to investigate indoor overheating risks and their impact on thermal comfort and the wellbeing of occupants in modern energy-efficient and highly insulated dwellings in Sweden during the summer period. The study commenced by establishing a definition for overheating, determining the rate and scale at which it occurs and by later investigating the potential to eliminate this issue using passive cooling methods. The study was performed using data measurements of temperature recordings from Swedish modern energy-efficient detached houses built between the years 2006 and 2015.

To gain further knowledge regarding the definition and characteristics of overheating, a literature review was performed on similar previous studies and the current criterion used in assessing and defining overheating and thermal comfort, which is applied in Sweden and other European countries.

The following research questions were articulated to assess and define the goals of this thesis:

- What are the current standards that define overheating and what are the health risks associated with it?
- Which aspects should be considered to develop new overheating benchmarks/thresholds?
- What are the drawbacks of the current Swedish definition of overheating compared to other standards?
- How often is the issue of overheating surfacing in Swedish modern detached houses?
- How can the implementation of passive cooling measures contribute to reducing overheating?
- Which of the suggested cooling measures is most effective in achieving thermal comfort and mitigating overheating related issues?

1.3 Limitations

The study considered newly built detached houses in Sweden, which stands for only a fraction of the building stock in the country. A single case study was fully investigated and simulated; hence any results or conclusions might not be applicable for other dwellings. The building model used in the simulations was simplified according to the available data provided. Occupant behaviour such as opening windows or using mechanical cooling during data collection might play a significant role in the outcome of the analysis and the results thereafter, however only assumptions in this matter were taken into consideration. Additionally, relevant data regarding properties and building materials of the remaining 149 houses was not possible to obtain, therefore some of the results could be impacted by this information.

1.4 Structure of the report

- The first part of this report introduces the problem of overheating in newly built dwellings in Sweden and depicts the importance of conducting the study.
- The second part highlights the definition of overheating and what it implies, in terms of thermal comfort and occupants' health and wellbeing and summarizes the findings from the performed literature review on similar cases in Sweden and European countries, to get a detailed picture on the impacts and trends of overheating, and the factors that are most probably impacting the phenomenon. It also includes a review of the assessment approaches and criterion that are used to evaluate the thresholds and extents of acceptable overheating hours and durations in this study.
- The third part includes the method section of this report, which consists of an analysis of temperature data recordings obtained over the summer period of 2018 from 150 newly built dwellings, across distinct locations in Sweden, and outlines the magnitude of overheating occurring in the given households that is exceeding the proposed thresholds. In the second part of the methodology, an evaluation of passive cooling methods to mitigate overheating is presented, conducted through thermal modelling simulation for different scenarios and proposing the most successful and effective procedures thereafter.
- The fourth part presents the results of the investigation performed, to assess the severity of overheating occurring in the studied dwellings and the outcome of applying different passive measures.
- The last parts present the conclusions derived from the findings of this study and subsequently discusses the strengths, weaknesses and the applicability of the tools and guidelines, used for the assessment of overheating risks, and sheds light on the interventions simulated in this study to limit overheating and reach acceptable and safe thresholds.

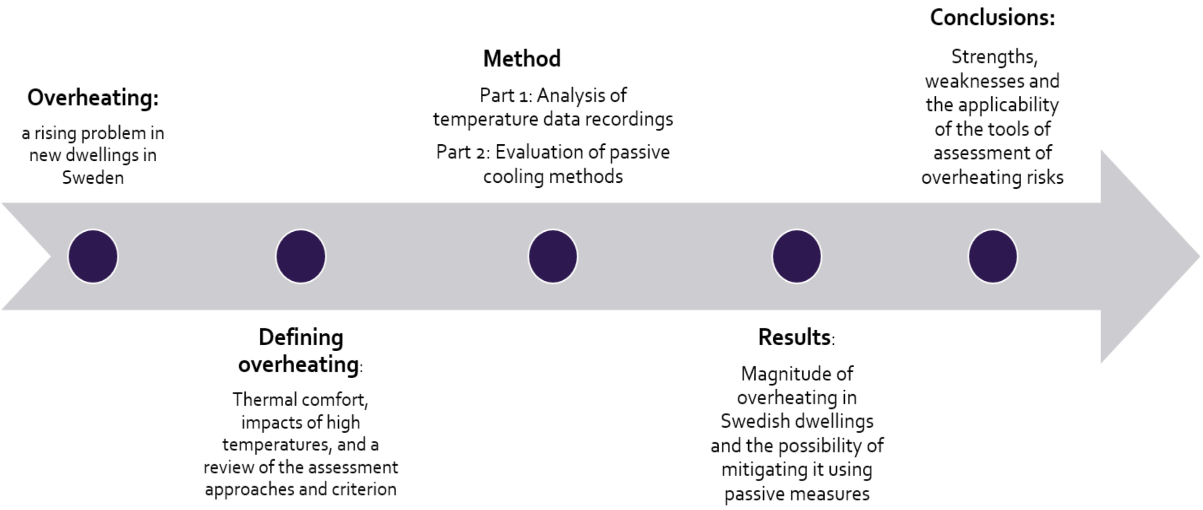


Figure 1: Schematic representation of the report's main sections

2 Literature review

The following chapter provides an overview of previous research conducted on the topic of overheating and thermal comfort, which will form the basis for this research. The literature review focuses on the significance of thermal comfort for occupants and their wellbeing, identifying risk groups that are most vulnerable to heat stress implications, in addition to current standards and regulations regarding overheating assessment, applying appropriate passive cooling measures to counter the impact of overheating as well as provide scientific predictions for the future trends regarding heatwaves and future climate norms.

2.1 Definition of Overheating

Overheating is defined as 'the phenomenon of a person experiencing excessive or prolonged indoor high temperatures resulting from internal and/or external heat gain and which leads to adverse effects on their comfort, health, or productivity (Zero Carbon Hub, 2015). In other words, overheating occurs when the state of excess heat in the indoor environment becomes intolerable and could possibly lead to endangering the health of occupants in certain cases. According to studies, experiencing overheating in households is directly related to increased health hazards and mortality risks as a consequence of heat stress placed on the human body (Kovats & Hajat, 2008). Then it is safe to say that unlike thermal comfort, overheating is not a matter of satisfaction or dissatisfaction with the surrounding environment; while thermal comfort is a relative concept dependent on individual perception, overheating on the other hand expresses the phenomenon of extreme heat that is hazardous to human beings and goes beyond thermal discomfort.

2.2 Causes of Overheating

According to the laws of thermodynamics, a building is considered a thermal system based on the energy balance of heat gains within and thermal losses through the building envelope. Overheating occurs when heat gains in a space surpass its heat losses for longer periods. In order to maintain thermal comfort within the indoor environment, thermal equilibrium should be achieved. Heat losses occur through the building's envelope, infiltration, thermal bridges, and ventilation while thermal gains are a result of solar heat gains and internal heat gains emitted by occupants, lighting, and appliances. In highly insulated and airtight buildings, the ability of the envelope to lose its excess heat is reduced hence increasing the risk of overheating.

Global warming triggered by the implications of climate change is considered the direct cause for indoor overheating (Hamdy, et al., 2017). Another cause for elevated temperatures in homes, is the phenomenon of the urban heat island occurring in crowded cities where natural ventilation and air quality are compromised, limiting the ability of residents to open windows for cooling. Buildings' surface areas as well as roads and cars contribute to more heat exposure; studies have shown higher mortality rates in urban areas than in rural zones (Kownacki, et al., 2019). Furthermore, the building sector in Sweden and Europe has been shifting towards constructing more insulated NZEB buildings with passive house standards to cut down overall emissions and reduce energy use; this is also another leading cause for overheating related to the material and thickness of insulation and the resulting airtightness of the building (Vidal, et al., 2020). Additionally, larger areas of unshaded glazing, especially south oriented and lacking solar control, are undoubtedly the primary cause for excessive solar gains and in turn overheating of the indoor environment (Vanhoutteghem, et al., 2015). Another important factor is the sum of internal sensible and latent heat gains emitted by the occupants and their activities, the intensity and energy expenditure of lighting fixtures and appliances within a home can be problematic during warmer seasons (Feist, 2020).

2.3 Thermal comfort in modern energy-efficient dwellings

A combination of several factors contributes to a healthy and safe indoor climate in dwellings, of which is visual and acoustic comfort, as well as good air quality, however thermal comfort is considered the most essential (Bülow-Hübe, et al., 2022). ASHRAE 55 defines thermal comfort as "the condition of mind that expresses satisfaction with the thermal environment" and states that indoor thermal climate can be defined as the sum of parameters that influence the human heat balance. Each person perceives comfort differently, therefore six parameters must be addressed in order to define the conditions of thermal comfort, and these are: 1) Metabolic rate, 2) Clothing insulation, 3) Air temperature, 4) Radiant temperature, 5) Air Speed and 6) Humidity.

Indoor thermal climate of a building can be influenced by several parameters, including the building’s geographical location and corresponding outdoor climate. Further, thermal comfort is also affected by the building’s envelope and construction, hence the building materials, insulation, windows, sun protection, ventilation rate and air tightness are direct influencers on thermal comfort. The ventilation system for heating, and when necessary, cooling also affects the building’s thermal climate. Nonetheless, the activity of the occupants and their use of the building in terms of lighting and equipment are also factors that affect the thermal balance of the space (Bülow-Hübe, et al., 2021).

The Swedish national board of housing, building, and planning (Boverket) states that ‘Buildings shall be designed to guarantee a satisfactory thermal environment of the occupied zone under normal operating conditions and therefore set certain guidelines to maintain healthy indoor environments (BBR, section 6:42). Since humans spend almost 87% for their time indoors (Diffey, 2011), it is crucial to provide the minimum requirements of thermal comfort such as good air quality and ventilation rates 0.35 l/s per m^2 of floor area , air speed less than 0.15 m/s, room temperatures no lower than 18 °C and not exceeding 26 °C within a maximum difference of 5 K between different points of the occupied zone, and relative humidity less than 75% to insure a healthy and comfortable environment for occupants (BFS 2014:3). The Public Health Agency in Sweden (Folkhälsomyndigheten) has also issued recommendations for operative temperatures between 20-24 °C indoors for “healthy buildings and materials”. Any disruption in the basic requirements of thermal comfort base levels can adversely impact our wellbeing, productivity, and health.

The international standard (ISO 7730, 2005) sets two indices, developed by (Fanger, 1970), to determine the status of satisfaction of occupants expressed as PMV (predictive mean vote) and PPD (Predicted Percentage of Dissatisfied expressed in %) that are used to assess the thermal balance and comfort of the inhabitants. Using the PMV index, the mean value of votes in a group of occupants can be evaluated based on the heat balance of the human body, on a scale of seven points each representing the level of sensation towards the perceived environment, where +3 indicates too hot thermal sensation, 0 for neutral, and -3 for too cold thermal sensations. In addition, PMV calculation requires given variables such as clothing insulation, metabolic rate, air velocity, relative humidity, and operative temperatures. On the other hand, the PPD index gives the percentage of people that express thermal discomfort due to drafts or high vertical temperature differences. In order for the indoor environment to be declared thermally comfortable, at least 80% of the occupants should be satisfied and the recommended thermal limit on the 7-point index to be between -0.5 and +0.5. According to CIBSE TM59, the guide for predicting overheating, if the PMV is over 0.5 with PPD>10% that would imply overheating of the assessed space.

2.4 The Heat Index (HI)

Temperature is perceived as a combination of dry-bulb temperature and relative humidity; it is then called apparent temperature or ¨real feel¨. A universal scale known as the heat index, was first developed by Robert G. Steadman (1970) and later advanced by several researchers and weather organizations, including the National Oceanic and Atmospheric Administration (NOAA). In Appendix A, the heat index is illustrated as a scale of 4 warning levels (caution, extreme caution, danger, extreme danger) for the combination of different temperatures. Temperature starts at 27 °C while relative humidity ranges between 40-100%. For example, a temperature of 33 °C and RH of 60% is perceived as 41°C and deemed as dangerous and requiring immediate interventions. A temperature of 30 °C and RH of 60% is perceived as 33 °C requiring extreme caution. If the combination falls in the level of extreme danger, detrimental health hazards are expected to take place. Relative humidity is regarded as a crucial factor in evaluating the level of heat stress on the human body since higher atmospheric moisture levels would hinder the rate of perspiration of the body needed to dissipate excess heat.

2.5 Health risks and impacts of overheating in homes

Several health issues and illnesses have been directly linked to poor thermal comfort and overheating in dwellings. In the evidence review conducted by The Zero Carbon Hub organization to examine the impacts of overheating in residential dwellings, the consequences of overheating were divided into two major risks: 1) Heat-related mortality and illnesses, 2) Sleep deprivation.

When a building fails to mitigate the effects of external temperatures due to poor ventilation or certain thermal properties, it starts to retain high temperatures intolerable by the human physiological systems, causing the body's thermoregulation and acclimatization ability to be severely impacted and diminished, which in other words means that the body can no longer maintain its core temperature (Hanna & Tait, 2015). This exposure to high temperatures has several effects on human health that are relatively mild such as dehydration, heat syncope, heat rash, heat stress and oedema (Leiva & Church, 2021) along with a reduction in productivity and concentration (Lee & Lim, 2018). Furthermore, evidence shows that high temperatures could lead to the onset of fatal heat strokes when the core body temperature exceeds 39.5 °C and triggers the collapse of major bodily functions. A heat stroke could lead to death within hours and survivors are often left with permanent injuries and impairment (Kovats & Hajat, 2008). During the extreme heatwave of 2003, at least 70 000 deaths were recorded in Europe due to heat-related mortality (Robine, et al., 2008).

There remains insufficient data regarding the exact thresholds beyond which adverse health effects start to take place, but a few studies show that extreme heat occurrences exceeding 26 °C indoors have been associated with the deterioration in health. High temperatures have also been linked to the exacerbation of certain mental disorders and behavioural diseases, such as dementia and schizophrenia and higher hospital admissions (Tham, et al., 2020). Furthermore, other more serious affects including heat strokes, cardiovascular diseases, respiratory diseases, high mortality, and morbidity rates have also been strongly linked to prolonged exposure to high temperatures indoors (NIEHS, 2022).

Additionally, rising temperatures, even slightly, in bedrooms during night times were linked to sleep disruptions and low-quality sleep caused by latency and wakefulness (Lan, et al., 2017). Continuous sleep deprivation could lead to various health ailments, anxiety and reduction in overall wellness and productivity. In more extreme cases, sleep deprivation could lead to serious health complications (Colten & Altevogt, 2006).

Recent studies have shown that several groups are even more vulnerable to heat stress than other individuals. People over the age of 60 and those suffering from obesity, cardiovascular diseases, diabetes, and other chronic diseases, are considered especially at risk and more susceptible to heat-related illnesses particularly, as they tend to spend more time indoors and have sedentary lifestyles (Kenny, et al., 2010). In an aging population and future heatwaves becoming more common, increasing health hazards are predicted. Nonetheless, young children and babies are also considered a high-risk group as their bodies are incapable of coping with high temperatures and could easily get dehydrated and fatigued leading to heat cramps, serious heat strokes and heat exhaustion (Zhiwei Xu, et al., 2013).

Even though Sweden is known for its moderate summer temperatures, heat-related health risks can still have a great effect. This is presumably due to the fact that people are more used to the Nordic climate and aren't adapted to higher temperatures, therefore have lower ability to acclimatize to sudden heat exposure. In this case, mortality rises already at lower temperature thresholds (Bülow-Hübe, et al., 2021). When it comes to climate change adaptation, state authorities, property suppliers, planners, and homeowners require precise appropriate guidance to direct their resources. This is particularly necessary when designing homes for vulnerable groups, such as the elderly, who are unable to manage or remove themselves from their surroundings, making heat stress hazardous. When selecting the most effective treatments, it is critical to consider the kind of tenants and their related occupancy profiles, as well as the dwelling construction specifications (Porritt, et al., 2012).

2.6 Overheating assessment methods and standards

In Sweden, greater focus is being directed towards reducing buildings' energy demand and maintaining acceptable temperatures in dwellings during heating season, while the rising phenomenon of increasing indoor temperatures during summertime remains unprioritized. Current Swedish standards and guidelines regarding overheating risks were found to be limited, where the only found guideline was setting a maximum recommended temperature of 26 °C indoors by the National Board of Housing (Boverket). On the other hand, the forum for energy-efficient constructions (FEBY) which is a non-profit Swedish organization that actively drives and supports sustainable low-energy and passive houses, has issued a requirement specifications handbook including guidelines for the management of thermal comfort in energy-efficient dwellings. FEBY specifies that indoor temperature during the period of April to September should not exceed 26 °C for more than a maximum of 10% of the time (FEBY18, 2018).

Realizing the complexity of assessing the risks of overheating, given all the factors that could influence it, the Chartered Institution of Building Services Engineers (CIBSE) has established a standardized methodology TM59, which is a technical memorandum, created for the purpose of addressing the issue of overheating in residential dwellings in a more profound and thorough approach. CIBSE is an international professional engineering association based in London and is recognized as an authoritative institution responding to the threats of climate change and promoting best practice in building services. The institution regularly publishes guidance and codes and sets criterion to ensure its goals. Its latest published methodology for the assessment of overheating risks in homes (CIBSE, 2017) attempts to define a threshold for the maximum limit of indoor temperature based on reasonable assumptions, considering all impacting factors, without compromising energy efficiency requirements and daylighting targets. The methodology of the standard is fundamentally based on using dynamic thermal modelling including appropriate zoning, building thermal properties, a weather file, and a set of profiles for different home usage patterns, which is then simulated on an hourly basis for the summer period. For naturally ventilated houses, windows are presumed to be open. The resulting outcome is assessed based on the Criteria for homes that are predominantly naturally ventilated and should pass the following criterion (as found in TM59):

a) *¨For living rooms, kitchens, and bedrooms: the number of hours during which ΔT is greater than or equal to one degree (K) during the period May to September inclusive shall not be more than 3 % of occupied hours.¨*

b) *¨For bedrooms only: to guarantee comfort during the sleeping hours the operative temperature in the bedroom from 10 pm to 7 am shall not exceed 26 °C for more than 1% of annual hours. (Note: 1% of the annual hours between 22:00 and 07:00 for bedrooms is 32 hours, so 33 or more hours above 26 °C will be recorded as a fail). ¨*

Furthermore, CIBSE's A guide for environmental design (2015) states that operative temperatures should not exceed 28 °C for 1 % of annual occupied hours in living areas, and 26 °C for 1 % of annual occupied hours in bedrooms, however, people would essentially start feeling exceptionally uncomfortable when temperatures exceed 25 ºC in living areas and sleep quality is compromised at temperatures above 24 °C.

2.7 Passive cooling measures

The increasing demand for space cooling is putting a burden on many countries' power infrastructure, as well as increasing greenhouse emissions. Without firm governmental policies, active cooling demand is predicted to soar in the upcoming decade. While it is necessary to maintain thermal comfort and have access to cooling means, the effects of the growing trend would result in detrimental consequences in energy use and global emissions (IEA, 2018).

Residential buildings in Sweden typically lack active cooling systems and more focus is set on the heating demand of spaces while disregarding or at least giving less significance to summer temperatures, as it does not cost any energy. However, the effects of climate change are manifesting more rapidly in the Nordic countries making them more vulnerable to the consequences of global warming and overheating risks for current and future climates, confirmed by the Swedish commission of climate and vulnerability (Arcanjo, 2018). To manage the increasing cooling loads of buildings during overheating occurrences and proceed with the Swedish design tendency for energy-efficiency, it is important to investigate the possibility to reduce high temperatures with passive cooling means and to quantify the magnitude of these actions. The benefits of passive cooling measures are numerous; other than regulating thermal comfort and controlling heat gains, they are considered environmentally safe as they do not employ a refrigerant, expend energy, or generate emissions. They are also considered economically beneficial since they do not require constant/much maintenance and are relatively easy to incorporate in the building envelope. Passive cooling may include the use of biological material solar shading tools, such as vegetation, on the dwelling's façades and roofs through the process of heat prevention, which in turn is beneficial to the environment in lowering CO2 levels (Figueroa-Lopez, et al., 2021).

Passive cooling measures are gaining more popularity in Sweden as they represent an alternative to traditional active cooling and their efficiency was proven in mitigating the effects of increased outdoor temperatures and minimizing energy use, by preventing, modulating, and dispersing heat build-up indoors, while maximizing the comfort and economic benefits for building occupants (Czachura, 2019). The most utilized methods in adapting new and existing dwellings with passive cooling involve planning the orientation and window to wall ratios of the building during the design phase, employing site shading using trees and vegetation, incorporating internal and external solar shading devices, applying solar control to window properties, opening windows, relying on natural ventilation and draughts or in some cases increasing supply ventilation rates. Nevertheless, the most effective methods in mitigating high temperatures were found to be opening windows and applying solar control to windows glazing (Farahani, et al., 2021), although opening windows might not be a good option in some cases where outdoor noise, pollutants or insects are to be avoided and adding solar control to windows might impair visual transmittance and cause high heat losses during the heating season, while outdoor shadings could affect the outer appearance of a building (Porritt, et al., 2012).

2.8 Heatwaves' history across Europe and Sweden

A heatwave, according to the Met Office for national meteorological service in the UK, occurs when daily maximum temperatures surpass a specified threshold for three days in a row (MetOffice, 2022), while the Swedish Meteorological and Hydrological Institute (SMHI) defines a heatwave as the extended period of unusual hot weather where the daily outdoor air temperature goes beyond the 25 °C threshold. Relative humidity, wind speed and global solar irradiance are also important factors that play a role in the severity of the heatwave and in what manner heat is eventually perceived (Katavoutas & Founda, 2019). With the predicted increase in extreme weather events due to global warming, regions with temperate climates such as parts of Europe and the USA have witnessed an unprecedently rise in recorded hot summers and heatwaves in the past decades, resulting in a substantial number of deaths, impacts on public health, as well as damages to the food industry (Lomas, et al., 2021).

In August 2003, Europe experienced one of its worse heatwaves where temperatures exceeded 40 °C in some locations and took the lives of over 40 000 inhabitants, mainly elderly and vulnerable risk groups. The heatwave was attributed to the loss of the glaciers over the European alps, placing large-scaled high pressure in the upper atmospheric wind flow (WMO, 2011). In 2018, Europe was hit by its worst heatwave in history between the 2nd of July and the 5th of August. Sweden was drastically impacted as well with record-breaking high temperatures lasting for an unusually prolonged duration. During the heatwave, 635 more deaths were recorded when compared to the same period in previous years (Åström, et al., 2019).

Heatwaves in Sweden have been a more common occurrence happening almost every 5 years, as compared to previous years, and the trend is only getting more frequent and is expected to be even warmer predominately in the southern Swedish parts. In the summer of 2018, record heat was perceived all over Sweden. Temperatures reached 30 °C for several days in a row and heat warnings were issued by SMHI. The Swedish Public Health Agency recorded an estimate of around 700 deaths more than normal during the heatwave that hit Sweden for 5 weeks. The announcement of outdoor high temperature occurs when the maximum temperature is at least 26 °C for 3 consecutive days. A Class 1 warning is declared when the maximum temperature is at least 30+ °C for 3 consecutive days and Class 2 is announced whenever the maximum temperature exceeds 30 degrees for 5 consecutive days or that the maximum temperature is at least 33 °C for 3 consecutive days (SMHI, 2022).

2.9 Overheating in a Future climate

Scientists warn that with the existing levels of greenhouse emissions, the changes and disruptions to the climate will only intensify and lead to more extreme weather events (EWE). As the earth’s temperature continues rising, which causes polar ice caps to melt and sea levels to rise, heat waves and draughts are also expected to become more common, particularly in Europe (European Commission, 2022). Numerous initiatives undertaken by governments, international organizations, and committees are dedicated to combat and mitigate the effects of climate change, and in turn global warming, on earth. However, these actions might not be able to reverse the damage caused to the environment and the O-zone layer by the different harmful emissions from fossil fuels and greenhouse gases (The Intergovernmental Panel on Climate Change, 2022).

In its report on the future climate of Sweden, SMHI has predicted a mean annual temperature rise in Sweden by 1.5 - 3 °C between the years 2021 and 2050, and a rise by 2.5 - 5.5 °C between the years of 2070 and 2090 (Anna Eklund, et al., 2015). The northern parts of Sweden will be the most impacted by the rise in temperatures. In the scenario of successfully limiting future emissions, an average rise of 3 °C, compared to the period 1961-1990, is very probable, while an expected rise of 6 °C on average is expected in a scenario of unmanaged emissions behaviour. Moreover, predictive calculations show a future increase in the occurrence of prolonged heat waves lasting between 8 and 12 consecutive days in most of the country, especially in southern Sweden by 2050, and lasting up to 26 days by 2100 (Anna Eklund, et al., 2015).

The projected increase in heat waves and high summer temperatures not only effects human health, but it can also affect buildings’ performance. Buildings’ energy balance (heating and cooling needs) will be severely affected, due to increasing internal temperatures, buildings without proper cooling mechanisms will become uncomfortable to inhabit and possibly endanger the health of the occupants (Hamdy, et al., 2017).

3 Method

The following section provides a comprehensive overview of the research methods employed in this study which consists of two fundamental parts. The first part presents the process of analysing the data retrieved from hourly temperature recordings measured in 150 relatively modern single-family detached dwellings in different locations across Sweden, from the south in Malmö to the north of Sweden in Kiruna, to determine the frequency and severity of indoor over temperatures, as well as performing a comparison between the different overheating standards utilized in Sweden, Europe and globally. The second part exhibits a case study targeting one of the aforementioned dwellings located in Sundsvall; where several simulations were performed on a simplified model of the building to determine the possibility of alleviating overheating through passive cooling measures.

3.1 Data collection and analysis in selected dwellings

For the purpose of this study, 150 single-family detached houses located in distinct climatic zones across Sweden were selected to collect hourly and daily temperature logs, as well as relative humidity records in bedrooms and living areas. Approximately two and a half million measurements from 150 households were recorded daily, in pre-set intervals to obtain average hourly temperatures and in turn average daily temperatures over the course of 3 years (2017-2019). The measurements were acquired as part of a separate study initiated by 'Formas', a Swedish research council for sustainable development, under the title (*Investigation of ventilation and indoor-environment related parameters in modern detached houses)*. It was decided to evaluate overheating in the bedroom areas for this analysis while further assessment could be performed on living rooms in future studies. Some recordings were found to be missing during the month of June for most dwellings, hence an analysis period of 2 months (July and August) in the summer of the year 2018 was selected for the assessment of overheating occurrences and thermal comfort issues.

The data was split into 3 sets as shown in Table 1. The first set included 50 dwellings located in different cities across Sweden, as shown in Figure 2, including Malmö (Latitude 56 °N, Longitude 13 °E) on the southwestern coast, the capital Stockholm (Latitude 59 °N, Longitude 18 °E) on the eastern coast and Kiruna (Latitude 68 °N, Longitude 20 °E) in the far north as well as other locations. The second set of 50 dwellings was situated in the municipality of Jönköping (Latitude 58 °N, Longitude 14°E) in southern central Sweden, while the third set of 50 dwellings belonged to the municipality of Umeå (Latitude 64 °N, Longitude 20 °E), the largest city in northern Sweden. The dwellings were all built between the years 2006 and 2015 and are therefore classified as energy-efficient dwellings with highly insulated and airtight building envelopes. Data records acquired from the respective dwellings were then analysed and assessed according to common Swedish and international thermal comfort guidelines and thresholds exhibiting the actual and expected magnitude of the overheating situation in Sweden.

Table 1: Data sets

	City	Number of dwellings
Data set number 1	Various Cities	50
Data set number 2	Jönköping	50
Data set number 2	Umeå	50

It could be noted that during data collection periods, the buildings were in use, and therefore occupants' behaviour was presumed to be responsive to temperature changes, implying that occupants may have applied certain measures to overcome the high temperatures, such as opening windows, closing curtains/blinds or using coolers and fans. Furthermore, certain periods during measurements might have been conducted in the absence of occupants in circumstances such as travel. Such changes might as well affect temperature recordings. Other factors could impact the occurrence of overheating as well, including the materials and insulation used in construction, the area of window coverage, the building's orientation, surrounding shading elements and geographical location, in addition to the number of present occupants. All information concerning the mentioned factors were not provided for the study. The respective annual outdoor temperatures and relative humidity data of the above-mentioned dwellings were provided by the Swedish Meteorological and Hydrological Institute (SMHI) in the form of daily and hourly logs.

Figure 2: Map of Sweden showing the major cities included in the study (Vemaps.com)

3.1.1 Overheating assessment in different criterion

The average hourly and daily recorded temperatures for all 150 dwellings were evaluated and analysed using Microsoft Excel, to establish whether issues with high temperatures were encountered during the summer season (July- August) in the bedrooms of the dwellings. The verification of overheating occurrences was determined and later compared according to 3 chosen guidelines used by governmental agencies and international building organizations, which vary in their conditions and regulations as seen in Table 2 below. The criterion recommended by the Swedish National Board of Housing (Boverket) to define overheating is limited only to the occurrence of operative temperatures above 26 °C indoors with no regard to occupants' time of presence, the function of the space, or the duration and frequency of the overheating periods. The FEBY standard for defining overheating accounts for the occurrence of temperatures higher than 26 °C during a period longer than 10% of all hours between April-September for all rooms regardless of any occupancy schedule. These standards are both applied in Sweden. Whereas CIBSE TM52 regulates the allowed number of overheating hours annually, according to Criterion b which applies to bedrooms only as mentioned before in section 2.6, which states that temperatures are not allowed to pass the 26 °C threshold for more than 1% of the occupied time between 10:00 pm and 7:00 am.

Table 2: Overheating criterion thresholds and allowed number of hours

Standard	Temperature threshold	Allowed number of hours	
CIBSE TM59	26° C for bedrooms	1% of the annual occupied period	(32 hours)
FEBY	26° C for all rooms	10% of the period April-September	(440 hours)
Boverket	26° C for all rooms	-	

3.1.2 Overheating probability of occurrence

The probability of overheating occurrences at temperatures above 26, 28 and 30 °C in the targeted dwellings, was assessed through a cumulative distribution function (CDF) in Microsoft excel, for each of the 3 data sets separately.

3.1.3 Duration of exposure to overheating

Since none of the current guidelines consider the duration of acceptable exposure to overheating, it was decided to follow the recommendations of a recent study that establishes the necessity for a new indicator in the assessment of overheating and concluded that overheating becomes hazardous beyond a period of 6 consecutive hours (Lee & Steemers, 2017). A VBA macro script in Microsoft Excel, provided for the purpose of this study, was used to determine the duration of overheating exposure for each case of the 150 investigated dwellings, by summing the number of consecutive hours where indoor temperatures exceeded 26 °C for each of the investigated dwellings.

3.1.4 The relationship between indoor and outdoor temperatures

An analysis of the average daily outdoor and corresponding recorded indoor temperature of the investigated dwellings was performed for each data set, during the period of July-August, to determine whether a correlation between the outdoor and indoor temperature exists or if outdoor temperatures could have an effect on indoor temperatures.

3.1.5 Indoor temperature/Relative humidity correlation analysis

The Swedish Standard EN ISO 7730 as well as ASHRAE 55 for thermal comfort conditions recommend an upper temperature limit of 26 °C at a maximum of 60% relative humidity. The Swedish National Board of Housing (Boverket) also recommends an upper limit of 75% for indoor relative humidity to ensure the safety and health of occupants. Another example for the importance of establishing a relation between temperatures and relative humidity is the heat index described in section 2.4, which basically suggests that higher relative humidity can have detrimental impacts when associated with high temperatures. Therefore, an analysis was performed on the data sets of the targeted dwellings to investigate the possibility of any occurrences that do not comply with the aforementioned recommendations. Average daily indoor temperatures and respective relative humidity recordings for the months of July and August from the investigated dwellings were plotted in a scatter graph and later assessed according to a threshold of the maximum allowed temperature of 26 °C and a relative humidity of 60%.

3.2 Sundsvall case study

Following the analysis of temperature data for the three sets, a single case study located in Sundsvall was selected for further investigation, regarding the potential and applicability of certain passive mitigation methods. By comparing recorded data measurements with data acquired through computer assisted simulations, a reference case was established. Sundsvall's case study house was modelled using IDA Indoor Climate and Energy simulation tool (EQUA, 2020). IDA ICE is a validated software created by EQUA solutions to simulate indoor environments under realistic conditions, considering the occupants' use of lighting and equipment, to acquire an accurate representation of the energy performance, air quality and thermal comfort of the indoor environment (EQUA, 2010). Several assumptions were made during simulations due to the lack of certain information.

In this part of the study, indoor temperatures for the bedroom zone during the months of July and August were considered. The studied house is located in the coastal municipality of Sundsvall (latitude 62°N) in Västernorrland County in the north-eastern part of Sweden, assumed to be constructed after the year 2008. Sundsvall is characterized by very cold winters, mild summers, and longer days between the months of May to August. The dwelling was presumed to lack an active cooling system and relied on a constant air volume (CAV) ventilation system and natural ventilation for summer-time cooling. For concrete and realistic simulations, the weather file for Sundsvall in 2018 was applied. The building is a one-storey single-family detached house of a total floor area of 149 m², a height of 2.6 m and is oriented 30° southeast. The building envelope is considered to be highly insulated as shown in Figure 5 with an insulation thickness of 0.285 m in the wall construction and a thickness of 0.41 m of insulation in the roof structure. It was estimated based on the provided architectural drawings that a total of 4 inhabitants occupied the dwelling which is divided into 8 total zones as shown in Figure 3 below. Marked in green is the bedroom zone selected for the analysis.

Figure 4 denotes the four different facades of the case study in four orientations: southern façade (upper left), eastern façade (upper right), northern façade (lower right) and the western façade (lower left).

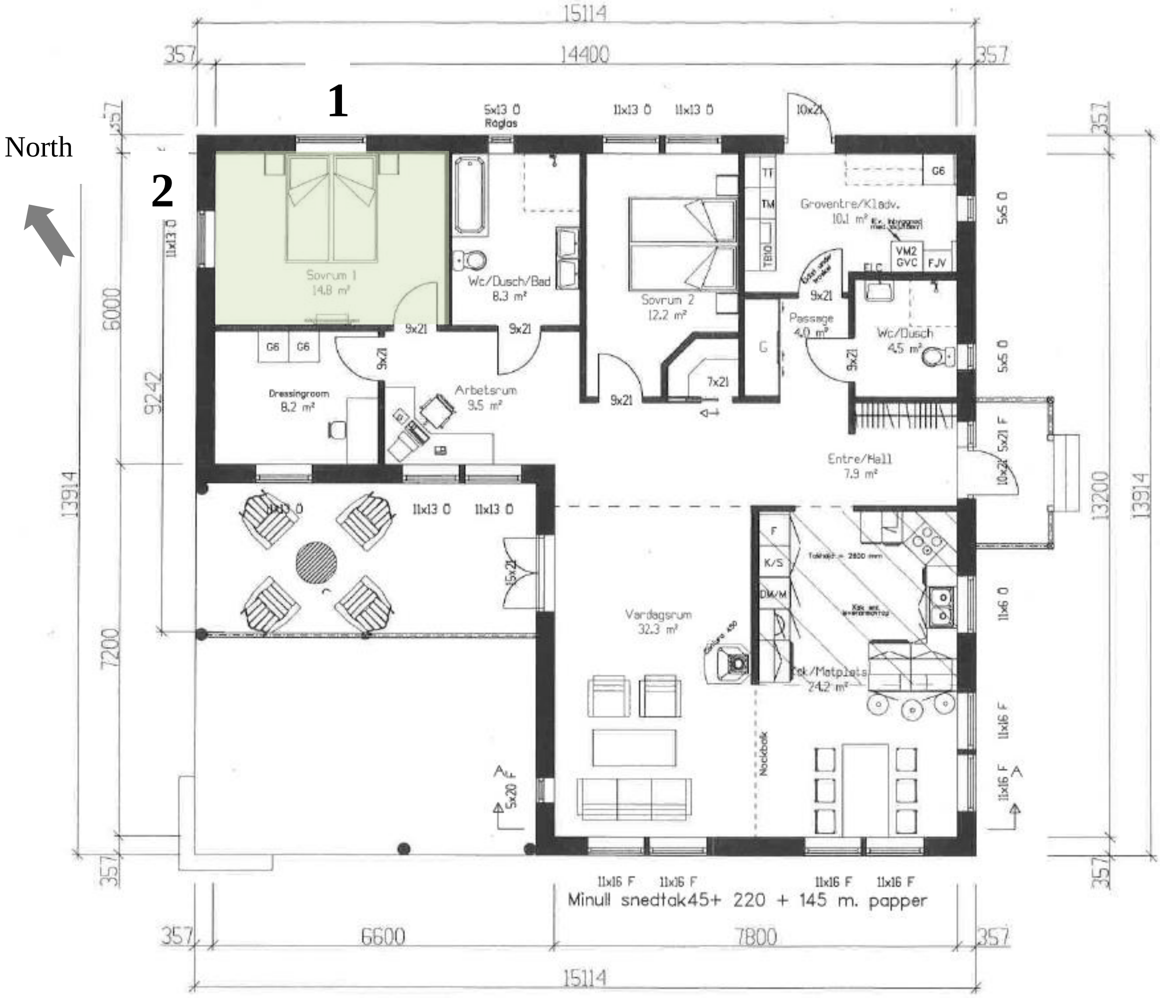


Figure 3: The plan layout of Sundsvall's case study

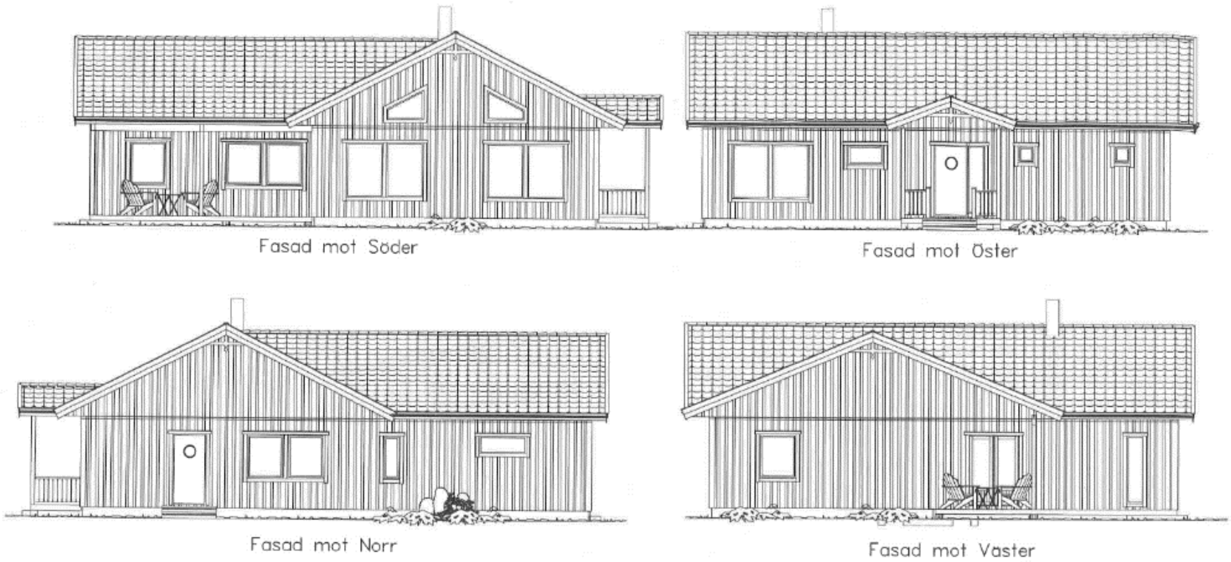


Figure 4 : Facade drawing including all four orientations

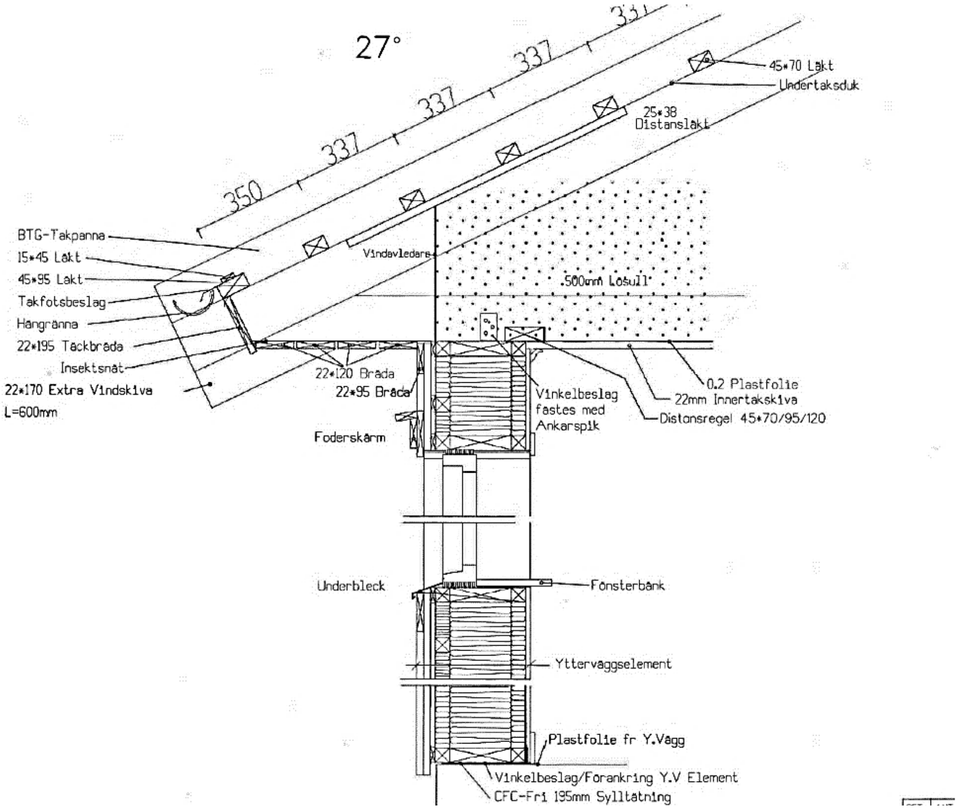


Figure 5 : Detailed Cross-Section of the wall and roof junction

3.2.1 Heat balance in IDA-ICE simulations

As previously mentioned in 2.2, the laws of thermodynamics, in particular the heat balance of a building, are primarily the actors driving the causes of overheating in the indoor environment, which occurs as internal heat gains surpass the amount of heat loss. IDA ICE fundamentally simulates a detailed heat balance for the investigated zone under specific conditions taking into consideration all variables effecting internal loads, solar loads, heat losses, ventilation losses and infiltration, calculated according to the heat balance in Equation 1 below and designated in Figure 6 (Fransson, 2020). The following equation is used to determine the extent and power needed for cooling.

$$dTair/dt \cdot Cair \ = Pint\ (t) + \ Psolar\ (t) + \ Pmass\ (t) - \ Ptr\ (t) - \ Pleak\ (t) - Pv\ (t) \quad [\mathrm{W}] \qquad \text{Equation 1}$$

Where, T_{air}: *Indoor air temperature* [K]

C_{air} : *Air heat capacity* [J/Kg.K]

t: *chosen time step* [seconds/minutes/hours]

P_{int}: *Power of internal heat gains* [W]

P_{solar}:*Power of solar heat gains* [W]

P_{mass}: *Power of the thermal mass* [W]

P_{tr}: *Power of heat transfer* [W]

P_{leak} : *Power of air leakage/infiltration* [W]

P_v: *Power of ventilation* [W]

According to the heat balance equation, overheating is a product of lower heat transmission losses through the building envelope (P_{tr}) and lower infiltration rates (P_{leak}), which are both properties of low energy houses. Internal loads as well play a role in overheating through adding heat emitted from occupants, equipment, and lighting (P_{int}). Other important factors that contribute to overheating are at the same time considered essential in low energy houses and include incorporating higher solar gains transmitted through windows (P_{solar}). External irradiation is even more penetrating and intense in rooms with large window areas such as those in some modern buildings and houses for architectural purposes.

Installing internal or external shading devices and lowering the g-value of windows could therefore retain the heat balance during warmer seasons and lower overheating occurrences. Further cooling could also require natural ventilation for added air flow as long as outdoor temperatures are lower than indoor temperatures. The cooling power from the air flow when opening windows is correlated to the magnitude of the airflow and the temperature difference between indoor and outdoor. The magnitude of airflow is then driven by the pressure difference from windspeed and temperature difference and consequently the size and orientation of the opening. Both wind, outdoor temperature and sun vary over time and thus make the use of transient calculations with IDA ICE a viable option.

Some other factors are constant and cannot to be altered for achieving thermal balance in the indoor environment such as those related to the construction performance and occupant-related heat gains, other factors could be successfully manipulated to serve in decreasing indoor temperatures such as lowering solar-related heat gains and increasing ventilation rates.

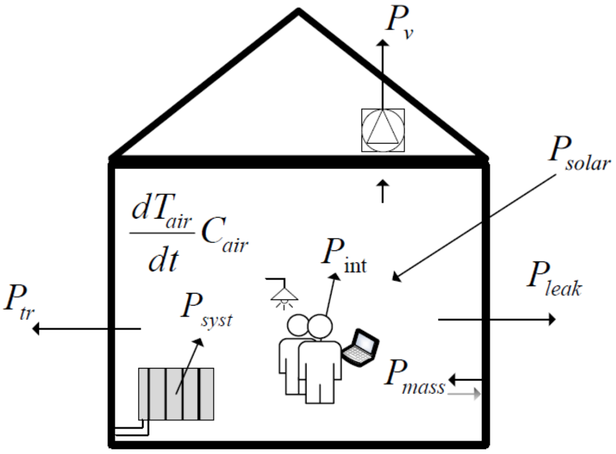


Figure 6: Schematic view of the heat balance in a building. (Obtained from Victor Fransson's doctoral dissertation,2020)

3.2.2 Base case simulation setup (Reference Case)

The building's layout and construction were re-created and modelled as close to the detailed drawings as possible, taking into consideration some assumptions that were proposed at certain points. The final model was thereafter simulated with numerous variations in internal shading and window opening schedules in order to match the recorded temperatures measured on site. The final Reference Case that was calibrated with the recorded measurements was employed thereafter in simulating mitigation measures discussed in the next sections. The Base Case inputs utilized in the setup of the model are listed in Table 3 below detailing the most critical setpoints and assumptions. The bedroom selected for the evaluation in the base case is a north-western room with two casement-window openings as shown in Figure 3 above with the following dimensions and areas:

i) window 1, north oriented 1.4 m · 0.5 m = 0.7 m^2
ii) window 2, west oriented 1.1 m · 1.3 m = 1.43 m^2

Table 3: Base case inputs and settings

Infiltration	0.05 ACH at n50	Assumed infiltration in newly built houses (Janson, 2010)
Cooling/Heating	No active cooling No heat exchanger	Most Swedish houses are not equipped with active cooling
Ventilation System	Constant Air Volume (CAV)	Building data
Supply/exhaust air volume	0.35 L/s·m^2	Ventilation requirements in Sweden (BBR)
External Walls Construction	Wood construction - 0.285 m Insulation U-value: 0.145 W/m^2·K	Derived from construction blueprints
Roof Construction	Wood construction/Clay tiles – 0.41 m Insulation U-value: 0.12 W/m^2·K	Derived from construction blueprints
Glazing Properties	Triple Clear glazing – Argon-filled U-value: 1.9 W/m^2·K G-value: 0.68 Visible Transmittance: 0.74	Assumed glazing type for houses after 2008
Window Shading	Internal blinds/curtains – Medium transmittance No existing external shading	Assumed based on typical Swedish houses As seen in 3d google maps
Internal Gains	Occupancy density: 0.068 persons/m^2 Lighting density: 1.36 W/ m^2 Equipment density: 2 W/ m^2	Calculated based on typical Swedish houses and the number of occupants
Occupancy schedule	10:00 pm – 7:00 am	Assumed sleeping period – Proposed by CIBSE
Duration	1st of July – 31st of August 2018	Analysis period
Simulation Output	Hourly intervals	Compared with actual measurements

The reference case was used as a starting point for conducting passive cooling measures and the following parameters and occupant behaviour were considered:

- Windows open between 7:00 am and 6:00 pm.
- Generic medium transparency blinds placed at the inner panes of the windows with none externally.
- Blinds were set to be open or closed whenever occupants needed to protect against high solar radiation. When blinds were closed it was assumed they were 100% shut.
- The material of the blind was characterized by:
  0.65 Multiplier of the g-value (G) and 0.16 for Transmittance (T).
- All windows were assumed to have internal blinds, and all were used simultaneously.
- The bedroom door was set to be open during the day and closed during the night.

3.2.3 Integration of passive cooling measures

Amongst several passive cooling methods that could be incorporated into a building, it was intended for this study to evaluate and assess the applicability and efficiency of four passive measures, that were considered as most suitable to integrate into an existing and occupied building without using extra energy. The proposed passive cooling measures were simulated in various designs and functions, results obtained from the simulations were later compared used to determine the measure which yielded optimal thermal comfort and minimized the number of overheating hours to meet acceptable thresholds. The suggested cooling measures include the use of internal and external shading devices, altering certain properties of the existing glazing to deter increasing solar gains, as well as opening windows and creating drafts to allow for natural ventilation and cooling under variable opening schedules and opening percentages. A combination of the most optimal measures could be used to create a well-improved building model, that could withstand prolonged heat seasons as well as protect against harsh summer solar radiation without resorting to active cooling measures.

3.2.3.1 Passive Cooling Strategy 1: Internal Shadings

The first method in mitigating the increase in indoor temperatures was minimizing the effect of solar exposure and radiation that was amplifying internal thermal gains. Different internal mobile shading techniques were simulated with a fixed schedule for opening/closing between 07:00 am and 10:00 pm, disregarding shading during the night where solar heat gain has no effect. Simulations were carried out by varying the percentage of opening (0%,50%), the windows to which internal shading was applied, the position of the shading relative to the panes (inner pane, in-between panes) and the material properties of the textile in terms of solar heat gain and solar transmittance. The parameters were simulated and compared against each other to determine the effect of each parameter on the performance of the shading. Generic tightly woven drapes of medium dark transparency were used as specified in Table 4 below. The reference case, as described in 3.2.2, was used as a starting point and a worst-case scenario without any shading was considered.

Table 4: Internal shading variations applied to the base case

Simulated case number	Shading Parameters	Alternative 1	Alternative 2
Reference Case	Shading closed/open according to occupant response against solar heat		
1.1	Opening percentage	50% half-open	0% (fully shut)
1.2	Included windows	Bedroom windows	All windows except bedroom
1.3	Position with respect to panes	Inner pane	In-between panes
1.4	Material Properties	G: 0.59 / T: 0.12	G: 0.75 / T: 0.54
1.5	Worst case scenario	No shading	

**Note: G: multiplier for SHGC / T: multiplier for solar transmittance*

3.2.3.2 Passive Cooling Strategy 2: External Shadings

The second strategy used in mitigating overheating was integrating mobile external shadings at the outer rims of the windows, to limit the impact of solar rays passing through the glazing, while allowing occupants to have full control over opening and closing the shadings, depending on the intensity of solar radiation and overheating episodes. Two types of external shadings were tested (drop-arm awning and external roller screen) applied at different orientations (north, east, west, and south) and at different schedules as shown in Table 5 and Table 6. The textile of the drop-arm awning shadings is a light grey generic textile characterized by 0.05 transmittance, 0.3 reflectance and 0.9 emissivity, while the textile of the external roller screens was characterized by 0.15 solar heat gain and 0.1 transmittance and were simulated according to different opening percentages (0%, 50%, 75%) as shown in Table 6. Both shading devices are illustrated in Appendix B. Fixed shading devices such as louvers and overhangs were not considered in this study.

Table 5: Drop-Arm Awning shading variations applied to the base case

Simulated case number	Shading Parameters	Alternative 1	Alternative 2	Alternative 3
Reference case	No external shading applied			
1.1	Textile Reflectance	0.1	0.3	0.6
1.2	Position	All windows	South-facing	East-West facing
1.3	Schedule	7:00 am – 1:00 pm	1:00 pm – 6:00 pm	7:00 am – 10:00 pm

Table 6: External Roller Screen shading variations applied to the base case

Simulated case number	Shading Parameters	Alternative 1	Alternative 2	Alternative 3
Reference case	No external shading applied			
1.4	Opening Percentage	0%	25%	50%
1.5	Position	All windows	South-facing	East-West facing
1.6	Schedule	7:00 am – 1:00 pm	1:00 pm – 6:00 pm	7:00 am – 10:00 pm
1.7	Window to pane gap	0.03	0.07	0.15

3.2.3.3 Passive Cooling Strategy 3: Solar heat gain coefficient

The Solar heat gain coefficient (SHGC) measures the glazing's ability to transmit solar radiation and is expressed as a number between 1 and 0, where 1 indicates a transmittance of 100% of solar heat and 0 indicates than the glazing does not transmit any heat, and this is usually the case in opaque materials. Although a higher g-value is advantageous in winter since the glazing absorbs the majority of solar radiation, it also means more overheating in the summer season. Larger facades and greater window to wall ratios can raise indoor temperatures during summer periods, by allowing more solar radiation to heat up the indoor environment. Therefore, g-values between 0.2 and 0.9 were simulated to investigate their impact on overheating hours as shown in Table 7 below. Case number 1.6 represents the base case with a g-value of 0.7.

Table 7: Windows g-value variations – applied to all windows

Simulated Case Number	**Glazing g-value**
1.1	0.2
1.2	0.3
1.3	0.4
1.4	0.5
1.5	0.6
1.6 (reference case)	0.7
1.7	0.8
1.8	0.9

3.2.3.4 Passive Cooling Strategy 4: Opening of windows

According to literature review and previous studies on the matter, it has been proven that the most effective passive method in decreasing and managing indoor temperatures is opening of windows. Numerous simulations were carried out with variations in opening schedules during the day and the night, while increasing the number of total hours the windows were open, until the resulting number of overheated hours was satisfactory and within the specified thresholds of Boverket, CIBSE and FEBY as shown in Table 8. There is a total of 18 openable casement windows with a total area of 21 m^2; the northern façade constitutes of 3.8 m^2 of openable window area, the eastern façade constitutes of 4.8 m^2, the western façade constitutes of 2.4 m^2, and the southern façade constitutes of the greatest glazing area of 10 m^2. All windows were considered openable for this study, however in some cases, some windows might be fixed; in which case, results might vary.

All windows were simultaneously simulated once as half open (50%) and once as fully open (100%) with different day and night schedules, in order to determine the impact of the total window opening area on cooling the indoor environment. A total of 28 simulations were performed as depicted in Table 8 for the daytime schedule and 12 simulations for the night-time schedule depicted in Table 9 below; the specified times were chosen randomly but related to the hours of the day where outdoor temperatures are highest. The simulations were carried out using the reference case as a starting point, with internal shadings set to be open during the night from 10 pm to 7 am and drawn during the day whenever solar radiation was intense and uncomfortable, representing a real-life occupant's scenario. Although some simulations were considered extreme and unrealistic, however, it was crucial for this study to investigate as many probable scenarios as possible to determine the applicability of opening windows.

Furthermore, another fundamental aspect to window opening which involved cross-ventilation was also investigated and used to complement the previous assessment. In order to create different schemes of draft patterns between rooms, several windows in different zones and different orientations were simulated simultaneously using labelled windows and their respective dimensions as in Figure 7. A total of 9 cases was simulated with a fixed number of open hours (8 hours) from 10:00 pm till 07:00 am (occupancy hours) and a percentage of 50% open window area as shown in Table 10.

Table 8: Windows opening schedules during daytime

Simulated Case Number	Windows opening schedule	Number of hours open	Number of windows open
Reference Case	-	-	-
1.0	Closed all day (worst case scenario / travel)		
1.1	11:00 am - 3:00 pm	4 hours	18
1.2	11:00 am – 4:00 pm	5 hours	18
1.3	11:00 am – 5:00 pm	6 hours	18
1.4	11:00 am – 6:00 pm	7 hours	18
1.5	11:00 am – 7:00 pm	8 hours	18
1.6	11:00 am – 8:00 pm	9 hours	18
1.7	11:00 am – 9:00 pm	10 hours	18
1.8	11:00 am – 10:00 pm	11 hours	18
1.9	11:00 am – 11:00 pm	12 hours	18
2.0	09:00 am – 11:00 pm	14 hours	18
2.1	07:00 am – 11:00 pm	16 hours	18
2.2	07:00 am – 12:00 am	17 hours	18
2.3	06:00 am – 12:00 am	18 hours	18
2.4	05:00 am – 12:00 am	19 hours	18

Table 9: Windows opening schedules during night-time

Simulated Case Number	Windows opening schedule	Number of hours open	Number of windows open
Reference Case	-	-	-
2.5	09:00 pm - 10:00 pm	1 hour	18
2.6	09:00 pm - 11:00 pm	2 hours	18
2.7	09:00 pm - 12:00 am	3 hours	18
2.8	09:00 pm - 01:00 am	4 hours	18
2.9	09:00 pm - 02:00 am	5 hours	18
3.0	09:00 pm - 03:00 am	6 hours	18

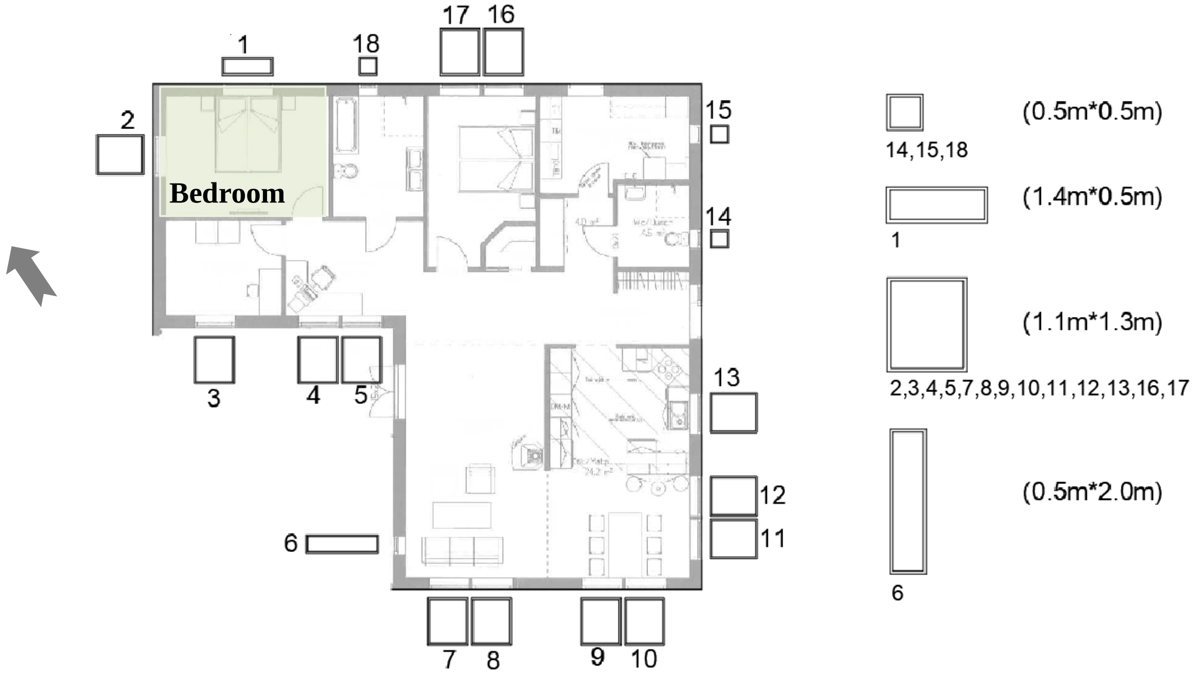


Figure 7: Existing windows' numbers and dimensions

Table 10: Cross-Ventilation simulations – Occupancy schedule 10pm-7am (half-open windows)

Simulated Case Number	Windows Open	Number of hours open
3.1	1 - 2	9 hours
3.2	1 – 2 – 4 - 5	9 hours
3.3	1 - 4	9 hours
3.4	2 – 11 - 12	9 hours
3.5	2 – 9 – 10	9 hours
3.6	2 - 5	9 hours
3.7	1 – 2 - 4	9 hours
3.8	1 – 2 – 7 -8	9 hours
3.9	1 – 2 – 13	9 hours
4.0	2	9 hours

4 Results

4.1 Data collection and analysis in selected dwellings

After the data was acquired, the relevant measurements were filtered for the year 2018, then the months of July and August, as well as for the bedrooms. Figure 8 below depicts the hourly recorded temperatures in the bedroom for one of the cases in Malmö during the analysis period (July, August) and the hours exceeding the 26 °C threshold applied in the analysis. The results evidently show prolonged hours of extremely high temperatures relative to the acceptable threshold. The longest duration recorded for this case lasted approximately from hour 529 till 837 (the end of July – beginning of august) which implies over 300 consecutive hours of temperatures above 26 °C.

The standards utilized in the analysis included the CIBSE standard, which demands that the assessment of overheating is restricted to the schedule of occupancy, in which an assumed sleeping schedule of 9 hours (between 10 pm and 7 am) was applied to acquire the number of hours where temperatures exceeded 26°C in bedrooms.

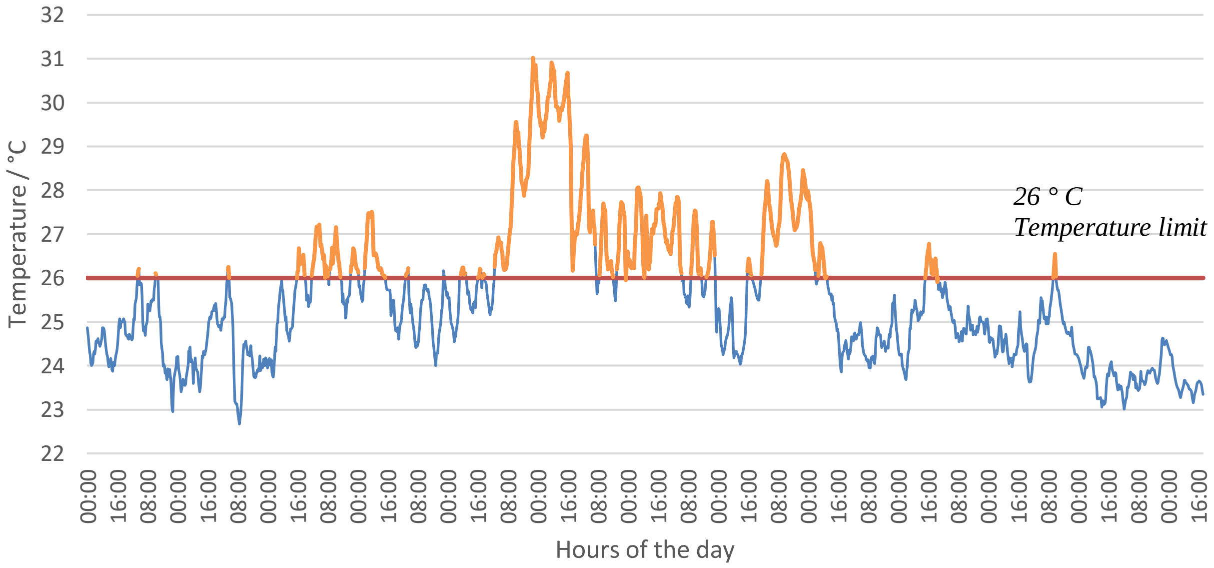


Figure 8: Hourly Recorded Indoor temperatures of an example case in Malmö for July-August

Figure 9 below represents the hours of the day for the duration of 48 hours for one of the cases in Jönköping during the analysis period, the highlighted occupied hours demonstrate the proposed schedule. According to CIBSE, overheating was defined when that number exceeded 32.8 hours, i.e., 1% of 3285 occupied hours/year. As for the FEBY standard, which accounts for overheating between the months of April-September, overheating was calculated for this period by summing the number of hours above 26° C and comparing it against the allowed threshold of 10% of the duration, which equals approximately 439.2 hours. In the National Board of Housing (Boverket) recommendation, once temperatures exceeded the 26° C threshold, overheating was determined.

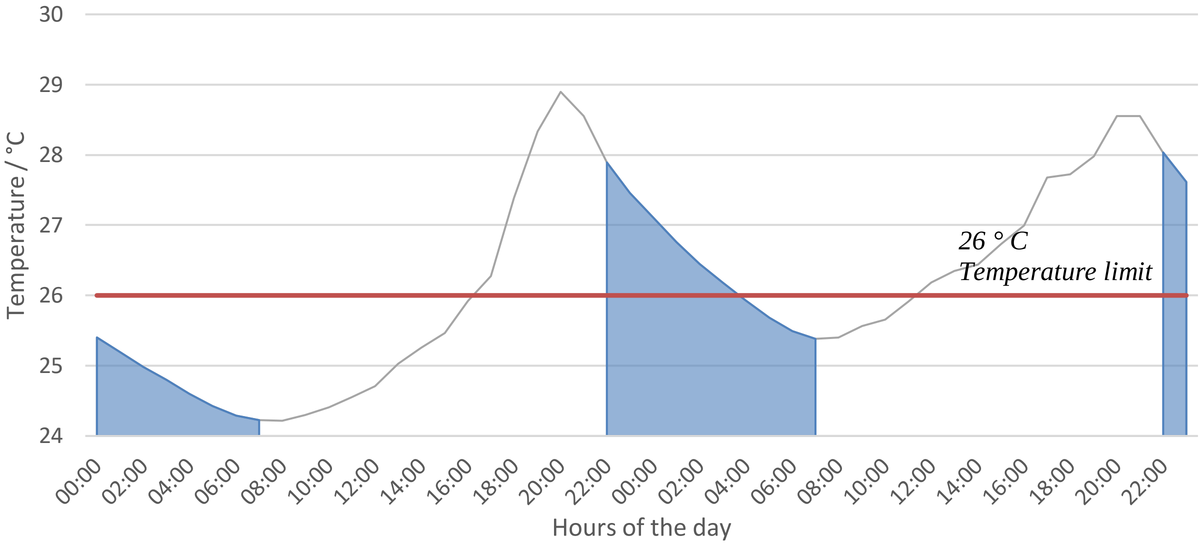


Figure 9: Hourly Recorded Indoor temperatures of an example case in Jönköping for a 48-hour period

4.1.1 Overheating assessment in CIBSE standards

Results from the analysis of the recorded indoor measurements of the bedrooms, based on the regulations set by CIBSE, revealed that for the first set of data, overheating occurred in almost 85% of the cases, with temperatures exceeding 26 °C for more than the 32 hours threshold, observed in Figure 10 below. Whereas for the second and third sets of data (Jönköping, Umeå), overheating was calculated in more than 25% and almost 30% of the cases respectively, shown in Figure 11 and Figure 12 below. The overall occurrence of overheating for all 3 data sets combined was also calculated in 46% of the cases, as shown in Figure 13 below.

It was noted that overheating was more evident in the first data set, specifically in Visby which recorded around 500 hours of temperatures above 26 °C whereas Stockholm recorded the second highest number of overheating hours of more than 450 hours and Malmö came third with almost 400 hours.

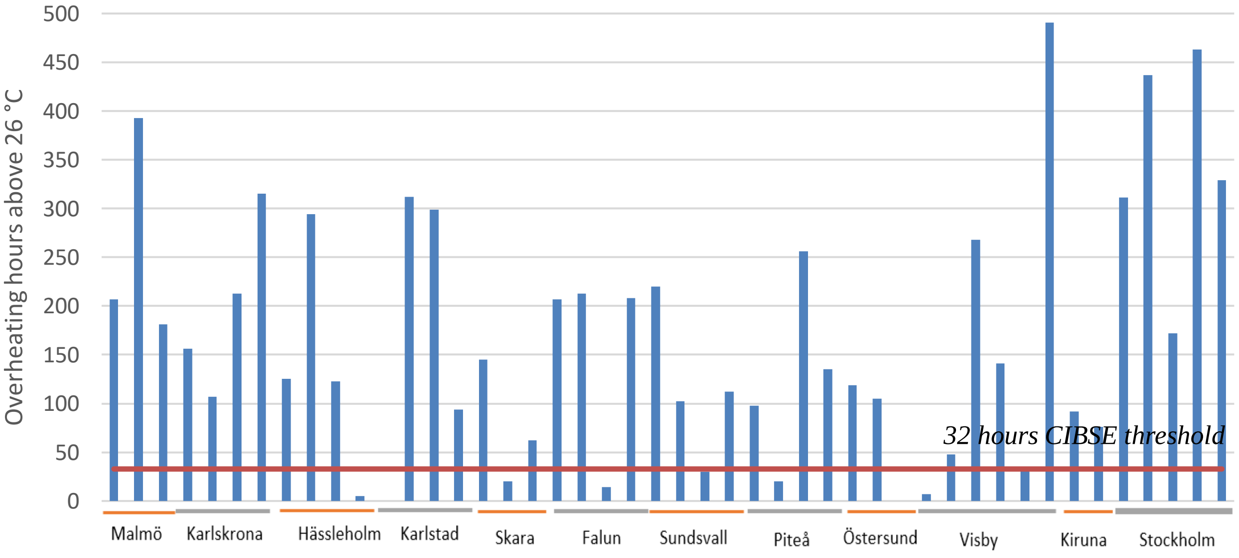


Figure 10: Overheating hours for the first data set (CIBSE)– Multiple locations

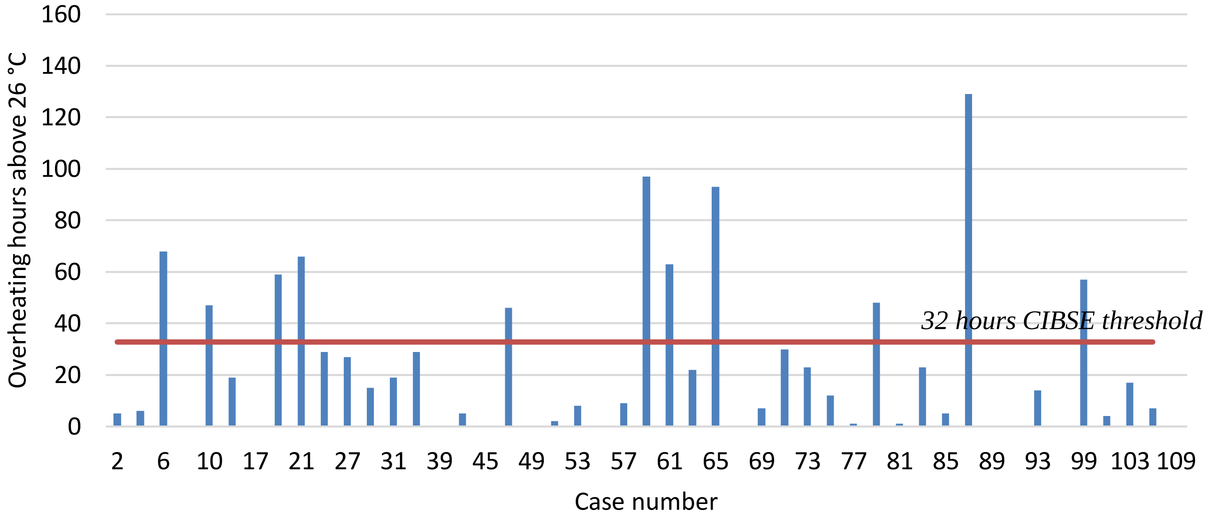


Figure 11: Overheating hours for the second data set (CIBSE) – Jönköping

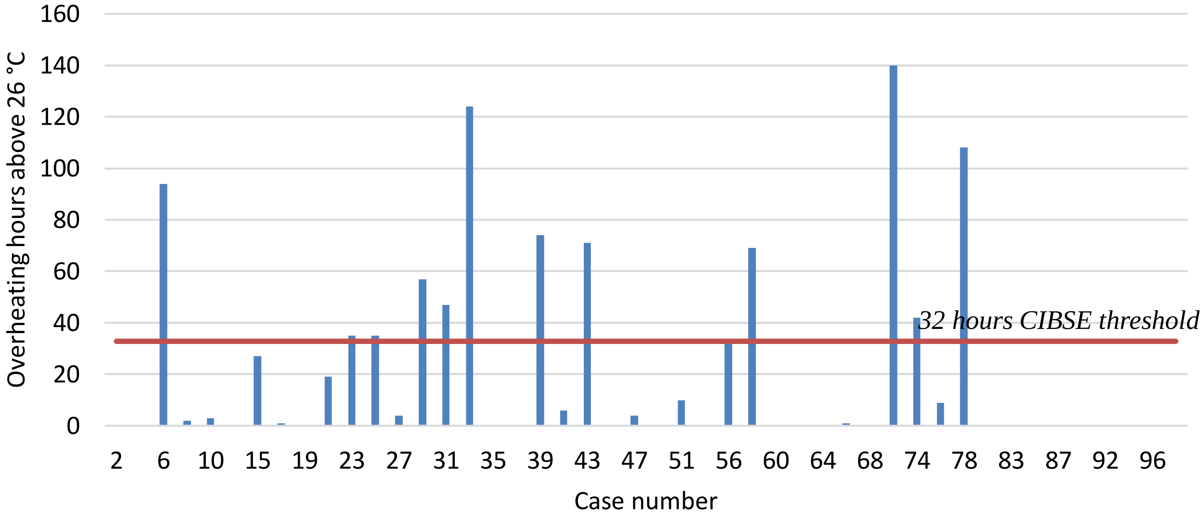


Figure 12: Overheating hours for the third data set (CIBSE)– Umeå

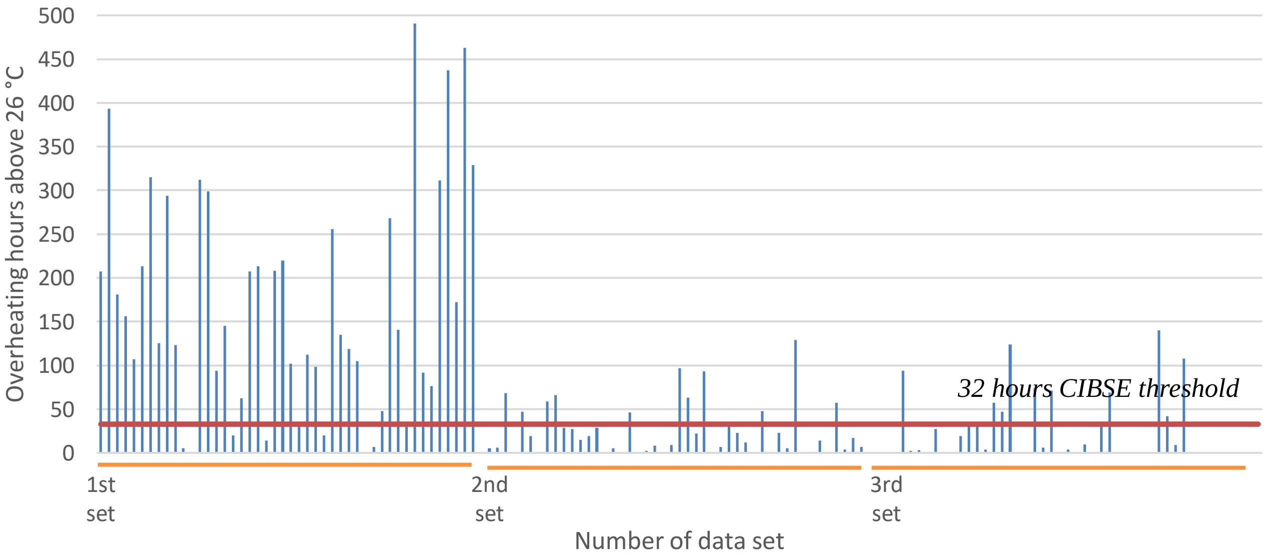


Figure 13: Overheating hours in all 150 dwellings according to (CIBSE) – 3 data sets

4.1.2 Overheating assessment in FEBY standards

According to the results of the analysis, 54% of overheating occurrences were calculated in the first set of data, no overheating occurrences in the second data set and only 2% for the third data set based on the 440 hour threshold specified by the FEBY standard, observed in Figure 14, Figure 15 and Figure 16 below. The occurrence of overheating hours for all 3 data sets combined was calculated to reach 18% of the 150 investigated dwellings, shown in Figure 17 below. This could suggest that the FEBY standard is probably more generous with the accepted number of overheating hours, allowing temperatures to exceed 26 °C for 440 hours during the period April-September.

The most overheating occurrences were also encountered in the same locations of the first data set as the CIBSE standard analysis, namely Stockholm, Visby, and Malmö.

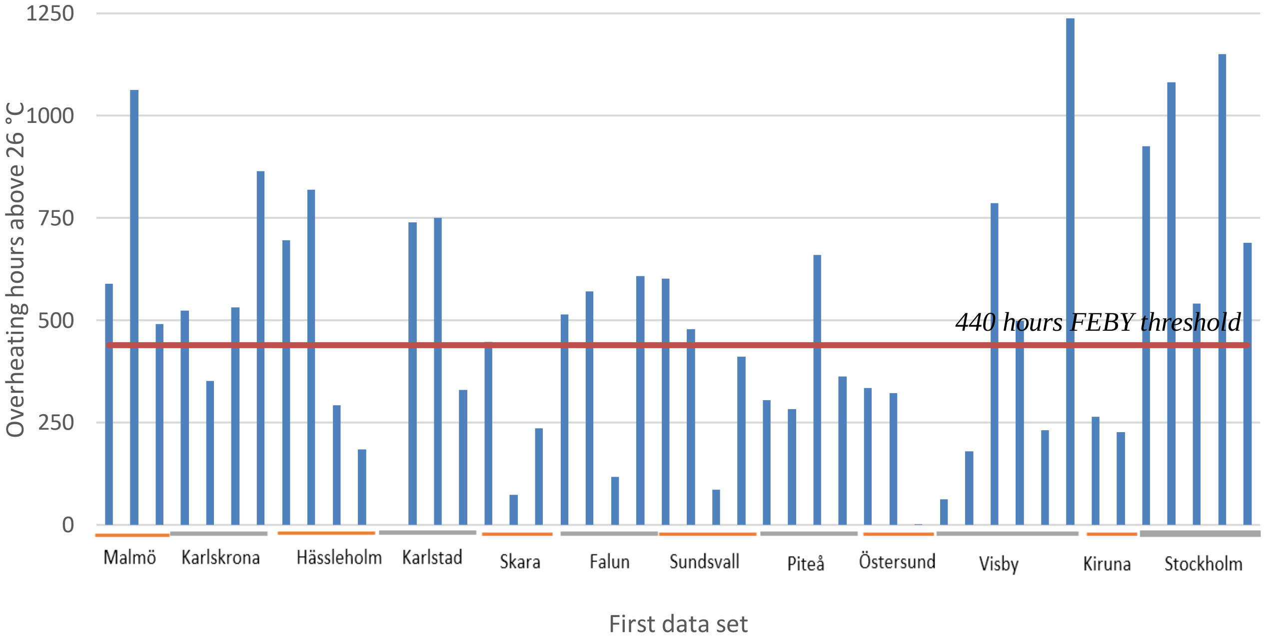


Figure 14: Overheating hours of the first set (FEBY) – Multiple locations

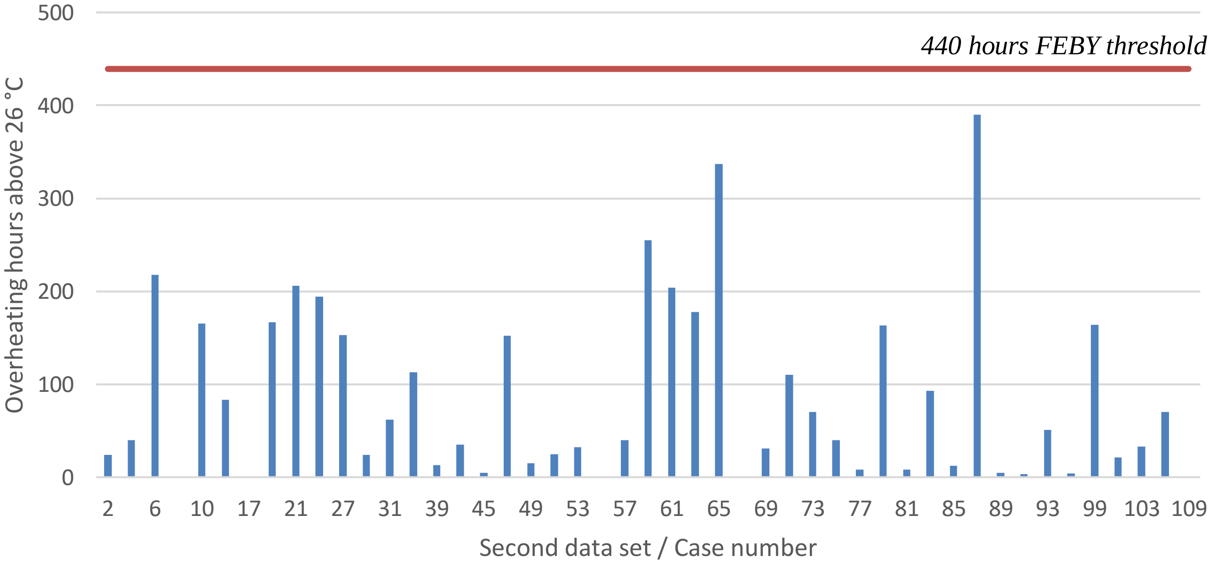


Figure 15: Overheating hours of the second set (FEBY) – Jönköping

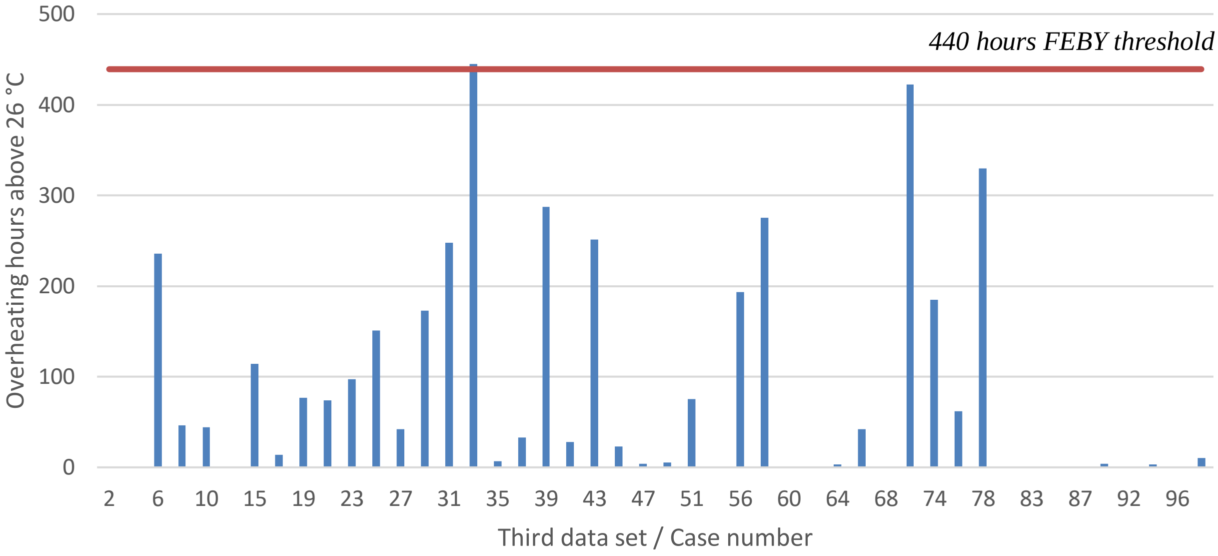


Figure 16: Overheating hours of the third set (FEBY) – Umeå

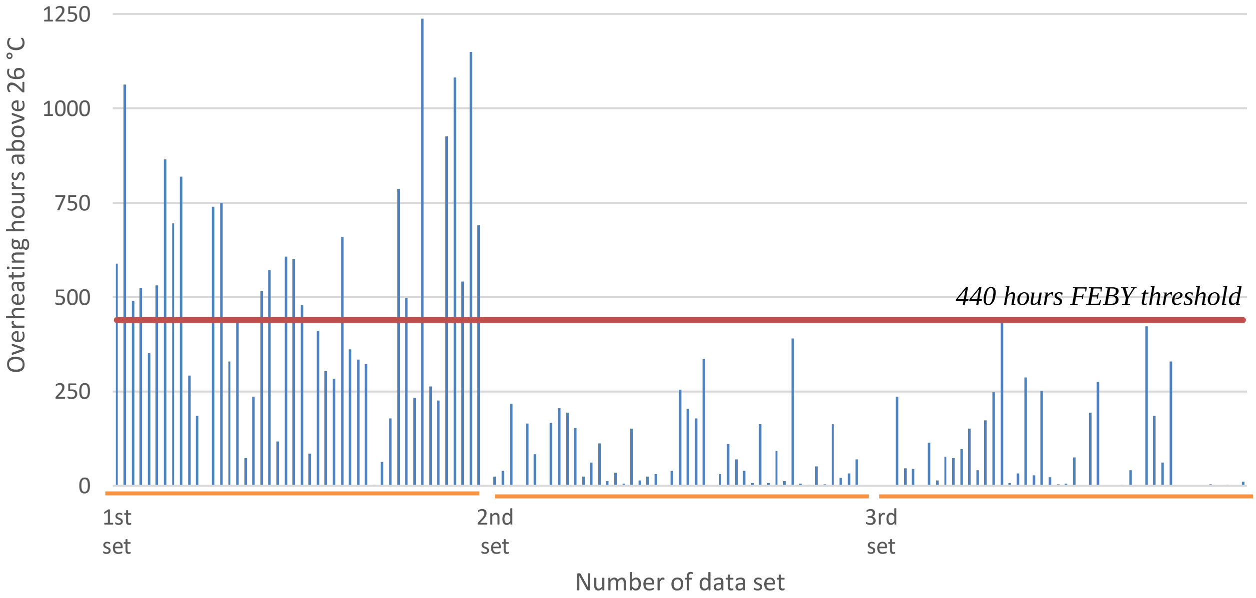


Figure 17: Overheating hours (FEBY) – 3 data sets

4.1.3 Overheating assessment in Boverket standards

It was evident that overheating was more apparent according to the Swedish National Board of Housing (Boverket) standards, which recommends a limit threshold of 26 °C. Overheating during July and August was calculated and the percentage of time where temperatures exceeded 26 °C was assessed thereafter. The results of the analysis indicated that for the first data set, overheating was detected in almost all cases, reaching more than 50% of the time in certain cases, as seen in Figure 18 below. As for the second and third data sets, overheating was also encountered in most cases, however with lower ratios, reaching a maximum of around 30% of the time during summertime for both cases, shown in Figure 19 and Figure 20 below.

Lower overheating occurrences were observed in most cases in the second and third data sets, in comparison to the considerably higher overheating occurrences observed in the first data set.

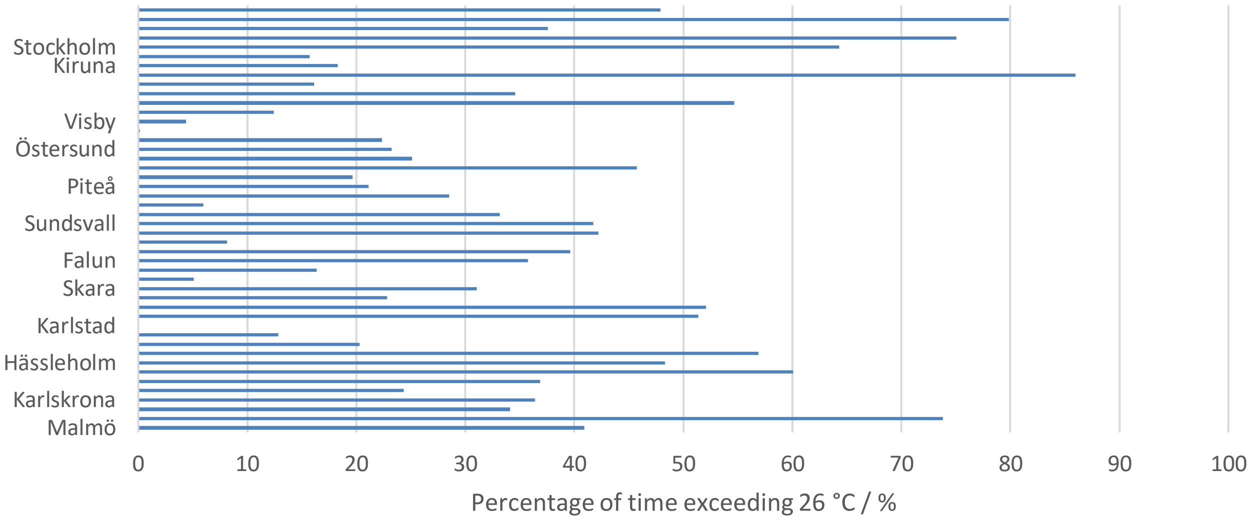


Figure 18 :Percentage of overheating in the first data set – Multiple locations

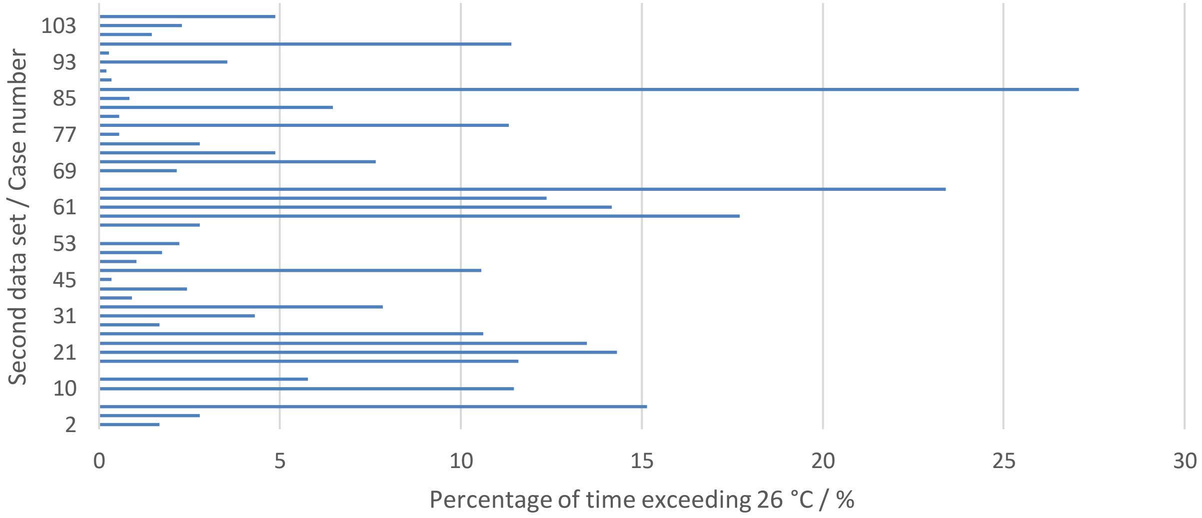


Figure 19 :Percentage of overheating in the second set – Jönköping

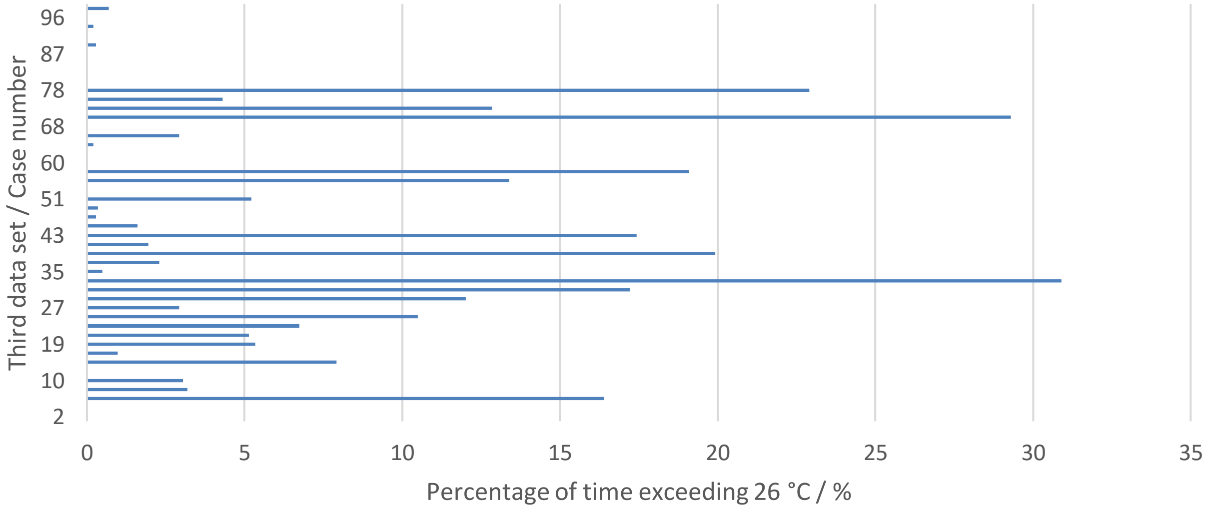


Figure 20: Percentage of overheating in the third set – Umeå

4.1.4 Overheating probability of occurrence

The results of the analysis revealed that for the first data set, 50% of the cases recorded an occurrence of more than 600 hours for temperatures above 26 °C, 300 hours above 28° C and 250 hours above 30 °C, seen in Figure 21 below. As for the second and third data sets, dwellings with recorded temperatures exceeding 26 °C were remarkably less, as seen in Figure 22 and Figure 23 below, whereas in the cases of exceeding 28 °C and 30 °C were lower by more than half, with 180 and 250 hours respectively above 26 °C, 50 hours above 28 °C and only 10 hours above 30 °C.

It was also observed from the results that dwellings in slightly overpopulated (or urbanized) locations, such as Stockholm and Malmö, resulted in a higher number of hours above 26 °C, indicated by the bumps in the distribution curve, and even for temperatures exceeding 28 °C and 30 °C, in the first data set. Similar to the first data set, a number of bumps in the curves for both dwellings located in the same area (Jönköping, Umeå) was apparent, which could indicate unknown factors contributing to an increase in overheating in these dwellings, such as location, orientation, or thermal mass.

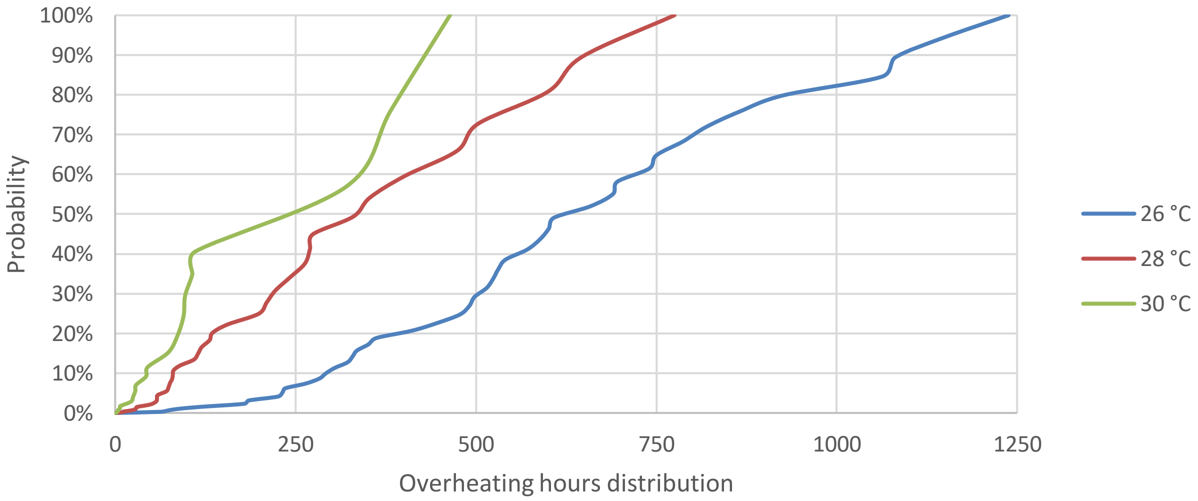


Figure 21: Probability of overheating occurrence for the first data set - Multiple

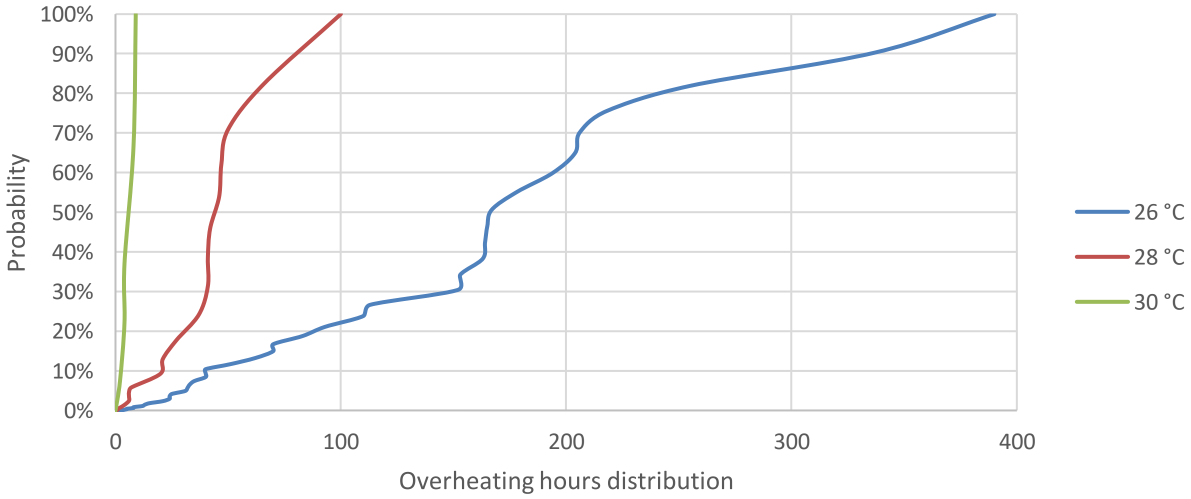


Figure 22: Probability of overheating occurrence for the first data set - Jönköping

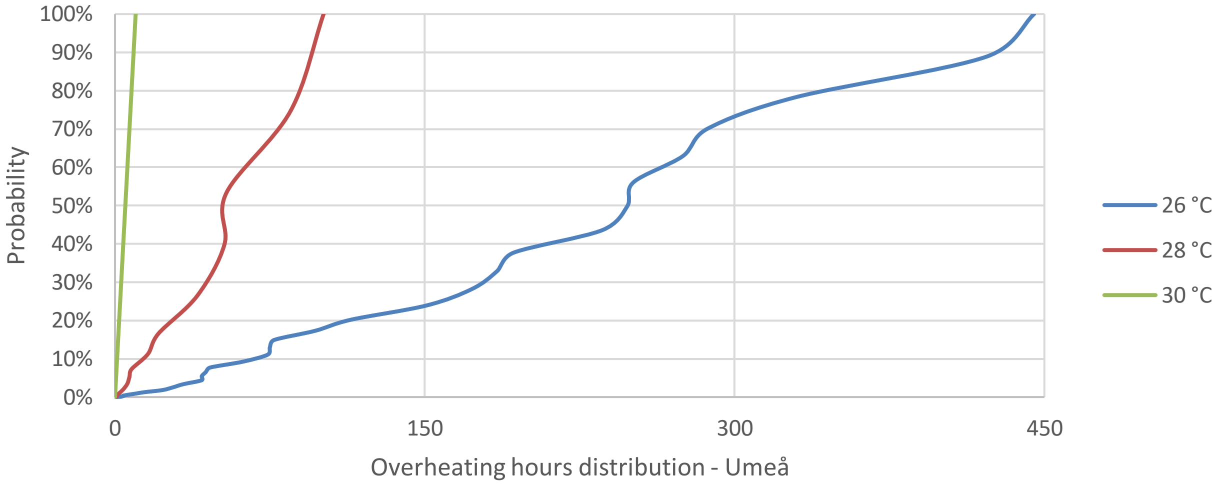


Figure 23: Probability of overheating occurrence for the first data set - Umeå

4.1.5 Duration of exposure to overheating

The results of the analysis revealed that a duration of more than 250 consecutive hours where temperatures exceeded 26 °C was reached in several cases, specifically in dwellings located in Stockholm, Malmö, and Visby, in the first data set, as observed in Figure 24 below. Results from the second data set were however significantly lower, reaching a maximum of almost 150 consecutive hours in several cases, as seen in Figure 25. The results from the third data set barely exceeded 100 consecutive hours except for one single case that reached 250 hours, as shown in Figure 26 below. However, these occurrences were not mutual for all dwellings and locations as it was difficult to attribute under which time and date, they took place.

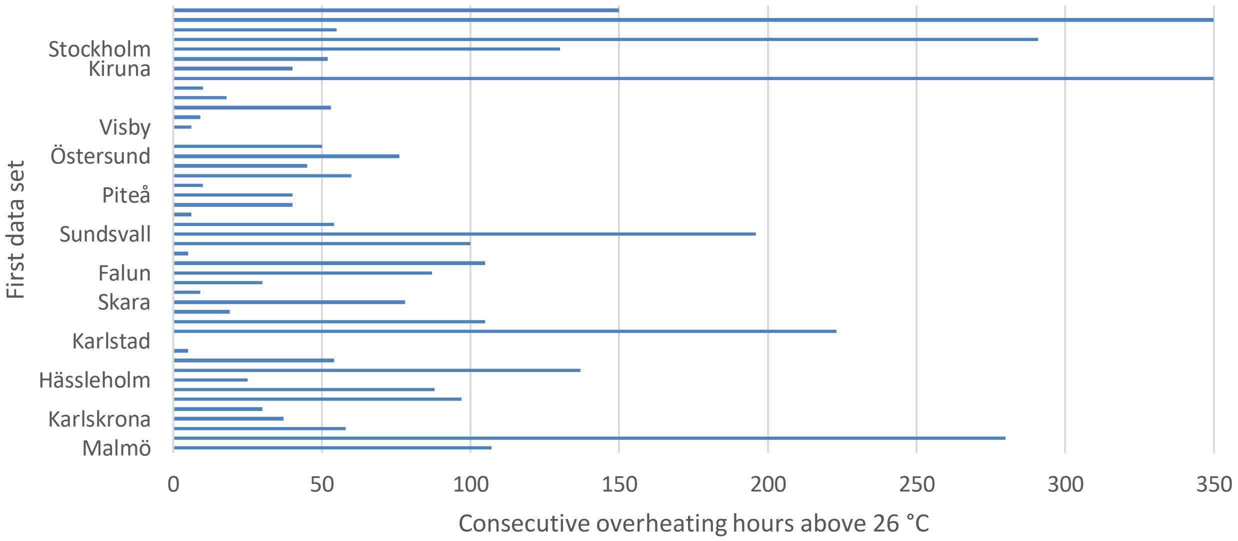


Figure 24: Consecutive overheating hours above 26 °C in the first data set – Multiple locations

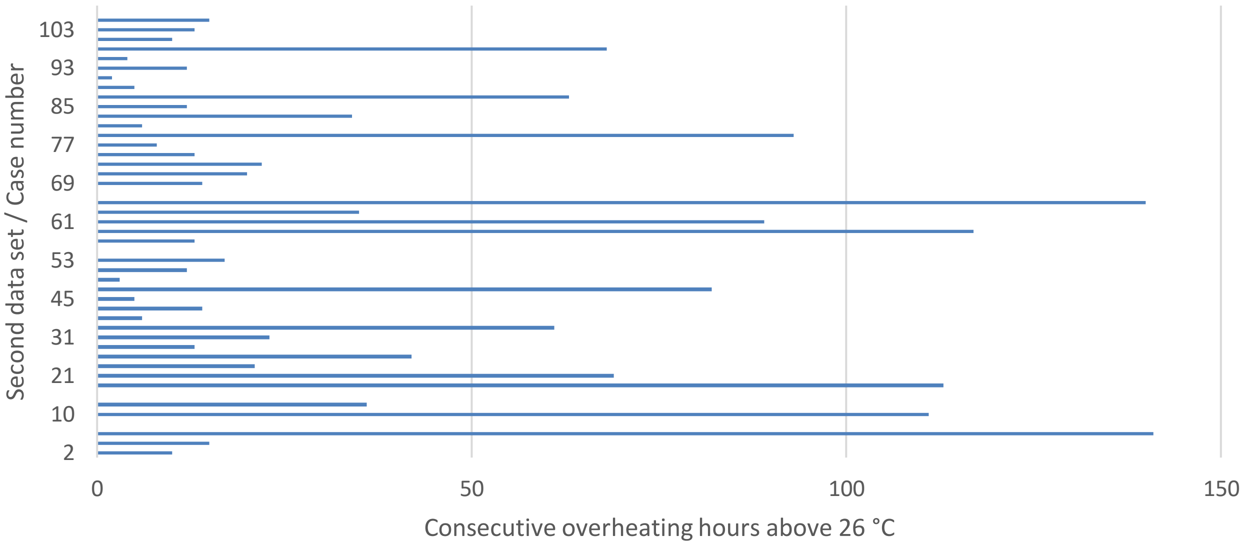


Figure 25: Consecutive overheating hours above 26 °C in the second data set - Jönköping

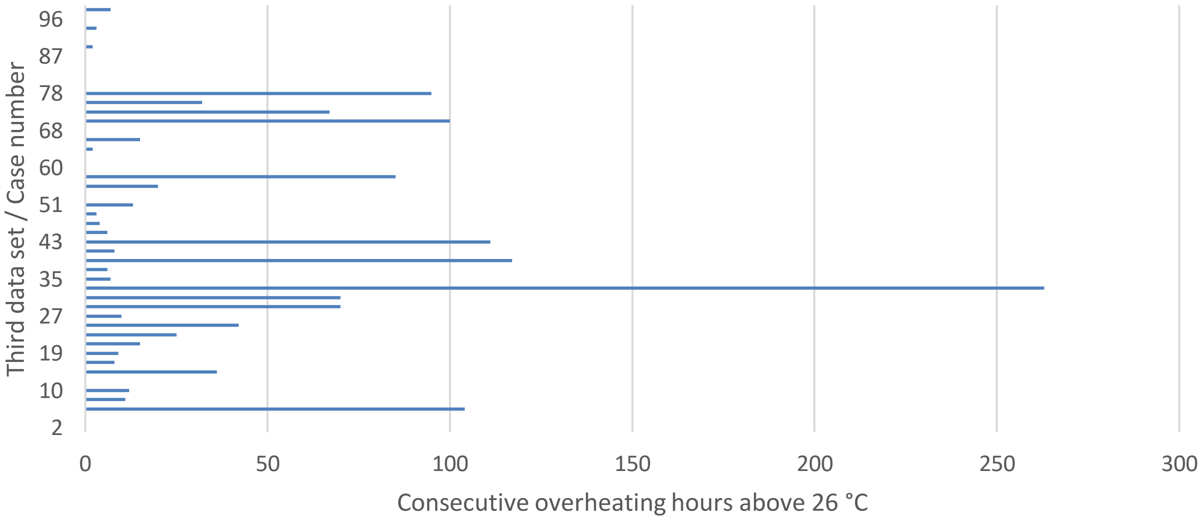


Figure 26: Consecutive overheating hours above 26 °C in the third data set - Umeå

4.1.6 The relationship between indoor and outdoor temperatures

Results of the analysis concluded that, for the first data set, outdoor temperature clearly had an impact on the indoor temperature, as indicated by the occurrence of increased recorded indoor temperatures as outdoor temperatures were elevated. When outdoor temperatures start to increase above 18 °C, a linear increase of indoor temperature takes place in correlation to the outdoor temperature, reaching a temperature as high as 30 °C indoors and a maximum temperature of approximately 27 °C outdoor, as observed in Figure 27.

According to the results of the other two data sets, shown in Figure 28 and Figure 29 below, this correlation was not as clear, as only average daily temperatures were considered and the fluctuations between extreme temperatures during daytime and night-time were contributing to this effect. Indoor temperatures were observed to exceed 28 °C in several cases, while outdoor temperatures were considerably lower.

It is worth noting that in the first data set, higher indoor temperatures were reached in accordance with consequent increased outdoor temperatures than in the other data sets, reaching a maximum indoor temperature of almost 35 °C, whereas in the other data sets, the maximum temperature was recorded at 29 °C indoors.

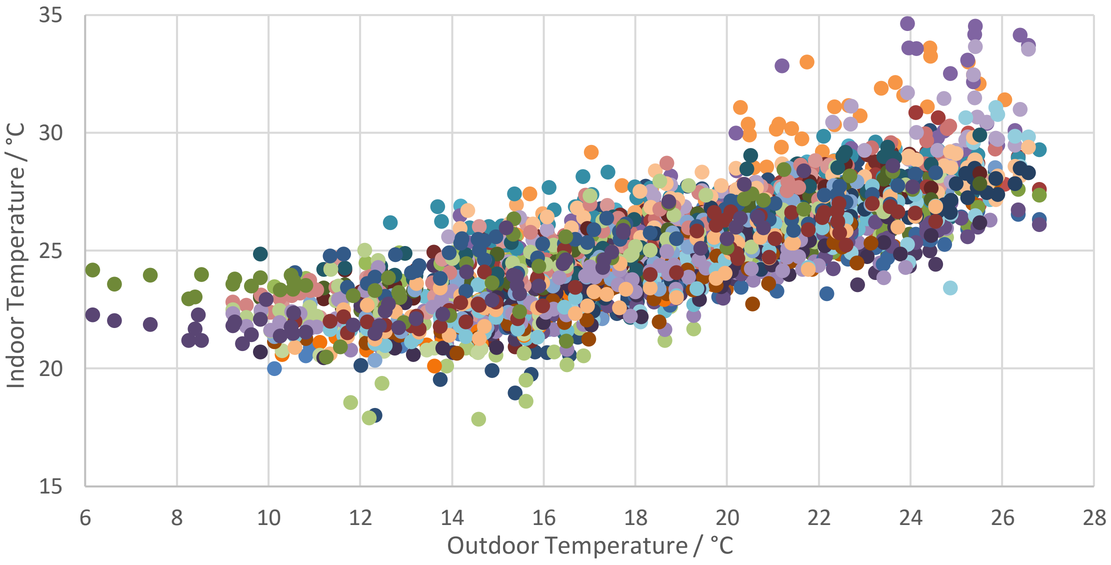


Figure 27: Temperature Scatter Plot of the First set – Multiple locations

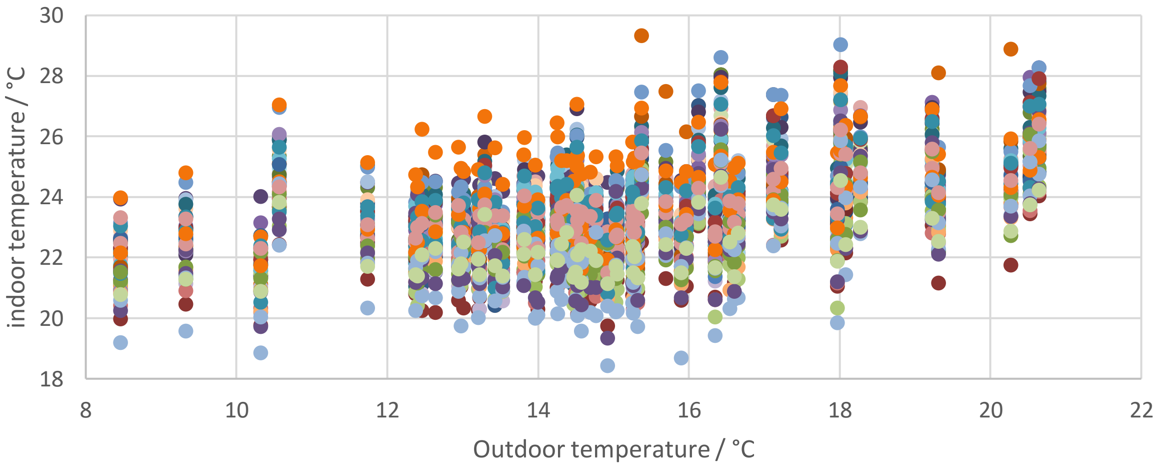


Figure 28: Temperature Scatter Plot of the Second set - Jönköping

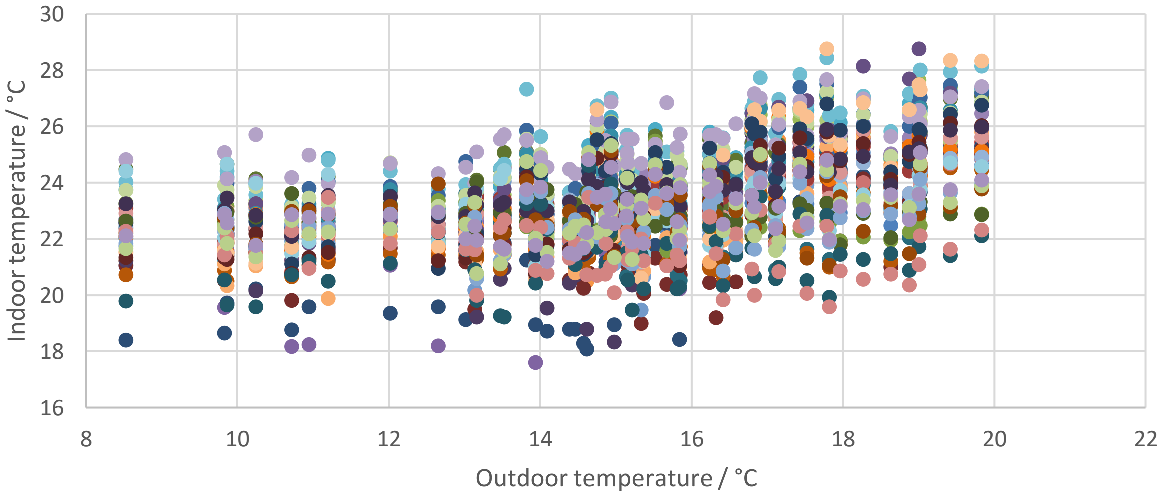


Figure 29: Temperature Scatter Plot of the third set - Umeå

4.1.7 Indoor temperature/relative humidity correlation analysis

The results from the analysis of the recorded average daily indoor temperatures and relative humidity for the 2 months period, indicated that the risk of exceeding the limit temperature of 26 °C at a relative humidity higher than 60% was minimal. In the case of the first data set of 50 dwellings, the occurrence of such conditions was noticed exactly 7 times, which is measured at less than 1%, observed in the upper quadrant of Figure 30 below. In the second and third data sets, relative humidity was observed to reach over 60% in several instances, however no noted occurrence of it coupled with the limit temperature was detected, as seen in Figure 31 and Figure 32 below.

The indoor relative humidity in the first data set was noted to reach higher levels than the other data sets, with instances between 65 and 75%. These numbers were not reached in the second and third data sets, where a maximum of below 65% relative humidity indoors was reached, the reason for this phenomenon is unclear and could perhaps be attributed to the behaviour and activity of the occupants.

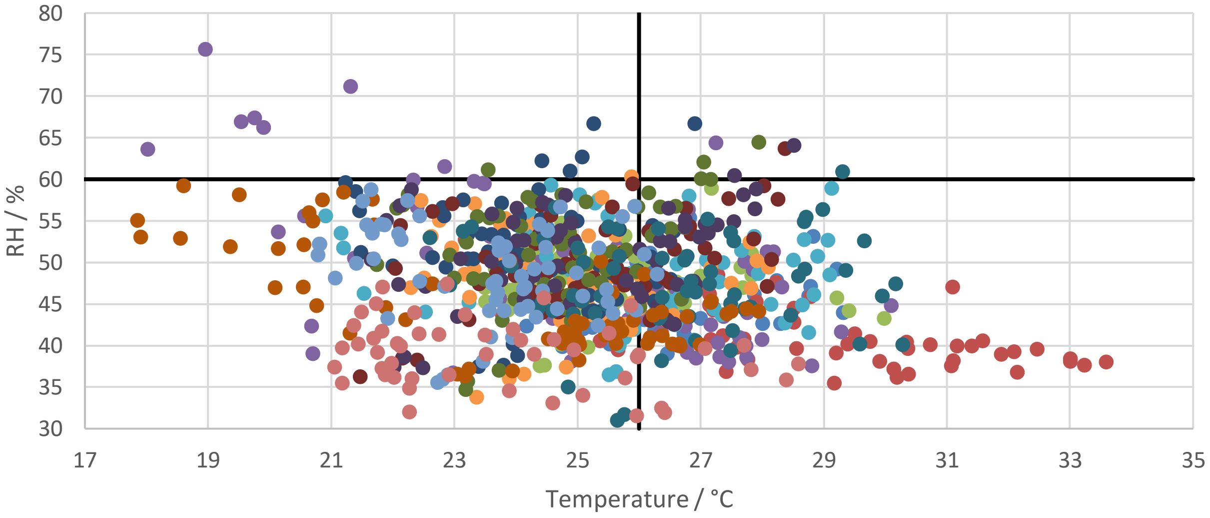


Figure 30:Scatter Plot RH/Indoor temperature of the first set - Multiple locations

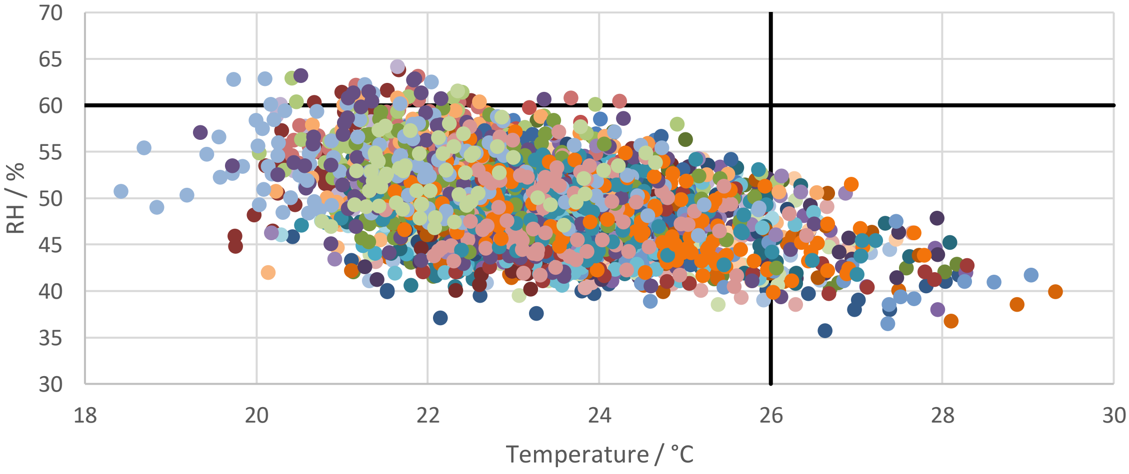


Figure 31: Scatter Plot RH/Indoor temperature of the second set - Jönköping

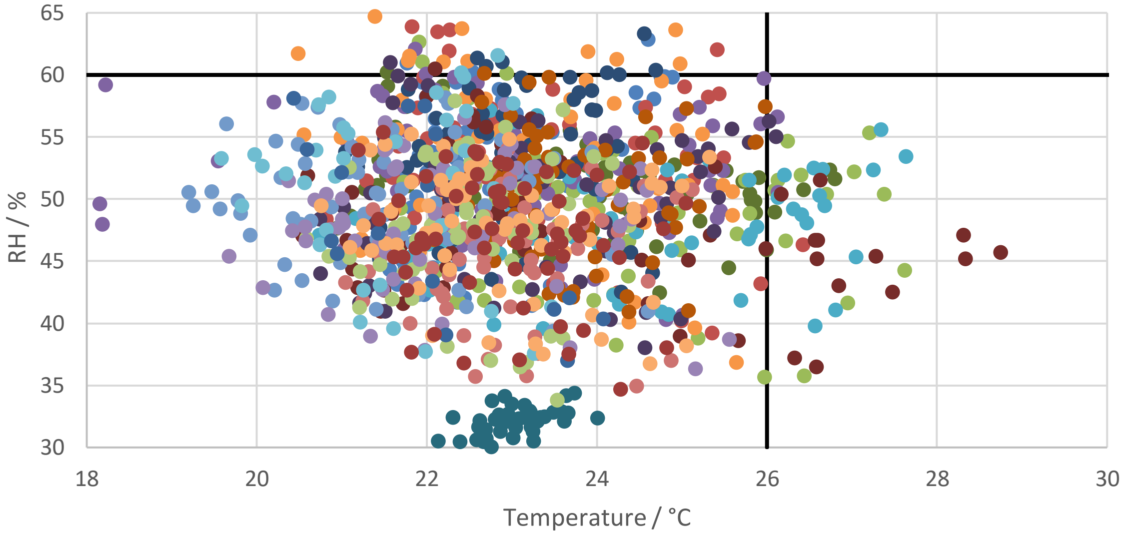


Figure 32: Scatter Plot RH/Indoor temperature of the third set - Umeå

4.2 Sundsvall case study

4.2.1 Base case simulation (Reference Case)

For the purpose of evaluating mitigation measures to overcome overheating, a simulated base case was calibrated with the recorded measurements in the bedroom of a study case in Sundsvall. The reference case was not meant to show the precise occupants' behaviour but rather an attempt to match the measured data. However, after simulating a close match to the measurements, seen in Figure 33 below, it was safe to assume that windows were half-open for prolonged periods during the day, specifically for approximately 11 hours (7:00 am - 6:00 pm), and internal shadings were often closed to protect from solar heat gains. Any possibility of using electrical cooling methods during measurements was disregarded. Nonetheless, even with the consideration of the mentioned strategies, the bedroom still failed to comply with the guidelines regarded in this study. Temperatures recorded much higher values than the recommended 26 °C by Boverket and exceeded the threshold by 600 hours and by 160 hours according to FEBY as well as exceeding CIBSE’s threshold by 188 hours between 10:00 pm and 07:00 am. Therefore, it was crucial to incorporate different strategies that could further decrease overheating to acceptable and safe thresholds.

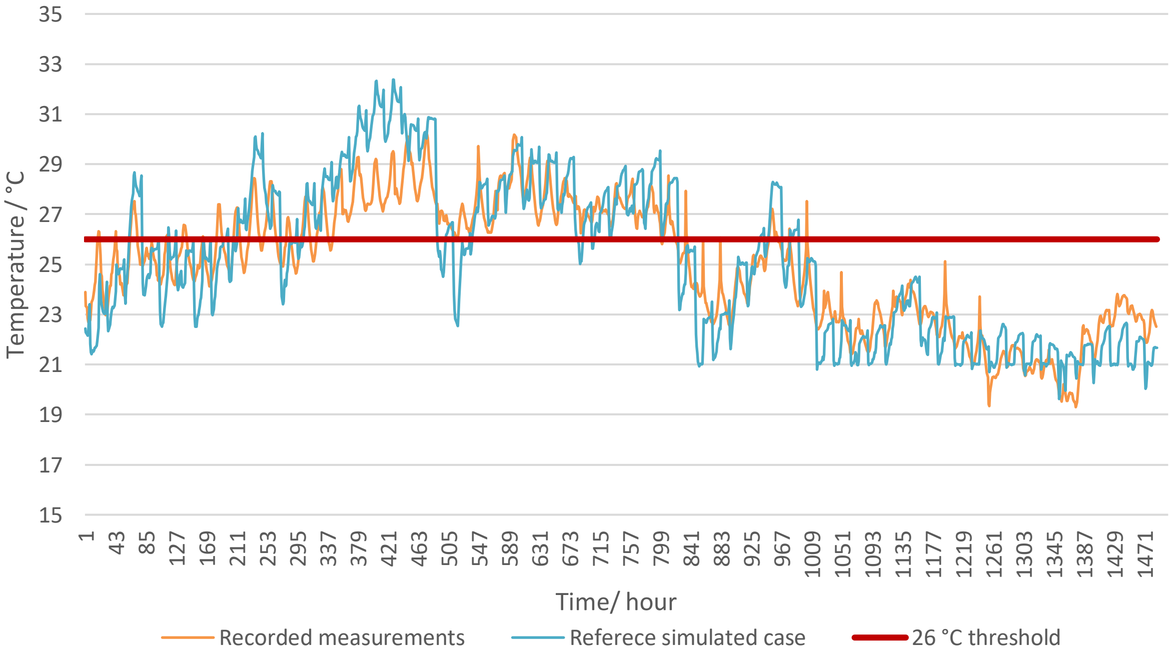


Figure 33: Simulated temperature measurements versus recorded temperature measurements

4.2.2 Integration of passive cooling measures

4.2.2.1 Passive Cooling Strategy 1: Internal Shadings

Internal shading simulation results were compared against the 3 overheating thresholds used in this study. As seen in Figure 34 (CIBSE criteria) and Figure 35 (FEBY and Boverket criterion), none of the attempted interventions using internal shading variations could reduce overheating hours to comply with any of the 3-criterion. The impact that internal shading had on overheating varied slightly between the different alternatives but did not reach acceptable overheating thresholds in any case. However, the method that resulted in the least number of overheating hours amongst the simulated cases was in case 1.1 (blue), according to both standards, during which curtains were fully closed (0% opening percentage) applied in all rooms and scheduled during the day between 07:00 am and 6:00 pm.

Applying internal shading to the investigated room versus applying shading simultaneously to all windows of the house as in case 1.2 did not have a noticeable difference in overheating hours. In case 1.3, alternating between curtains located at inner panes versus those located in-between panes had almost the same effect on overheating hours. Moreover, a comparison between different textile properties as in case 1.4 where the g multiplier varied yielded better results with a smaller value implying that textile choice could potentially play a role in the behaviour of internal shading against overheating. In case 1.5, where internal shading was completely removed, overheating hours were the highest, however the number of hours did not significantly exceed the cases where shading was involved. Therefore, internal shading was deemed to be a method used to control uncomfortable direct solar radiation but not an effective measure to control overheating and should rather be incorporated with other interventional measures to reduce the impact of overheating in the indoor environment.

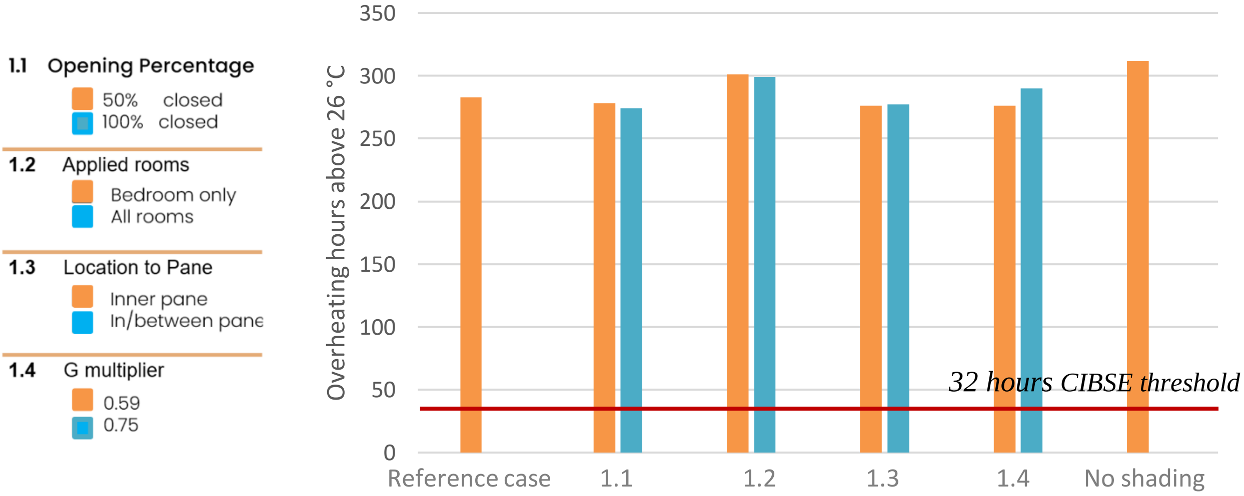


Figure 34: Simulation results for Internal shading interventions – according to CIBSE

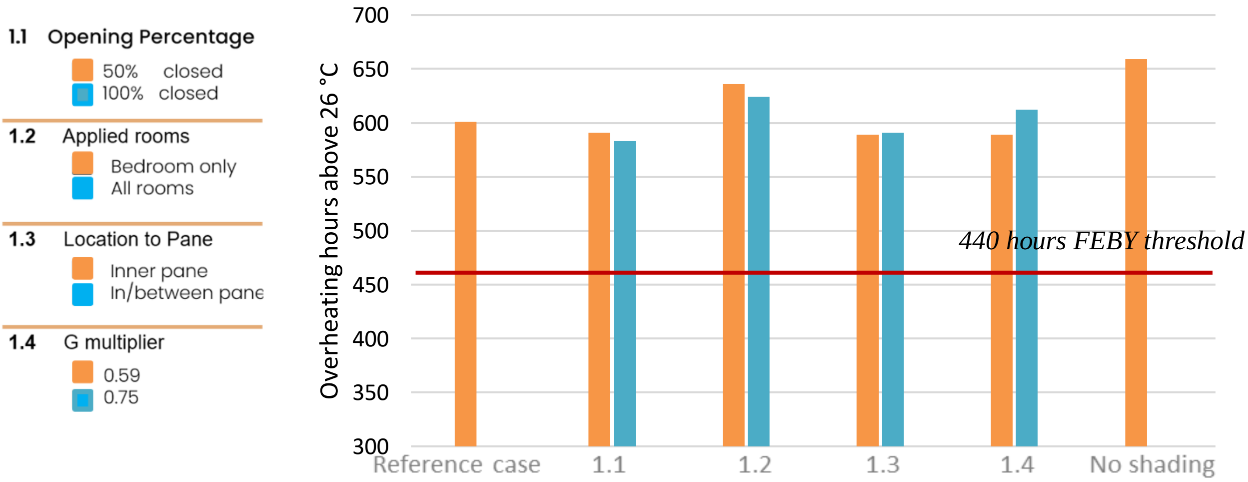


Figure 35: Simulation results for Internal shading interventions – according to FEBY

4.2.2.2 Passive Cooling Strategy 2: External Shadings

The resulting outcome of the simulations for the two external shading systems (drop-arm awning and roller screen) had almost similar results, as shown in Figure 36 and Figure 37 below according to the CIBSE and FEBY criterion. None of the cases in both external shading systems have succeeded to comply with the CIBSE threshold of 32 hours which allows overheating to exceed 26 °C for only 1% of the annual occupied time. However, according to FEBY, which allows overheating for 10% of the period between April and September, cases 1.4 (orange) where external roller shades were fully shut and case 1.6 (purple) where external roller shades where used from 7 am to 10 pm, have resulted in overheating hours below FEBY's threshold of 440 hours. Hence, in this comparison, external roller shades have outperformed the drop-arm awning system in two cases.

For the drop-arm awning system, case 1.1, where variable reflectance of the textile was used, the results were very similar, hence textile reflectance was deemed insignificant to overheating. In case 1.2, where external shading was placed at different orientations, the southern windows seemed to benefit more than eastern and western oriented shadings, however applying external shading to all façade orientations gave the optimal outcome in this case. Lastly, varying the time of the day the shadings were used resulted in a reduction in overheating hours during the duration between 1 pm to 6 pm versus the duration between 7 am to 1 pm, and the best outcome was reached when shading was used for the entire day between 7 am to 10 pm as seen in case 1.3 (purple) in the drop-arm awning figures.

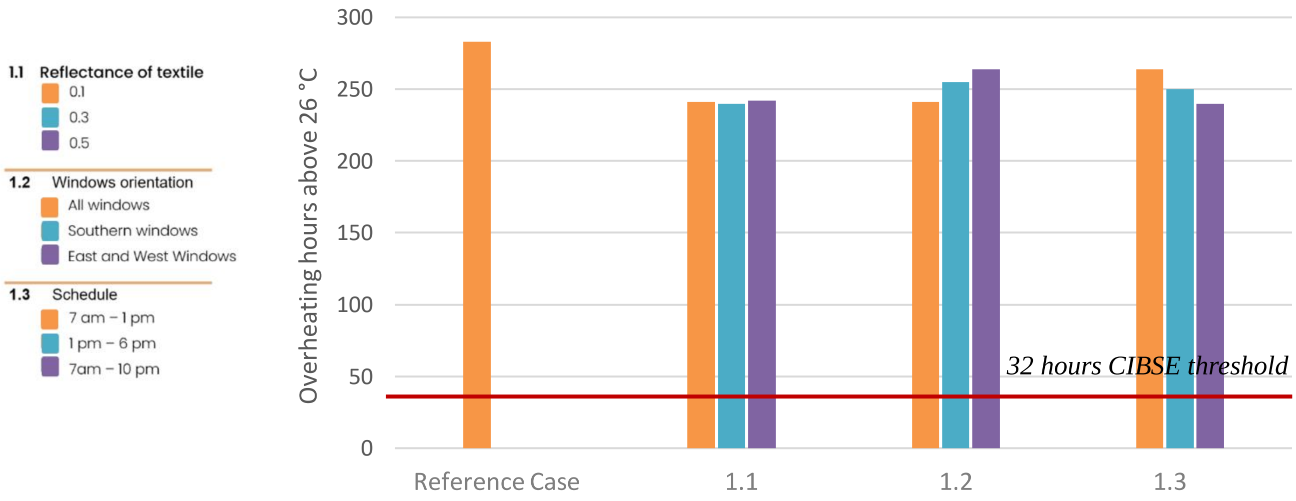


Figure 36: Drop-Arm Awning Simulations – CIBSE criteria

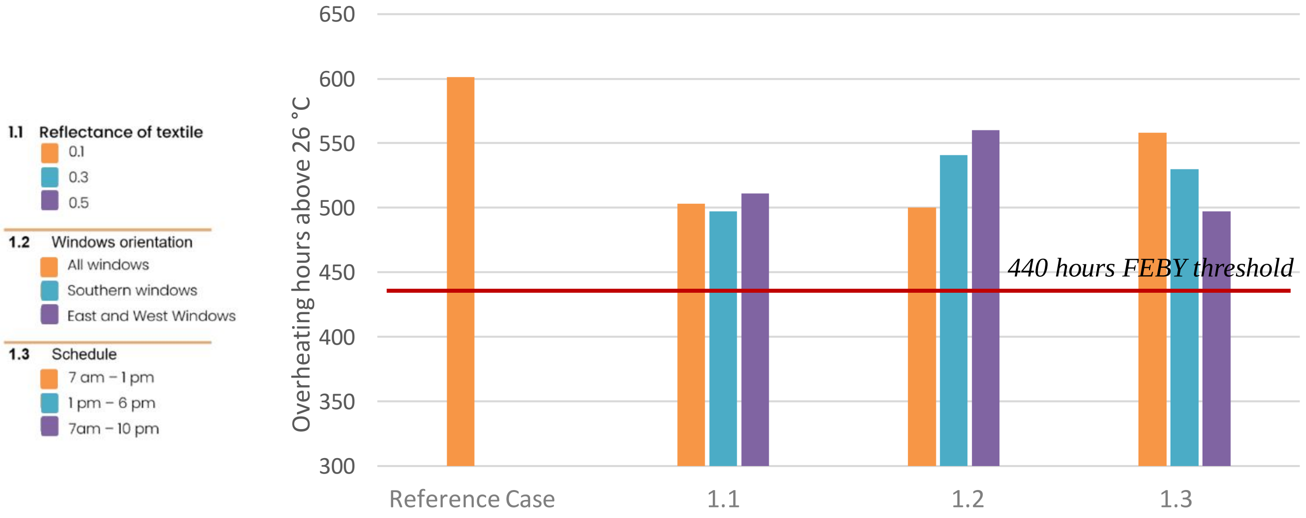


Figure 37: Drop-Arm Awning Simulations – FEBY criteria

On the other hand, external roller shades resulted in lower overheating hours in almost all cases when compared to drop-arm awning system. The best performing alternative was using the roller shades fully shut as in case 1.4 (orange). In a similar behaviour to the drop-arm awning, applying the shading to the southern oriented windows yielded better results than using shading on eastern or western facades, whereas applying shading to all orientations did give the best result amongst all alternatives. Moreover, using the shading for the entire day between 7 am and 10 pm proved to be very effective in reducing overheating hours even to values below the threshold of FEBY. Lastly, a gap distance ranging between 0.03 m and 0.15 m between the shades and the glazing was also tested, however gave no distinct results.

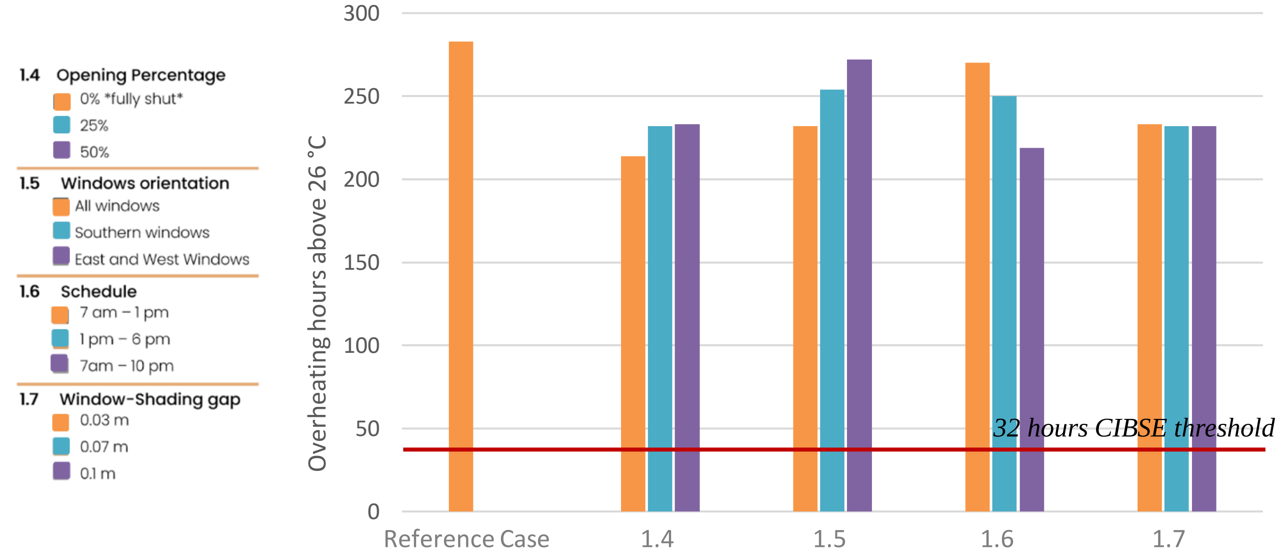


Figure 38: External roller shades simulations - CIBSE criteria

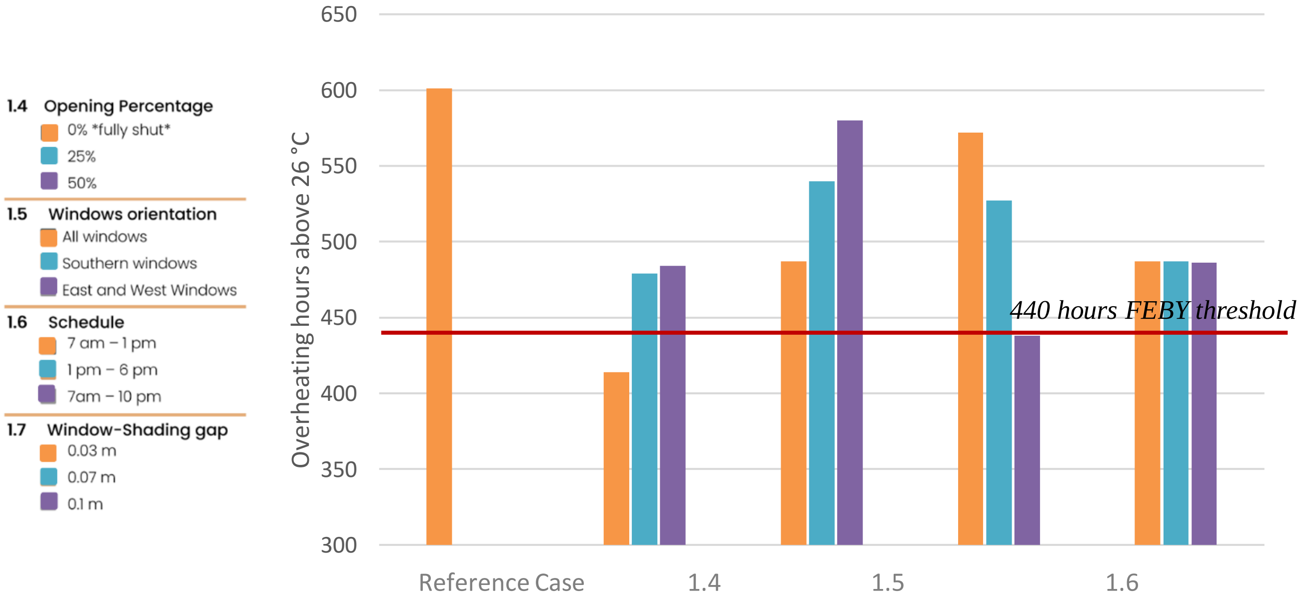


Figure 39: External roller shades simulations – FEBY criteria

4.2.2.3 Passive Cooling Strategy 3: Solar heat gain coefficient

The results of replacing the current glazing which was assumed to have a g-value of 0.68, as a typical value in windows of energy-efficient houses, gave promising outcomes in windows with lower g-values which was in fact anticipated as solar radiation plays an undeniable role in intensifying indoor overheating and any addition of solar control could benefit and improve thermal comfort during summer periods as shown in the figures below. However, lower g-values are definitely not a reliable factor on their own and even the lowest values could not meet the CIBSE threshold in any of the simulated cases as seen in Figure 40, however for cases with a g-value between 0.2 and 0.3 overheating was successfully mitigated according to the threshold set by FEBY for summertime occupancy as seen in Figure 41. However, very low g-values are not preferable in residential dwellings as it drastically decreases the thermal heat transmitted through the window increasing heating loads during cooler winter seasons which goes against energy efficiency efforts. Therefore, a g-value between 0.4 and 0.5 would be best to incorporate with other measures to mitigate overheating.

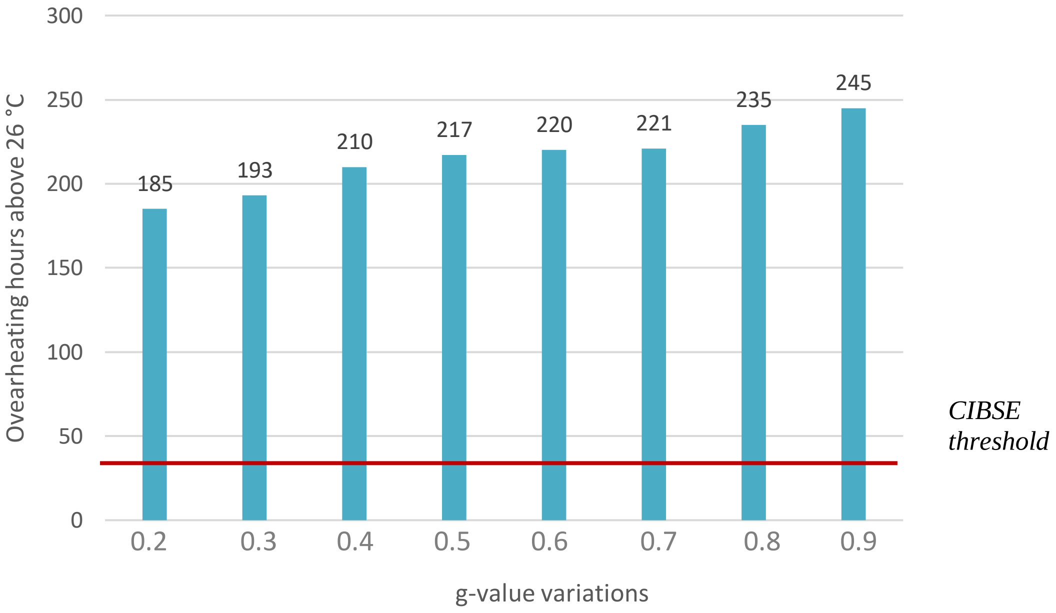


Figure 40: Simulating g-value variations - CIBSE criteria

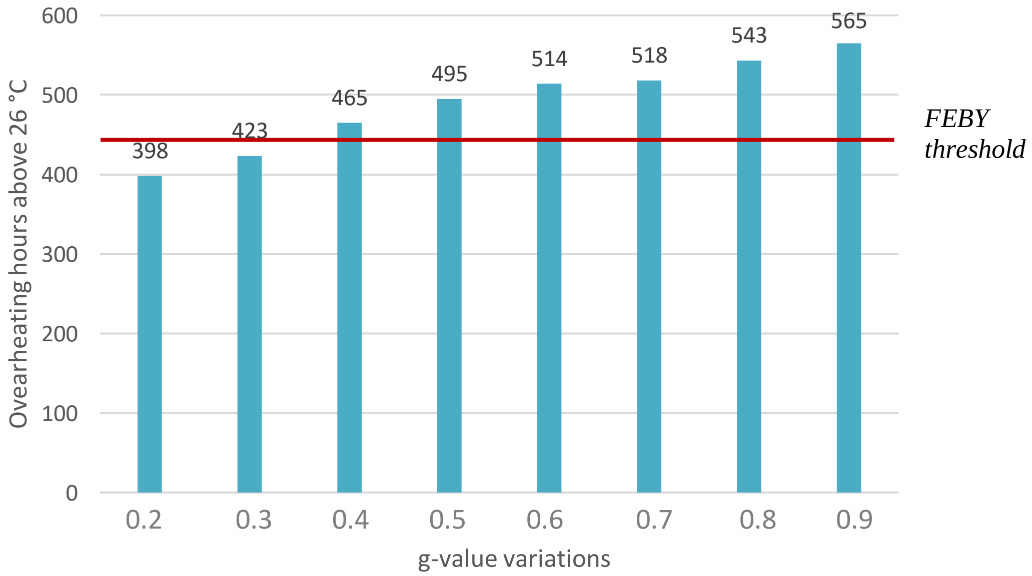


Figure 41: Simulating g-value variations - FEBY criteria

4.2.2.4 Passive Cooling Strategy 4: Opening of windows

The assessment of various window opening scenarios granted overall positive results in terms of meeting overheating requirements and thresholds regarding all standards used in this study. It was observed that prolonged window opening can remove overheating completely in some cases which complies with the Boverket recommendations. Hence, natural ventilation was considered the most effective and successful amongst all four passive cooling measures.

The reference case, as described in 3.2.2, was used as the starting point for the simulations. All 18 windows were tested simultaneously as half-open (50%) and then as fully open (100%) during both day and night opening schedules. The first part of the simulations was carried out during the day starting with the first case where windows were open for 4 consecutive hours during the day and the duration was then increased by 1 hour or 2 hours until the results became compliant with the suggestions of Boverket, CIBSE and FEBY as observed in Figure 42 and Figure 43.

Illustrated in Figure 42 below, the number of overheating hours significantly decreased as the schedule of opening windows increased by the hour. However, only extended periods of opening hours which are particularly above 19 hours during daytime with partially open windows (50%) showed results below the CIBSE threshold of which states a limit of 32 hours of overheating above 26 °C during the occupied period between 10 pm and 7 am. In the cases where windows were fully open (100%), an acceptable level of overheating was reached for a duration of 17 consecutive opening hours.

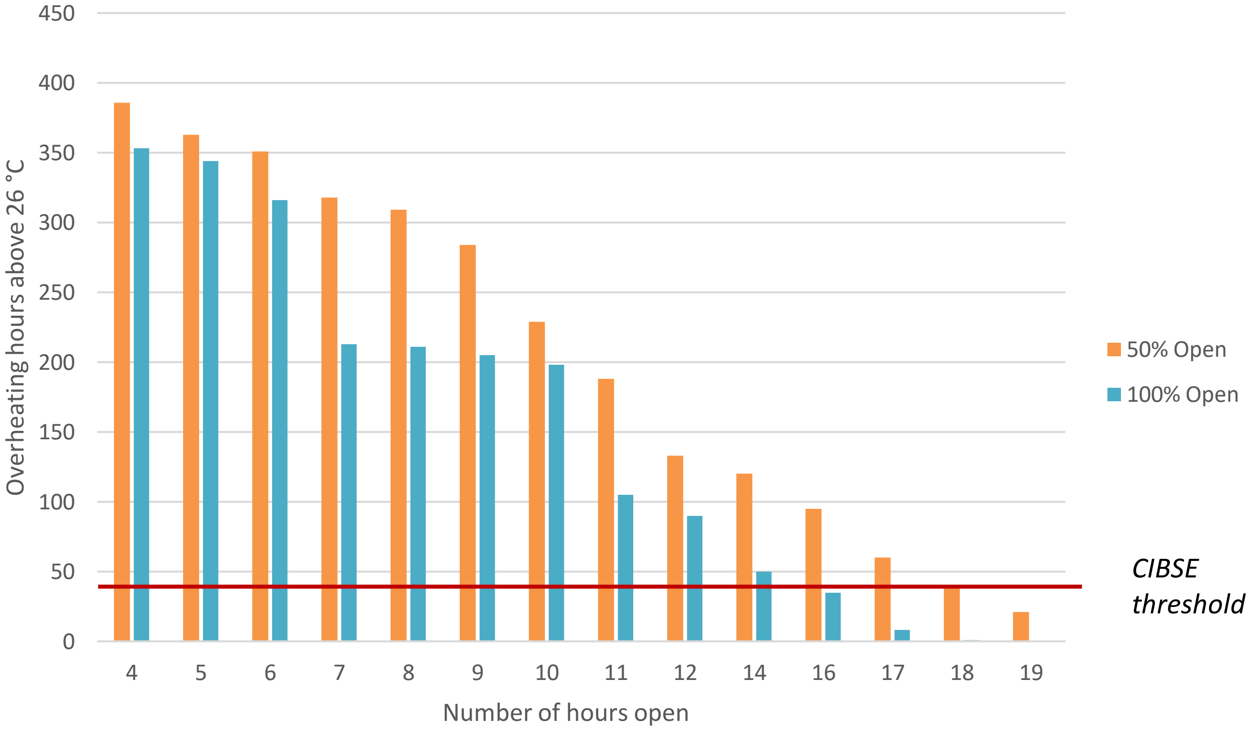


Figure 42: Impact of opening windows duration on number of overheating hours, half open vs. fully open during daytime schedules / CIBSE criteria

On the other hand, FEBY's criteria which allows overheating to reach a maximum of 440 hours during the period between April and September, resulted in more cases being satisfactory and compliant with the standard. As observed in Figure 43, fully open windows for 11 consecutive hours during the day could be considered within the limits set by FEBY for overheating, while in the case of half-open windows, a duration of 12 consecutive hours resulted in 383 overheating hours below the 440 hours threshold. Furthermore, according to the Boverket suggestions, which does not recommend temperatures to pass the 26 °C threshold, none of the simulated cases were considered to be within the allowed levels of overheating.

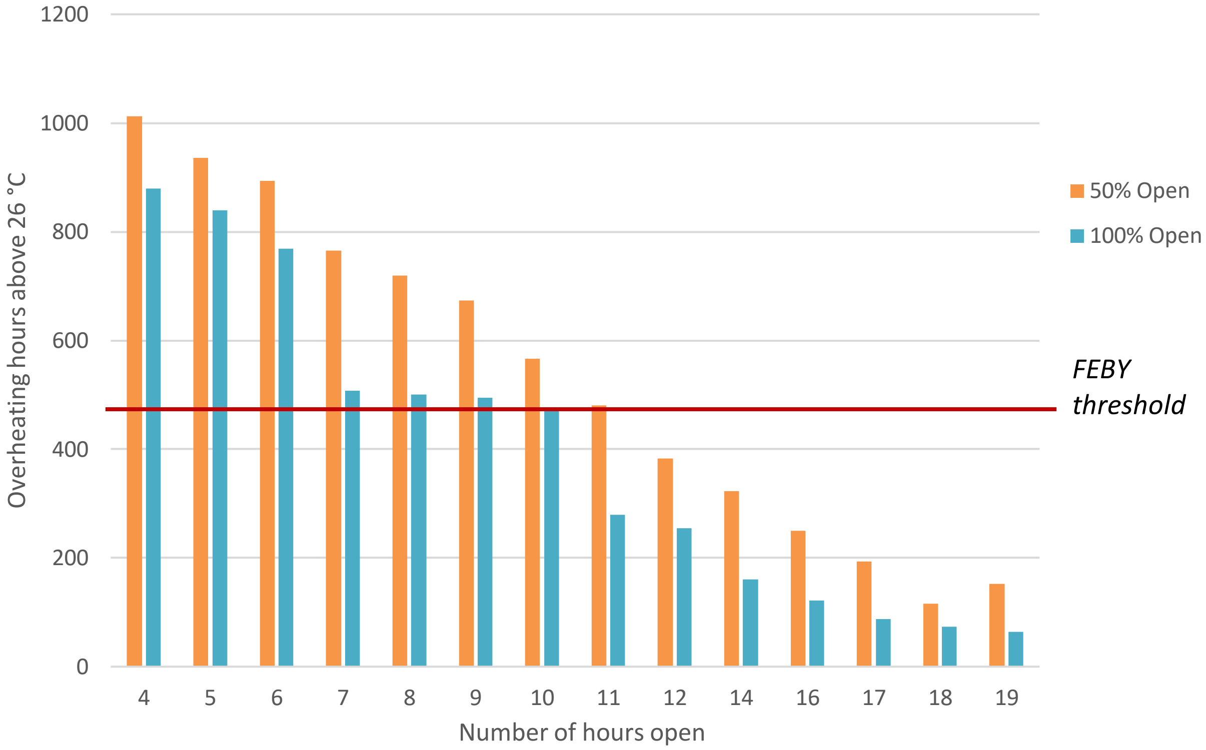


Figure 43: Impact of opening windows duration on number of overheating hours, half open vs. fully open during daytime schedules / FEBY criteria

In the second part of the simulations, night-time schedules between 9 pm and 3 am were employed to investigate the impact of night cooling on the number of overheating hours in bedrooms. Starting with 1 hour opening duration and increasing the duration hourly until results were satisfactory, the cases that were compliant with the CIBSE standard (32 hours threshold) involved fully opening the windows for 5 consecutive hours during the night, while half-open windows needed to be open for 6 consecutive hours to reach the proposed threshold by CIBSE, as illustrated in Figure 44 below.

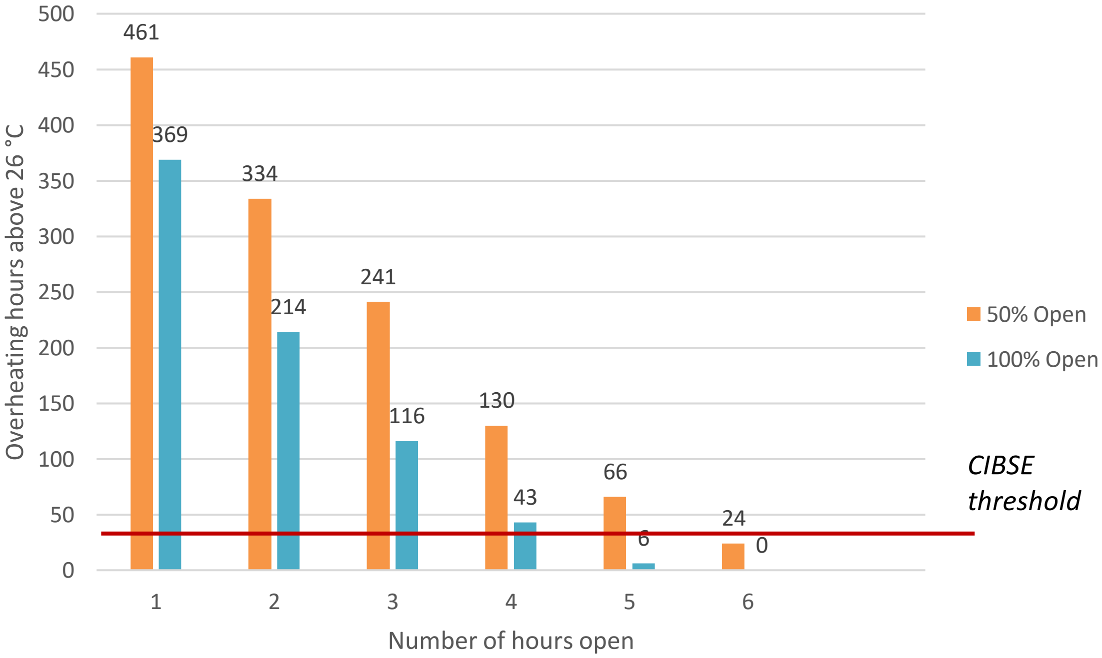


Figure 44: Impact of the duration of opening windows half open vs. fully open during night schedules / CIBSE criteria

However, according to FEBY's criterion shown in Figure 45, fully open windows for 4 consecutive hours complied with the proposed threshold of 440 hours, while half open windows needed to be open for 5 continuous hours during the night.

When compared to daytime opening hours, night-time opening periods significantly reduced overheating hours during much lower durations. The reason could be attributed to night cooling/ventilation phenomenon where the building's fabric and thermal mass releases excess heat and cools the building; the resulting effect lasts throughout the day due to the insulation of the thermal mass.

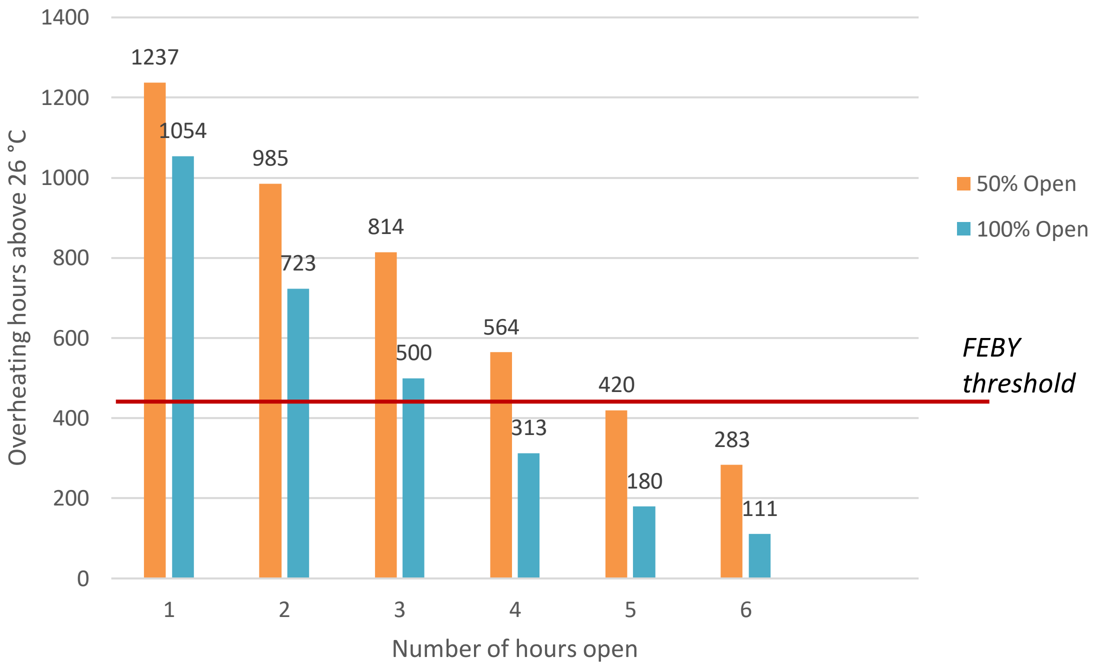
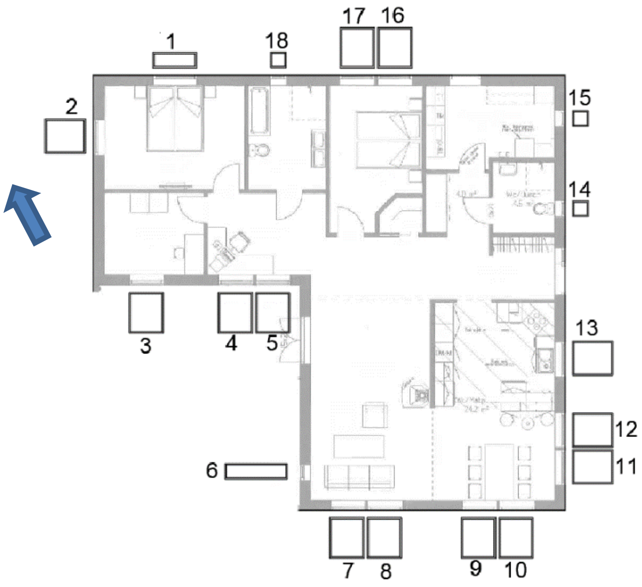


Figure 45: Impact of the duration of opening windows half open vs. fully open during night schedules / FEBY criteria

In continuation with the study on window opening, various cross-ventilation scenarios were tested, and results were compared against the two criteria of CIBSE and FEBY, as indicated in Figure 46 and Figure 47 below. The numbered windows used in the study are illustrated in detail in Figure 7 in the methodology section and in the legend figure below. Windows were simulated as half-open for a constant duration of 9 hours during the occupied period of the bedroom (10 pm – 7 am).



Simulated Case Number	Windows Open
3.2	1 - 2
3.3	1 – 2 – 4 - 5
3.4	1 - 4
3.5	2 – 11 - 12
3.6	2 – 9 – 10
3.7	2 - 5
3.8	1 – 2 - 4
3.9	1 – 2 – 7 -8
4.0	1 – 2 – 13
4.1	2

According to CIBSE criteria, two cases were compliant with the threshold of 32 hours as indicated in Figure 46 below. Case 3.3 where windows 1,2,4 and 5 were open simultaneously achieved the lowest overheating hours amongst all other cases, the air in this case flows between the southern and northern directions. The second case that passed the CIBSE criterion was case 3.8 where windows 1,2 and 4 were open. Both cases shared the same direction and distance of air flow, therefore similar results were detected. In the worst-case scenario (3.4), where windows 1 and 4 were open, the highest overheating hours were recorded above 26 °C. Although case 3.4 shares the same direction and distance of flow as the previous optimal results, the narrowed height of window 1 and the reduced number of open windows significantly affected the results. Hence, the size and number of windows play an important role in achieving successful cooling effects.

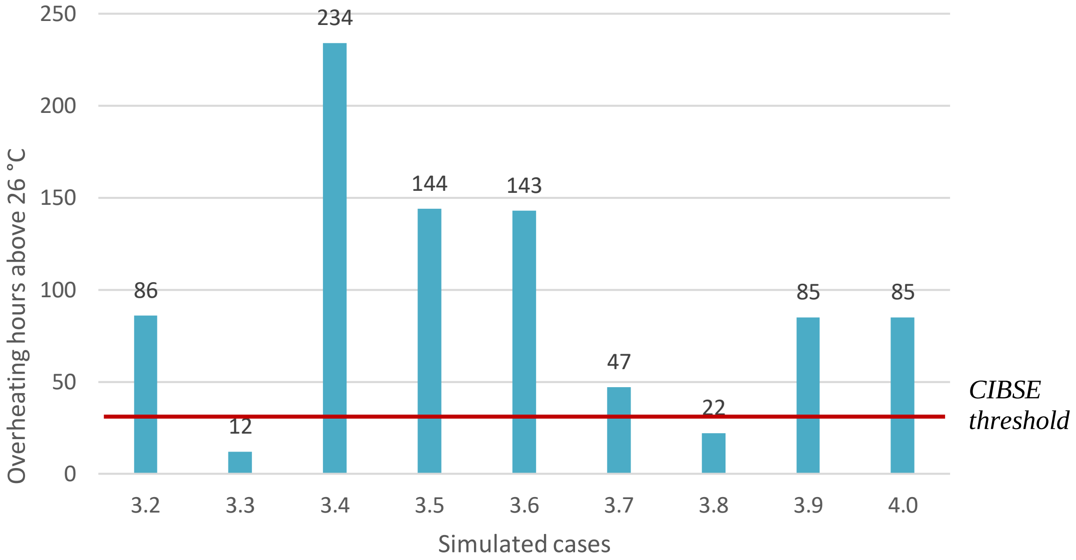


Figure 46: Cross ventilation simulations - CIBSE criteria

On the other hand, FEBY's criterion classifies cases 3.3, 3.8 as well as 3.7 as compliant with its threshold of 440 hours, indicated in Figure 47 below. Case 3.7 involves opening windows 2 and 5 with a direction of North-South air flow. It is worth noting that all best-case scenarios were distanced at around 8 m apart and shared the same direction of flow. Worst case scenario according to FEBY was case 3.5 where windows 2, 11 and 12 were open with an approximate distance of 18 m apart and a north-south direction of air flow.

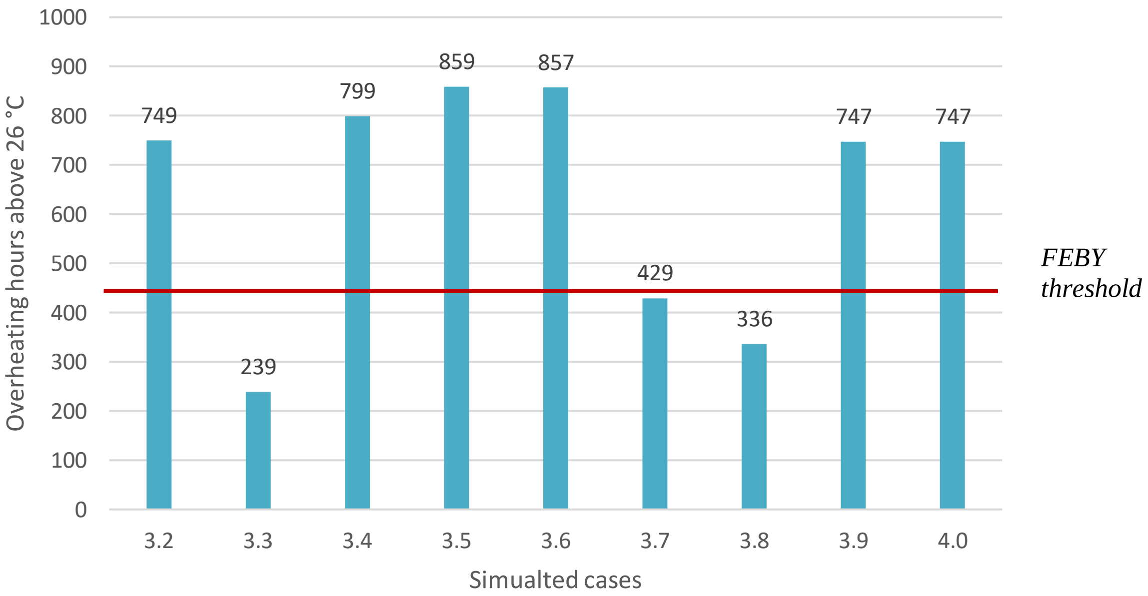


Figure 47: Cross ventilation simulations - FEBY criteria

5 Discussion

In the analysis conducted on the data measurements recorded in Swedish low energy dwellings, three standards were employed to assess the magnitude of overheating during the period between July and August of 2018. All three standards share a common temperature limit of 26° C beyond which overheating occurs. The criteria employed by the three standards (Boverket, CIBSE and FEBY) allow for different percentages of overheating occurrences according to occupancy, type of room, period of analysis or in some cases none. However, several other factors that were found to play an important role in overheating assessment were not considered by any of the standards, such as the duration of exposure to overheating and the significance of relative humidity and outdoor temperature, which were investigated in this study.

When applying the FEBY standard, which allows a maximum of 440 hours to exceed the temperature limit of 26 °C between April and September, the least heating occurrences were observed in all data sets. CIBSE's standard on the other hand demands a relatively lower threshold of 32 hours, as it considers an annual occupancy schedule, hence resulting in significantly higher number of overheating occurrences. Furthermore, considering the recommendation issued by Boverket, resulted in the highest overheating occurrences recorded in all cases and for extended durations of the time, indicating the necessary presence of further defining factors. An important note to mention is that the resulting overheating hours detected in this study could even be higher and more occurring since the investigated period was limited to two single months, whilst overheating could well occur outside this period as well and effect the results even more.

It was also observed that amongst all three sets, the first data set recorded the highest number of overheating hours especially in Visby and Stockholm, which could be associated with the urban heat island phenomenon, whereas the data sets of Jönköping and Umeå recorded the least overheating with almost 0% occurrences in some cases. The abrupt increases in the probability distribution curves additionally confirmed that overheating reached its highest in dwellings located in larger cities and urbanized areas.

Since current research has yet to reveal the consequences of prolonged exposure to overheating on the human health, the duration of exposure to overheating analysis revealed prolonged and recurrent durations of overheating reaching more than 300 consecutive hours in several cases of the first data set, whereas lower durations were observed in the second and third data sets.

A clear linear increase of internal temperature was discovered during periods of increased external temperature in the first data set. As for the risk analysis of high relative humidity coupled with the limit temperature of 26° C, to ensure that hazardous conditions of the heat index were not encountered, minimal occurrences were recorded, and a distinctive pattern was not established within the data.

Additionally investigated in this study was the potential use of passive cooling measures in deterring overheating in dwellings. The measures were limited to those that could be applied to already constructed buildings as part of a renovation plan. Internal shading was found to be non-viable in the reduction of the total overheating hours, whereas following the investigation performed on external shading devices under various variations of parameters, it was ultimately considered an effective passive cooling measure if used for prolonged periods of time, while being fully shut during the day. However, since this method would completely obscure windows from the outdoor environment and hinder visual transmittance for extended periods, it was deemed unreasonable and unappealing to occupants unless used for limited periods where solar radiation would be intolerable. In some cases, the visual appearance of the outdoor building with external shading can also be a disadvantage for occupants. Similarly, variable g-values of the windows' glazing were tested as well, resulting in promising outcomes for values lower than 0.3, however low g-values are not applicable in Sweden due to their effect on limiting solar gains during the winter season.

Furthermore, detailed simulations of windows opening and cross-ventilation scenarios were conducted using variable opening schedules and different air flow patterns, revealing that windows should be open for extensive periods of time, up to 17 and 19 consecutive hours during the day, while it only required 4 to 6 hours of opening during the night to give the same effect, concluding that night cooling is the most appropriate intervention method in significantly reducing the number of overheating hours. Successfully reducing overheating occurrences and lowering peak cooling demands to safer acceptable thresholds steers occupants away from mechanical cooling methods.

This research has been conducted on single family houses where occupancy per floor area is considerably lower in comparison to that in residential apartments implying that overheating would have a much higher impact in crowded apartments and smaller spaces, hence the need for further research in that area. Additionally, the evaluated passive interventions to reduce overheating were applied to pre-existing dwellings, whereas new constructions would have much higher chances of incorporating a wider range of passive strategies.

6 Conclusion

Indoor overheating has been an escalating effect of climate change for the past decade, raising alarming threats to the health and wellbeing of occupants in Sweden and the world. The continuous efforts in decreasing heating loads in European houses have also caused overheating occurrences to consistently rise in response to more insulated and airtight constructions. In the absence of adequate investigative means and warming future climates, irreversible and devastating impacts could eventually take a toll on the population.

Governmental organizations and decision makers in the residential sector should take responsibility to act upon issuing updated and relative legislations concerning the thresholds of acceptable overheating hours and durations. Vulnerable and risk groups susceptible to high temperatures should be prioritized. Preventive passive cooling measures should be well planned out during the design and construction phases or incorporated into current buildings experiencing summer overheating. In other extreme cases, air conditioning could be a final step to maintain a healthy environment.

Overheating assessment tools considers all hours above certain thresholds equally; one overheated hour above the threshold should not be compared to 200 hours above the proposed threshold in the same context, similarly a temperature of 26.1 °C should not also be regarded equally as a temperature of 29 °C since the severity of both temperatures varies tremendously even though both surpass the accepted threshold of 26 °C, as implied previously by Zero Carbon Hub. In this study, an occurrence of 250 hours of temperatures above 30 °C was even detected in almost 50% of the cases of the first data set proving that additional criteria are required to complement the current ones to convey a more detailed and reliable assessment of the issue.

The duration of exposure of overheating is not tackled by most standards and guidelines and no threshold for consecutive hours of overheating was established. It was established through this study that occurrences of more than 200 consecutive hours reaching up to 350 hours in some cases were observed particularly in the first data set in bigger cities like Stockholm, Visby, and Malmö. In multiple cases in Jönköping and Umeå overheating even exceeded 100 consecutive hours. These extremely prolonged hours of high temperatures would be exceptionally intolerable and hazardous to occupants' health and wellbeing. Insufficient data on the risks related to the length of the period of overheating made it difficult to relate certain health hazards to specific overheating periods although some medical studies associate heat stress with prolonged hours of exposure hence the urgent need for more comprehensive studies on the matter,

Natural ventilation and night cooling were proven to be beneficial as passive cooling alternatives to active cooling and have the potential to even reduce overheating to below 26 °C. However, in some cases where pollution and noise or security reasons might prevent some occupants from opening windows, other alternatives could be implemented.

This study could eventually assist governmental decision makers, building developers and owners in shaping suitable regulations regarding overheating in dwellings during summertime, taking into consideration the occupants' comfort, health, and wellbeing.

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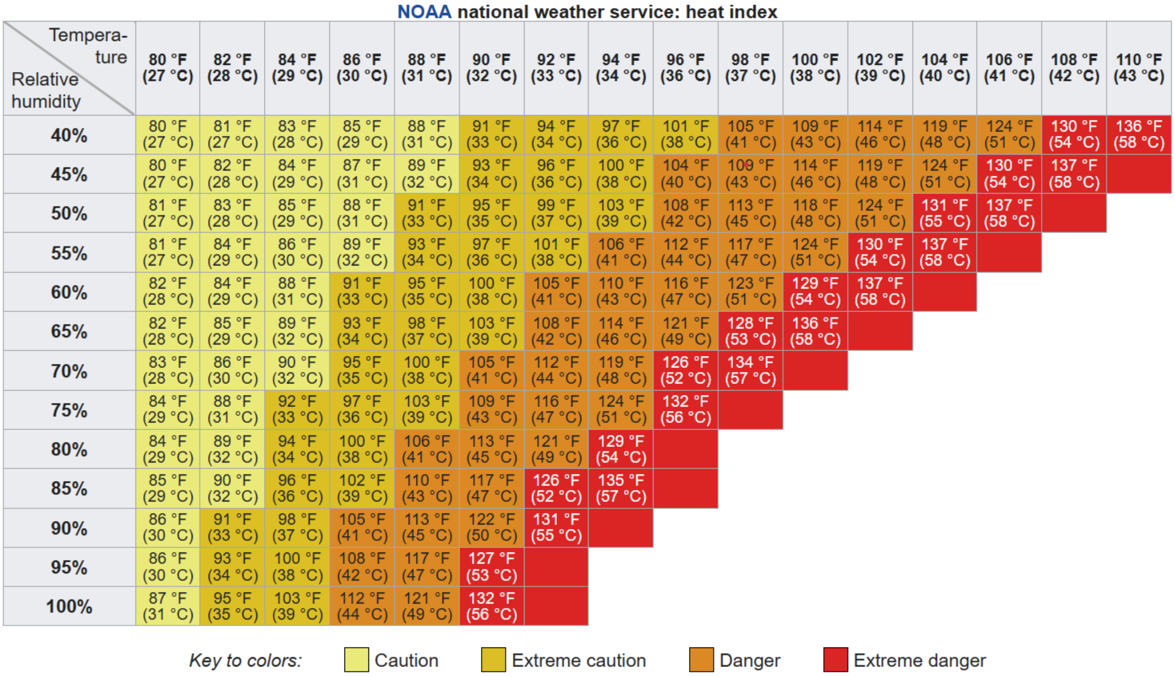
Appendix A



NOAA national weather service: heat index

Temperature / Relative humidity	80 °F (27 °C)	82 °F (28 °C)	84 °F (29 °C)	86 °F (30 °C)	88 °F (31 °C)	90 °F (32 °C)	92 °F (33 °C)	94 °F (34 °C)	96 °F (36 °C)	98 °F (37 °C)	100 °F (38 °C)	102 °F (39 °C)	104 °F (40 °C)	106 °F (41 °C)	108 °F (42 °C)	110 °F (43 °C)
40%	80 °F (27 °C)	81 °F (27 °C)	83 °F (28 °C)	85 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	94 °F (34 °C)	97 °F (36 °C)	101 °F (38 °C)	105 °F (41 °C)	109 °F (43 °C)	114 °F (46 °C)	119 °F (48 °C)	124 °F (51 °C)	130 °F (54 °C)	136 °F (58 °C)
45%	80 °F (27 °C)	82 °F (28 °C)	84 °F (29 °C)	87 °F (31 °C)	89 °F (32 °C)	93 °F (34 °C)	96 °F (36 °C)	100 °F (38 °C)	104 °F (40 °C)	109 °F (43 °C)	114 °F (46 °C)	119 °F (48 °C)	124 °F (51 °C)	130 °F (54 °C)	137 °F (58 °C)	
50%	81 °F (27 °C)	83 °F (28 °C)	85 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	95 °F (35 °C)	99 °F (37 °C)	103 °F (39 °C)	108 °F (42 °C)	113 °F (45 °C)	118 °F (48 °C)	124 °F (51 °C)	131 °F (55 °C)	137 °F (58 °C)		
55%	81 °F (27 °C)	84 °F (29 °C)	86 °F (30 °C)	89 °F (32 °C)	93 °F (34 °C)	97 °F (36 °C)	101 °F (38 °C)	106 °F (41 °C)	112 °F (44 °C)	117 °F (47 °C)	124 °F (51 °C)	130 °F (54 °C)	137 °F (58 °C)			
60%	82 °F (28 °C)	84 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	95 °F (35 °C)	100 °F (38 °C)	105 °F (41 °C)	110 °F (43 °C)	116 °F (47 °C)	123 °F (51 °C)	129 °F (54 °C)	137 °F (58 °C)				
65%	82 °F (28 °C)	85 °F (29 °C)	89 °F (32 °C)	93 °F (34 °C)	98 °F (37 °C)	103 °F (39 °C)	108 °F (42 °C)	114 °F (46 °C)	121 °F (49 °C)	128 °F (53 °C)	136 °F (58 °C)					
70%	83 °F (28 °C)	86 °F (30 °C)	90 °F (32 °C)	95 °F (35 °C)	100 °F (38 °C)	105 °F (41 °C)	112 °F (44 °C)	119 °F (48 °C)	126 °F (52 °C)	134 °F (57 °C)						
75%	84 °F (29 °C)	88 °F (31 °C)	92 °F (33 °C)	97 °F (36 °C)	103 °F (39 °C)	109 °F (43 °C)	116 °F (47 °C)	124 °F (51 °C)	132 °F (56 °C)							
80%	84 °F (29 °C)	89 °F (32 °C)	94 °F (34 °C)	100 °F (38 °C)	106 °F (41 °C)	113 °F (45 °C)	121 °F (49 °C)	129 °F (54 °C)								
85%	85 °F (29 °C)	90 °F (32 °C)	96 °F (36 °C)	102 °F (39 °C)	110 °F (43 °C)	117 °F (47 °C)	126 °F (52 °C)	135 °F (57 °C)								
90%	86 °F (30 °C)	91 °F (33 °C)	98 °F (37 °C)	105 °F (41 °C)	113 °F (45 °C)	122 °F (50 °C)	131 °F (55 °C)									
95%	86 °F (30 °C)	93 °F (34 °C)	100 °F (38 °C)	108 °F (42 °C)	117 °F (47 °C)	127 °F (53 °C)										
100%	87 °F (31 °C)	95 °F (35 °C)	103 °F (39 °C)	112 °F (44 °C)	121 °F (49 °C)	132 °F (56 °C)										

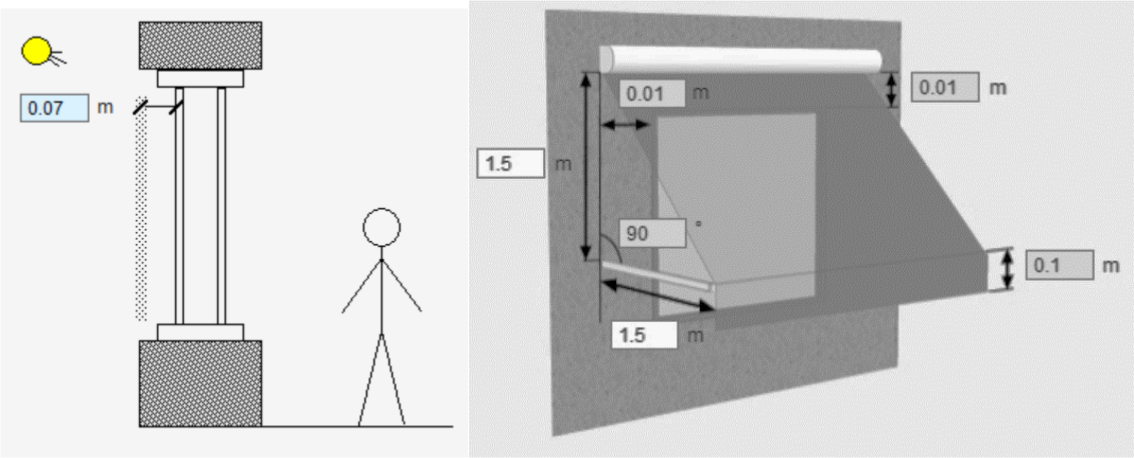
Key to colors: 🟨 Caution 🟨 Extreme caution 🟧 Danger 🟥 Extreme danger

The heat index chart – Apparent temperature as a factor of relative humidity and air temperature

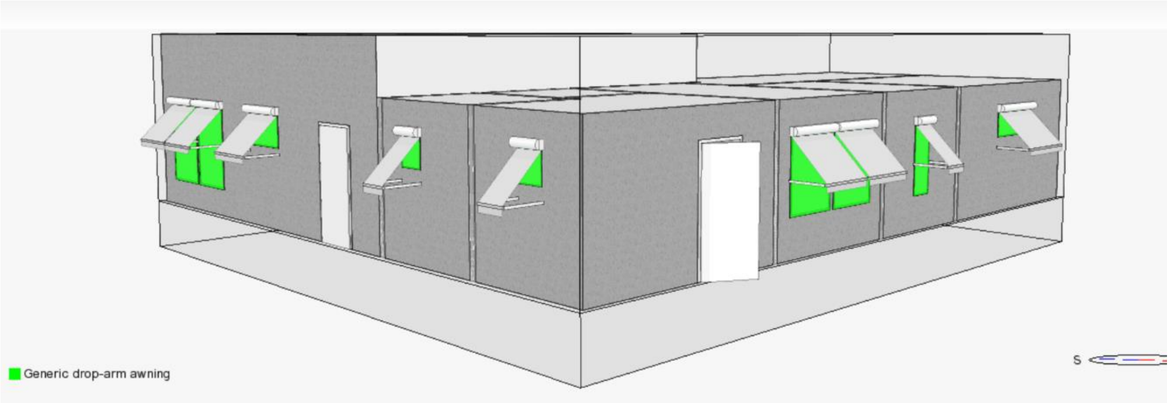
- **Caution:** (27-32 °C) : Fatigue is possible with prolonged exposure
- **Extreme caution:** (32-39 °C) : Heat exhaustion, heat cramps, heat stroke are possible with prolonged exposure
- **Danger:** (39-51 °C) : Heat cramps and exhaustion are likely, heat stroke is possible with prolonged exposure
- **Extreme danger:** (51+ °C) : A heat stroke is highly likely
-

Source: (Heat index chart and warnings obtained from www.weather.org)

Appendix B



Source: (IDA ICE – integrated shading / external shading)



Source: IDA ICE - Simulated model with drop-arm awning external shading

LUND UNIVERSITY

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