

Evaluation of Overheating Risk in a Danish Primary School Classroom During Normal Summer and Heatwave Conditions Using Adult and Children-Adjusted Adaptive Comfort Models



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Abstract: This study investigates the overheating risk in a representative Danish primary school classroom during normal summer conditions and a future heatwave scenario. Thermal comfort was evaluated using two models: adaptive thermal comfort model for healthy adults and the children-adjusted thermal comfort model. The overheating was evaluated using the TM52 criteria. Using building performance simulations in BSim, multiple renovation cases and their combinations were evaluated in terms of their effectiveness in reducing overheating. The results show that the adults' thermal comfort model consistently underestimates the level of thermal discomfort experienced by children. Regarding the renovation cases, the improved envelope alone increases overheating, while the combination of shading and night cooling proves to be the most effective in reducing overheating.

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Abbreviations

Abbreviation	Term
ACH	Air change per hour
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BR	Bygningsreglementet (Building Regulations)
BPS	Building performance simulation
BSA	Body surface area
C3S	Copernicus Climate Change Service
DRY	Design reference year
DS/EN	Dansk Standard / European Standard
EEA	European Environmental Agency
EWE	Extreme weather event
IEQ	Indoor environmental quality
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
PMV	Predicted mean vote
PPD	Predicted percentage of dissatisfied
RMR	Resting metabolic rate

1. Introduction

The increasing intensity and frequency of extreme weather events (EWEs), such as heatwaves, floods, storms, and wildfires, caused by climate change, pose one of the most significant challenges to the resilience of the built environment [1]. The definition of resilience within the context of this study is further defined and presented in Chapter 2.1. The increased occurrence of EWEs is particularly critical in Europe, which is the fastest-warming continent. Its climate is changing rapidly, threatening both infrastructure and public health [1]. As the urban areas are expected to expand significantly in the next couple of decades [2], as well as the rising global temperatures [3, 4], the inability of buildings to maintain a healthy indoor environmental quality (IEQ) is becoming one of the most challenging concerns. This leads to conditions that negatively impact the occupants' well-being.

Buildings are designed to provide a comfortable IEQ for all occupants, and although existing thermal comfort standards acknowledge vulnerable groups through stricter comfort criteria, they assume that the adult thermal perception is representative of all occupants. Current thermal comfort standards, such as ISO 7730:2005, ASHRAE 55:2023 and DS/EN 16798:2018, only consider healthy adults [5-7]. Vulnerable groups include children (typically under the age of 15), people with existing health conditions, pregnant women and the elderly (typically over the age of 65), who are the most critical [8], given that more countries are experiencing rapid ageing [9].

This gap in the standards is crucial, since physiological differences among these groups affect their thermal comfort. Korsavi and Montazami [10] demonstrated that children have higher metabolic rates per body weight and lower sweating rates, making them more vulnerable to temperature fluctuations and higher temperatures. On the contrary, older adults and the elderly have lower metabolic rates due to muscle weakness and reduced sweat production [9].

Buildings' design and operation must reflect the physiological differences of these groups, since it is not solely a matter of their comfort, but also their health under a changing climate. One key approach is building renovation, a crucial strategy in reducing carbon emissions, improving the energy performance and maintaining IEQ [11]. However, building renovations must remain effective during EWEs. Consequently, it is important to evaluate renovation strategies for their effectiveness in preserving the thermal comfort of vulnerable occupants during such events.

1.1. Extreme Weather Events

According to Copernicus Climate Change Service (C3S) and the Intergovernmental Panel on Climate Change (IPCC), the average global temperature has increased by at least 1.3 °C since 1850, with the majority of the warming occurring since 1970 [3, 4]. As a consequence of this temperature rise, the frequency and intensity of extreme weather events have increased [12]. Power outages have become a frequent issue during such EWEs [13], as they can disrupt the operation and efficiency of various essential building systems and compromise IEQ. This generally increases the impact of heatwaves, resulting in higher indoor temperatures and increased mortality rates, particularly among vulnerable groups [14]. Additionally, a study by Sengupta et al. [15] demonstrates that among various disturbances

that cause overheating in buildings, heatwaves are the most critical. Furthermore, studies indicate that the severity and frequency of EWEs are expected to increase, meaning that overheating will become an increasingly serious issue in the future. [3, 4, 16].

1.2. Defining Resilience in the Built Environment

There is no clear consensus on a single definition of resilience. The definition has been explored and interpreted in many fields of study, some including psychology, engineering and economics. Regarding the built environment, the IPCC Glossary [17], has defined resilience as: “*The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure.*” In this study, resilience is based on the IPCC’s definition but applied to the challenge of maintaining IEQ during an extreme weather event. Therefore, resilience can be defined as: The ability of a building or system to maintain operation, safety, and sufficient IEQ throughout and after disruptive events such as extreme weather.

2. Literature Review

2.1. Current/existing Standards and Thermal Comfort Models

Even today, with standards and regulations becoming increasingly rigorous, international and European standards for IEQ and especially thermal comfort still primarily focus on healthy adults in steady-state conditions.

ISO 7730:2005 [7], specifically assumes that “healthy men and women” perform sedentary work under “moderate thermal environments”. The thermal comfort model used in this standard is the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) developed by Povl Ole Fanger in the late 1960s [18]. As stated in the standard, the PMV depends on physical activity (met), and assumed clothing level (clo), as well as the environmental parameters such as air temperature, mean radiant temperature, air velocity and air humidity. When these parameters have been estimated, the PMV can be calculated. The model is valid for mechanically conditioned buildings and assumes mainly steady-state thermal conditions.

The DS/EN 16798-1:2019 [5] uses the same thermal comfort model as ISO 7730 (PMV/PPD), with the addition of the adaptive comfort model for naturally ventilated buildings [19]. This model is valid for buildings that are not mechanically actively cooled, during warm outdoor conditions, when occupants can regulate their thermal conditions by, for example, opening the windows. It applies to occupants performing sedentary tasks without mandatory clothing policies. This standard divides the IEQ into four categories based on the occupants' IEQ expectations. Though Category I is intended for individuals with a higher level of IEQ expectation (the elderly, children and people with health conditions or special needs), the standard does not separate the vulnerable groups from healthy adults physiologically. The categories are presented in Table 1.

Table 2.1: Categories of IEQ

Category	Expectation Level
I	High
II	Medium
III	Moderate
IV	Low

Note: Adapted from “Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics” by: DS/EN 16798-1:2019, European Committee for Standardization, p.18.

Similarly to the ISO 7730, ASHRAE 55 [6], an American standard, specifically states that: “*Thermal environmental conditions acceptable for healthy adults at atmospheric pressure equivalent to altitudes up to 3000 m (10,000 ft) in indoor spaces designed for human occupancy for periods not less than 15 minutes.*” This standard uses both the PMV/PPD and

the adaptive comfort model; however, once more, it is limited to healthy adults and does not consider vulnerable groups.

In Denmark, the Danish Building Regulations (BR18) [20] define that for buildings with a similar usage pattern as office buildings, there should be no more than 100 hours above 26 °C and 25 hours above 27 °C. BR18 additionally refer to DS 474 [21] for the control, specification and verification of the indoor thermal climate, and ISO 7730 [7] for further methods and guiding specifications. Although BR18 defines fixed overheating thresholds, these criteria do not consider adaptive thermal comfort or differences in thermal sensitivity between different groups.

Table 1.2: Overview of the current standards and Regulations, their Thermal Comfort Models, Focus and Consideration for Vulnerable Groups

Standard	Full Name	Thermal Comfort Model	Focus	Consideration for Vulnerable Groups
ISO 7730:2005	International Organization for Standardization (ISO)	PMV / PPD (Fanger,1970)	Based on steady-state conditions, assumes healthy men and women performing sedentary activity in moderate environments	Not considered,
DS/EN 16798-1:2019	Dansk Standard / European Standard	PMV / PPD + Adaptive comfort model (more specific for European climates)	Divides IEQ into four categories (I–IV) based on occupant expectations	Category I intended for the elderly, children, and vulnerable people, but no separate physiological differences
ASHRAE 55 (2013)	American Society of Heating, Refrigerating and Air-Conditioning Engineers	PMV / PPD + Adaptive comfort (more specific for U.S. climates)	Specifies conditions for healthy adults at altitudes ≤ 3000 m, for occupancy ≥ 15 min	Not considered

A critical review of the standards by Khovalyg [22] additionally highlights that ISO 7730, DS/EN 16798, and ASHRAE 55 do not adequately address demographics, building types and climate differences. Furthermore, the review states that the thermal comfort models, such as PMV/PPD, are based on steady-state conditions and do not account for transient conditions and extreme weather events.

3. Existing Research

3.1. Existing research regarding children's thermal comfort

There has been a growing body of research recognising that thermal comfort varies between healthy adults and vulnerable groups. Several studies have shown that children's thermal comfort differs significantly from that of adults, due to differences in thermal preferences and ways they adapt to temperature changes. Research by Teli et al. [23, 24] and Korsavi and Montazami [10] highlight significant physiological differences in children, such as higher metabolic rates and lower sweating rates.

A study in the UK (United Kingdom) conducted by Korsavi and Morazami [10] in primary schools with naturally ventilated classrooms, revealed that during heating seasons, children generally have a lower comfort temperature and feel overheated much faster than adults. Furthermore, the study has shown that approximately 15% of children experience overheating during both heated and unheated seasons; however, personal actions such as removing a sweater or moving to a different location, and environmental actions such as opening a window, vary from season to season.

Mors et al. [25] conducted a study on children aged 9-11 in unconditioned classrooms during the winter, spring, and summer. The results showed the PMV thermal comfort model underestimated children's thermal sensation by up to 1.5 scale points, meaning that they prefer cooler temperatures.

A subsequent study by Teli et al. [26] backs these results. A field study was conducted in naturally ventilated primary school classrooms, and the results once more showed that children's thermal sensations did not align with either the PMV or the adaptive thermal comfort model.

From the literature, it can be seen that the thermal comfort methods currently in use for primary schools are inaccurate, and complying with these requirements does not necessarily result in a comfortable environment for children. As a response, Teli et al. [24] developed a thermal comfort model adjusted for children, based on extensive data gathered in primary schools across the UK. This model offers a more reliable base for assessing and creating thermal conditions in educational institutions.

3.2. Existing research regarding elderly thermal comfort

Studies on thermal comfort in elderly individuals show distinct physiological and behavioural characteristics compared to children and younger adults. The physiological differences between the elderly and younger adults mainly include decreased sweating efficiency, lower core temperature, and differential metabolic heat production [9].

A field study conducted by Zheng et al. [27] revealed that the elderly make an effort to adapt through clothing insulation and personal actions; however, the adaptation is limited due to older-age mobility issues and health status.

A study by Hwang and Chen [28] interestingly revealed that during both the heated and unheated seasons, the elderly, compared to healthy adults, tend to rely more on personal actions, such as putting on or removing clothing, and environmental actions, such as opening or closing windows, rather than mechanical heating or cooling systems.

Similar to the case of children, the PMV model shows inaccuracies for this group, with results that are typically 0.5 scale units lower than those observed in healthy adults, meaning that the elderly prefer higher temperatures. [29, 30]

Since adaptive comfort models inadequately represent the thermal preferences of the elderly as well, researchers developed modified adaptive comfort models that were specifically designed for the elderly. One of the models was developed in the Mediterranean region [31], while the other was developed in China [32].

3.3. Knowledge Gap

Despite an emerging body of research regarding the thermal comfort differences between adults, children and the elderly, a significant knowledge and regulatory gap remains. As demonstrated in Chapters 3.1 and 3.2, several studies reveal that the PMV and adaptive thermal comfort models fail to accurately represent the real thermal sensation of both children and the elderly.

Although recent studies have suggested adjusted thermal comfort models aimed at these groups, such as Teli et al.'s children's thermal comfort model [24] and Jiao et al. [32] and Forcada et al. [31] elderly-adjusted adaptive models, their scope and geographical applicability remain limited.

In conclusion, existing standards and regulations primarily assume steady-state IEQ conditions, and do not adequately offer guidance for performance during extreme weather events. As a result, buildings continue to be designed and assessed in terms of IEQ using parameters for healthy adults, rather than for vulnerable groups, highlighting the necessity of further research into their thermal comfort during an extreme weather event.

4. Aim of the Research

Despite literature indicating that both children and the elderly exhibit different thermal comfort sensations compared to healthy adults, this study focuses specifically on children's thermal comfort. Since an adaptive thermal comfort model exists for this group, it enables a valid comparison with the adaptive thermal comfort model for healthy adults. Furthermore, maintaining a high level of IEQ expectation in educational buildings and classrooms is crucial since inadequate conditions may negatively impact teaching activities and students' learning outcomes [33].

Considering that heatwaves are one of the most frequent and serious EWEs in all of Europe [1], this research investigates the children's thermal comfort in a typical Danish classroom during a heatwave. Due to the absence of measured data, the scenario is simulated using the tool BSim.

The aim of the study is to create a simulation-based evaluation of children's thermal comfort in a typical Danish classroom during normal summer conditions and during a heatwave, evaluating the results using the adaptive thermal comfort model for adults and the adjusted thermal comfort model for children. The findings may reveal how current standards fail to accurately represent children's actual thermal comfort.

Furthermore, the study investigates the effectiveness of specific renovation cases, such as improved envelope (thicker insulation and new windows), shading, night cooling and their combinations in maintaining acceptable thermal indoor conditions during heatwaves.

To fulfil the aim of the paper, the following research questions were developed:

1. How does the overheating risk in a classroom differ when using both adult and children-adjusted adaptive thermal comfort models during normal summer and heatwave conditions?
2. Which renovation cases reduce overheating in the classroom the most and improve children's thermal comfort?

5. Methodology

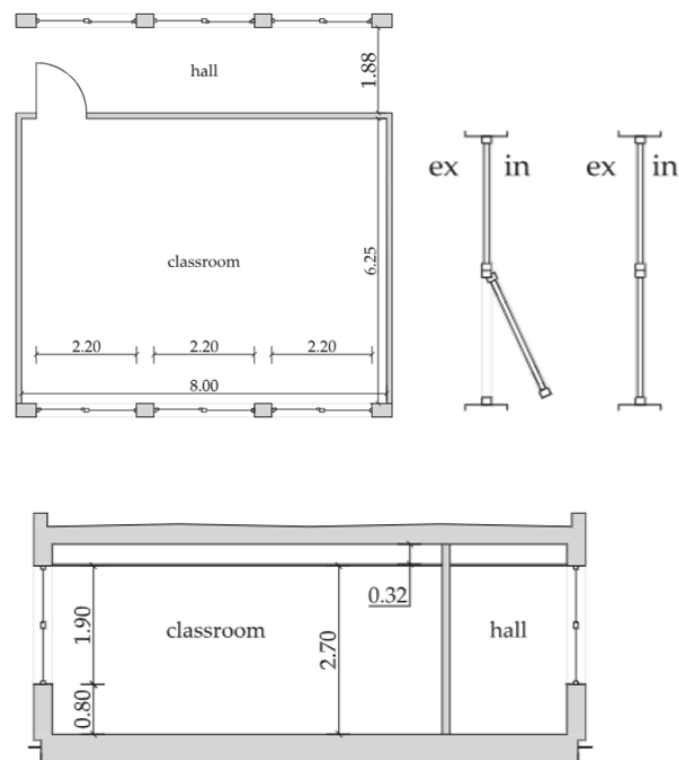
The following chapter outlines the methodological framework used in this research. It describes the model of the classroom, the input parameters and the weather files.

Furthermore, the chapter explains the proposed renovation cases, the thermal comfort models used in the research and the approach used to evaluate the results.

5.1. Model's Construction Description

Using a Building Performance Simulation (BPS) approach in the program BSim, a model was created. It is a fabricated representation of a typical Danish classroom, defined in the previous research conducted by multiple universities and research institutes [34, 35]. The building is a one-storey school from the 1960s located in Aalborg, Denmark. The modelled classroom is oriented towards the South, with an attached hallway in the North. It is semi-exposed, meaning that a part of it faces the outdoors, while the other part faces the interior, or is attached to other building zones. The floor plan of the classroom, the section and the window opening principle are adapted from previous research and are presented in Figure 5.1. [36]. A detailed overview of the classroom's construction parameters is presented in Table 5.1.

Figure 5.1: Classroom Floor Plan, Window Opening Principle and the Classroom Section



Note: From “A novel solution for school renovations: Combining diffuse ceiling ventilation with double skin façade” by L.A. Bugenings, M. Schaffer, O.K. Larsen, C. Zhang, *Journal of Building Engineering*, p.6, (<https://doi.org/10.1016/j.jobee.2022.104026>), cropped.

Table 5.1: Overview of the Classrooms Construction, the Parameters and their Values

Section	Parameter	Value
Classroom dimensions		
	$h \times w \times d$	2.70 m \times 8.00 m \times 6.25 m
	height of suspended ceiling	0.32 m
Hall dimensions		
	$h \times d$	2.70 m \times 1.875 m
	height of suspended ceiling	0.32 m
Windows classroom		
	nr. \times h \times w	3 \times 2.2 m \times 1.9 m
	parapet height	0.80 m
	glazing	$U=2.7 \text{ W/m}^2\text{K}$; $g=0.74$; $\tau=0.80$
	Frame	$U=1.9 \text{ W/m}^2\text{K}$
Windows hallway		
	nr. \times h \times w	3 \times 2.2 m \times 1.9 m
	parapet height	0.80 m
	glazing	$U=2.7 \text{ W/m}^2\text{K}$; $g=0.74$; $\tau=0.80$
	frame	$U=1.9 \text{ W/m}^2\text{K}$
Construction		
	facade infill	aerated concrete/insulation/brick - $U = 0.50 \text{ W/m}^2\text{K}$
	facade column	aerated concrete/brick - $U = 0.92 \text{ W/m}^2\text{K}$
	floor	screed/concrete/expanded clay - $U = 0.43 \text{ W/m}^2\text{K}$
	roof	concrete/insulation - $U = 0.45 \text{ W/m}^2\text{K}$
	internal partition	gypsum/insulation
	internal ceiling	gypsum
	windows	hardwood frame, double glazing

The parameters described in the following subsections are derived from a combination of peer-reviewed literature and professional assumptions, and visits to Danish schools and classroom observations. The calculations for the parameters are provided in Appendix A.

5.1.1. People Load

In line with a publication by the OECD [37], the model consists of 21 occupants, 20 students (children), and one teacher. To ensure consistency in the BSim calculations, the teacher was characterised as a child, having the same Resting Metabolic Rate (RMR) and Body Surface Area (BSA) characteristics, meaning that in the tool, the final input parameter was 21 children.

To accurately reflect the physiological characteristics of the actual occupants, the inputs were based on the values provided in the research by Teli et al. [26], which specifically represent primary school children, rather than healthy adults. They calculated the BSA, or the total skin surface area, to be 1.14 m^2 , while the BSA of an adult is 1.74 m^2 . The RMR, which is the

amount of heat produced by the body at rest, is based on a dataset collected by Amorin [38]. For a healthy adult, the RMR is 58 W/m^2 , whereas that of a child of average age 10 is 48.8 W/m^2 .

The occupancy schedule was set from Monday to Friday, 08:00 to 16:00, guaranteeing that internal heat gains correspond to the times when the space is actively used.

5.1.2. Equipment

The equipment load is typical of a modern Danish classroom with a modern teaching setting. The model includes one desktop PC of 49W, a monitor of 36W, a projector of 210W, an interactive whiteboard of 200W, and one laptop of 35W per student. The power values were based on an Excel tool for calculating equipment heat load [39].

A daily operation schedule from Monday to Friday, 08:00 to 16:00, was used to represent realistic teaching hours and equipment usage.

5.1.3. Ventilation

No mechanical ventilation parameters were included in the model. Although mechanical ventilation can be included, the adaptive thermal model does not include active cooling systems. (Previously explained in Chapter 2.1) This is also reasonable since around 50% of Danish schools were built in the 1960s and 1970s [34], same period when the fictional school is set. Buildings from that period also typically rely on natural ventilation, given that ventilation requirements were first introduced in BR95 [40].

5.1.4. Venting

Venting was calculated according to SBI Anvisning 213 (BE18), Section 6.4 - Ventilation om sommeren [41]. During occupied hours, SBI states that for manually operated windows, the ventilation rate can generally be assumed to be 1.2 l/s per m^2 , equivalent to 1.6 Air Changes per Hour (ACH). For night ventilation, the rate can be assumed to be 0.6 l/s per m^2 , equivalent to 0.8 ACH.

Opening the window in schools mostly occurs when indoor temperatures rise and become uncomfortably high; therefore, a venting control was implemented. According to SBI Anvisning 213, Section 3.1.2 Setpunkt for udluftning [41], windows automatically open only when the operative temperature exceeds 23 degrees Celsius. Moreover, temperatures above 24 degrees Celsius can cause discomfort, fatigue, headaches, and negatively influence children's performance [42]. The schedule was set from Monday to Friday during warm periods, from May to the end of September. The time was set from 08:00 to 16:00, representing occupied hours.

5.1.5. Infiltration

The infiltration rate was calculated in accordance with SBI Anvisning 213 (BE18), Section 6.2 - Infiltration [41]. Since the blower-door measurements are unavailable for the representative building, values given in the SBI 213 were used. During occupied hours, an infiltration rate of 0.13 l/s per m^2 was used, resulting in an ACH of 0.17 for the classroom. During unoccupied hours, SBI recommend a rate of 0.09 l/s per m^2 , equivalent to 0.12 ACH.

Infiltration happens constantly; therefore, two schedules were made, one for the occupied hours and one for the unoccupied hours. This approach emphasises that infiltration is a constant occurrence independent of the occupancy.

5.1.6. Lighting

According to the standards, a lighting level of 300 lux was determined [43]. The lighting type is standard fluorescent tube lighting with an assumed power of 14.5 W/m² [35]. The total lighting power calculated and inserted into BSim was 0.73 kW.

The schedule was set from Monday to Friday, 07:00 to 17.00, accounting for early preparation and after-class cleaning.

An overview of the parameters and the schedules can be seen in Table 5.2 - Overview of the parameters and schedules.

Table 5.2: Overview of the System Parameters and their Schedules

System	Parameter input	Schedule
People Load	21 people Heat gen. per person= 0.055 kW	100% 08:00-16:00 Weekdays Jan-Dec
Equipment	Heat load= 1.2 kW	100% 08:00-16:00 Jan-Dec
Ventilation	No mechanical ventilation	-
Venting	ACH= 1.6 h/1	08:00-16:00 Weekdays May-Sep
Infiltration	Occupied hr = 0.17 h/1 Unoccupied hr = 0.12 h/1	Always
Lighting	Lighting load= 0.73 kW Lighting level= 300 lux	07:00-17:00 Weekdays Jan-Dec

5.2. Weather Data

In this study, two weather data files were used:

a) Baseline weather data

The first dataset is a Design Reference Year (DRY) file, representing a Typical Meteorological Year (TMY) in Denmark. It represents average Danish climate conditions, and it is used to evaluate the IEQ under “normal” summer conditions.

b) Heatwave weather data

The second data set represents the most severe heatwave scenario, happening in 2054. It was developed for “Annex 80: Resilient Cooling for Buildings”, a project aiming to study the impacts of climate change and heatwaves, and consequently, develop various building adaptations [44]. Among the developed heatwave files, the 2054 most severe scenario was chosen, as it combines extreme peak temperatures and a longer duration, thereby deeming it the most impactful for the occupants.

Both datasets include: wind speed, atmospheric pressure, relative humidity, ambient air temperature, and both direct and diffuse solar irradiance.

5.3. Renovation Cases

In the event of a renovation, the changes must comply with the BR18 [20]. Several renovation cases are suggested. Each case is simulated individually in BSim to evaluate its impact on the thermal comfort of the occupants. The calculations are provided in Appendix A. All individual renovation cases in the subchapters below are based on the suggestions from School of the Future paper [35].

5.3.1. Improved Envelope

The first renovation case aims to improve the building envelope. The external walls in the current condition have a U-value of $0.50 \text{ W/m}^2\text{K}$, while the column structures have $0.92 \text{ W/m}^2\text{K}$. Both constructions are currently above the maximum U-values set by the BR18, which is $0.18 \text{ W/m}^2\text{K}$. [20]

Multiple solutions could be carried out. For example, to avoid demolition, an extra layer of insulation could be added to the interior or the exterior; however, the interior insulation would reduce available floor space [35]. Another solution could be to remove the exterior brick layer, make the insulation much thicker and again, lay bricks for the external layer. To avoid reducing the available floor space, the second solution is chosen and simulated. The interior concrete layer would remain untouched, followed by adding a new insulation layer of 240mm, and then an external brick layer of 120mm. For the purpose of this study, the external walls and columns will be treated as a single construction in the renovation case. The improved U-value will be $0.17 \text{ W/m}^2\text{K}$.

The current windows have a U-value of $1.9 \text{ W/m}^2\text{K}$ for the hardwood frame and $2.7 \text{ W/m}^2\text{K}$ for the glazing. The g-value is 0.74 [45]. Although BR18 does not specify a fixed U-value threshold for windows, it does specify an annual energy balance of $\leq 17.0 \text{ kWh/m}^2$ per year [20]. Nonetheless, these windows are significantly less efficient than modern windows; therefore, new ones are proposed. When replacing old windows, investing in a long-term investment is important. An adequate replacement would be a triple-glazed window with a low-e coating. Triple-glazed windows provide much better energy efficiency [46]. Therefore, the existing windows will be replaced with new triple-glazed windows, such as those from Kastrup, which have a U-value of $0.78 \text{ W/m}^2\text{K}$ and a g-value of 0.43 [47].

5.3.2. *Shading*

Implementing shading in a classroom would reduce excessive solar heat gains, therefore reducing overheating and improving thermal comfort for the children. [48]

There are four types of shading in BSim: simple shading, screen shading, curtain shading and venetian shading. Simple shades are a fixed type of shading. They can only block the sunlight at certain angles; hence, they are not considered effective for dynamic classroom use. Screen shading, or in other words, roller screen blinds and curtain shading, are less common in educational buildings due to maintenance, durability and hygiene concerns. Finally, venetian shades are horizontal slats, typically made of metal or wood. The slats are adjustable and can be tilted or lifted to adjust light, visibility and privacy. Given that they are commonly used in educational buildings, external venetian shading has been selected as the renovation case solution. Additional information about the selected shading can be seen in Appendix A.

5.3.3. *Night cooling*

According to SBi Anvisning 213 (BE18), Section 3.1.3 and 6.4 [41], when the classroom's temperature rises above 24 degrees Celsius, night cooling or, in other words, natural ventilation during the night should be utilised. During warm periods, the outdoor temperature typically decreases during the night. Night cooling takes advantage of those lower temperatures to remove the accumulated heat inside the building. It is also proven that night cooling lowers the temperature of the building structure and thereby the mean radiant temperature [48].

The efficiency of the night cooling depends on the window opening area and the air flow path strategies, which in this case is single-sided ventilation. Additionally, security risks should be considered when opting for night cooling [48]. This concern can be solved by installing window restrictors, simple external security grills or louveres [49].

The ACH was set to 0.8 1/h, and the schedule was set from May to the end of September, from 23:00 to 07:00. Lastly, a control schedule was set. It is activated when the operative temperatures exceed 24 degrees Celsius.

In addition to the individual renovation cases, combined renovation scenarios were developed to evaluate how certain improvements perform together and to represent realistic renovation solutions for the school. Hence, the following combined renovation scenarios were simulated:

- a) Shading and night cooling

- b) Improved envelope, shading and night cooling

5.4. Evaluation Methods

To evaluate the indoor thermal conditions of the fictional classroom, two thermal comfort models are utilised, together with the overheating criteria described in TM52 [50].

- a) The adaptive thermal comfort model for adults, defined in the DS/EN 16798-1:2019 [5], and additionally referenced by the BR18 [20].
- b) The adjusted thermal comfort model for children by Teli [24].

The utilisation of both models could reveal instances where the conditions are met by the DS/EN 16798-1:2019 and BR18 for the adults, yet children would feel uncomfortably warm. If that were the case, it would indicate the regulatory gap in current standards and regulations, thereby confirming the aim of the research.

5.4.1. The Adaptive Thermal Comfort Model for Adults

The indoor thermal conditions for adults are evaluated using the adaptive thermal comfort model, previously described in Chapter 2.1. The model is defined in DS/EN 16798-1:2019 [5]. The model defines the optimal operative temperature as follows:

$$T_c = 0.33 \cdot T_{rm} + 18.8$$

Four categories (I-IV) of IEQ expectations are described in this standard. Category I has the highest expectations, while Category IV, which has values outside the recommended range, is not defined by a limit formula. For classrooms, category II is desired and therefore used as the comfort category for adults in this study. The categories are as follows:

Category I upper limit: $T_o = 0.33 \cdot T_{rm} + 18.8 + 2$

lower limit: $T_o = 0.33 \cdot T_{rm} + 18.8 - 3$

Category II upper limit: $T_o = 0.33 \cdot T_{rm} + 18.8 + 3$

lower limit: $T_o = 0.33 \cdot T_{rm} + 18.8 - 4$

Category III upper limit: $T_o = 0.33 \cdot T_{rm} + 18.8 + 4$

lower limit: $T_o = 0.33 \cdot T_{rm} + 18.8 + 5$

Where: T_c = optimal operative temperature, °C

T_o = indoor operative temperature, °C

T_{rm} = running mean outdoor temperature, °C

5.4.2. Adjusted Adaptive Thermal Comfort Model for Children

Since DS/EN 16798-1:2019 and the adaptive thermal comfort model assume healthy adults, they fail to physiologically differentiate them from other vulnerable groups, such as children. Therefore, Teli et al. adjusted adaptive thermal comfort model for children is used as well [24]. The formula for this model is as follows:

$$T_{conf_child} = 0.26 \cdot T_{rm} + 18.2$$

The category offsets are the same as in the adults' model, just with the adjusted formula. For the children, category I is desired and used in this study. To provide an example, category I is presented below:

$$\text{Category I upper limit: } T_o = 0.26 \cdot T_{rm} + 18.2 + 2$$

$$\text{lower limit: } T_o = 0.26 \cdot T_{rm} + 18.2 - 3$$

Where: T_{conf_child} = optimal operative temperature, °C

T_{rm} = running mean outdoor temperature, °C

5.4.3. Temperature metrics

Three temperature metrics are used in the analysis: the hourly indoor operative temperatures for the evaluation, the daily and running mean outdoor temperatures, which are merely used as inputs for calculating the adaptive comfort limits. The thermal comfort and overheating evaluations are conducted only for the occupied period, from 08:00 to 16:00.

a) Indoor Operative Temperatures

These temperatures are obtained from the BSim simulations for every hour of the occupied period.

b) Daily Mean Outdoor Temperatures

Derived from both weather files as the mean of the 24-hour outside temperatures for each simulation day.

c) Running Mean Outdoor Temperatures

Exponentially weighted running mean outdoor temperatures, used to reflect how the occupants thermally adapt. Defined in DS/EN 16798 [5]. When the daily running mean outdoor temperatures are not available, the simplified formula is applied. With this formula, the running mean temperature of a certain day is estimated using the daily mean outdoor temperatures from the previous seven days with fixed coefficients:

$$T_{rm} = (T_{ed} - 1 + 0.8T_{ed} - 2 + 0.6T_{ed} - 3 + 0.5T_{ed} - 4 + 0.4T_{ed} - 5 + 0.3T_{ed} - 6 + 0.2T_{ed} - 7)/3.8$$

Where: T_{rm} = outdoor running mean temperature for a certain day ($^{\circ}\text{C}$)
 T_{ed-1} = daily mean outdoor temperature for the previous day
 T_{ed-2} = daily mean outdoor temperature for the day before and so on.

5.4.4. Overheating Criteria

The overheating criteria referenced in TM52 were compiled by Teli et al. [24]. The paper states: “overheating criteria are based on the ‘adaptive’ approach to thermal comfort, which shows that occupants’ comfort temperature in naturally ventilated buildings responds to the outdoor weather conditions.” (p.846). The criteria are as follows:

Criterion 1: Hours of Exceedance (He)

Number of occupied hours when the indoor operative temperature (T_o) exceeds the upper limit of comfort temperature range (Category I for children, Category II for adults) by 1°C or more.

$$T_o > T_{max} + 1$$

There is overheating if:

$$He > 3\% \text{ of occupied hours}$$

Criterion 2: Weighted Exceedance (We)

For each day and for each 1°C above the upper limit of the comfort temperature range, the sum of the weighted exceedance should be less than or equal to 6.

$$We = \sum(\Delta T \times \text{time})$$

There is overheating if:

$$We > 6$$

Criterion 3: Absolute Upper Limit Temperature (T_{upp})

No indoor operative temperature must exceed the upper comfort limit by 4°C or more

$$T_o \leq T_{max} + 4$$

$$T_{upp} = T_{max} + 4$$

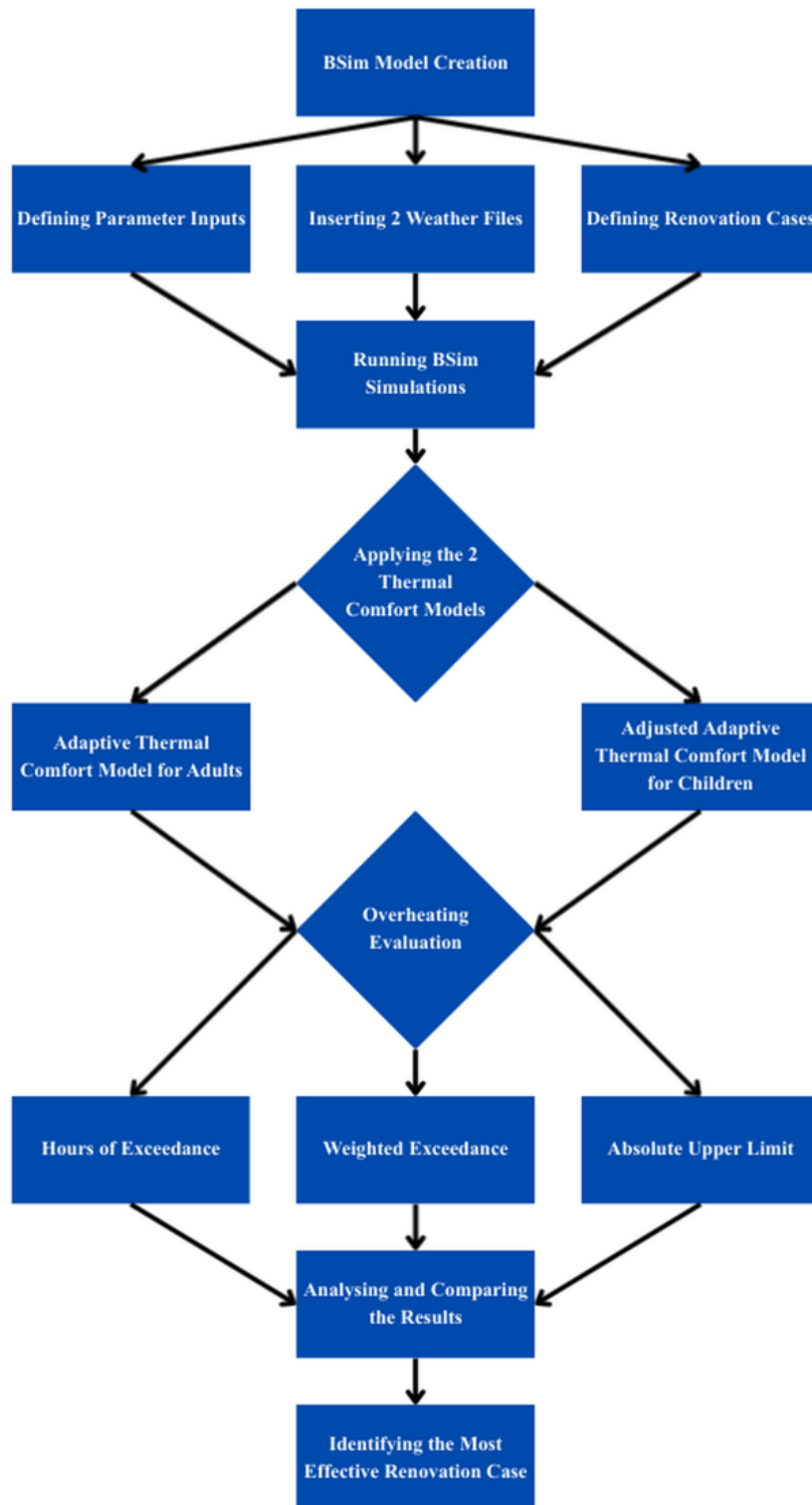
5.4.5. Simulation Period

According to the IEA EBC Annex 80 – Dynamic Simulation Guidelines [51], simulations must cover a period starting from one week before the heatwave to one month after the heatwave. As a baseline, a full-year simulation was carried out, with the warm period, from May to September, being evaluated for thermal comfort. In the future weather file, the heatwave occurs between 09/07/2054 and 05/08/2054. To evaluate the most sensible scenario, it is presumed that the classroom is being used in July (for example, other educational purposes); therefore, people load, equipment, and lighting schedules described in Subchapters 5.1.1-5.1.6 apply during the entire warm period.

To conclude, thermal comfort is evaluated for the occupied hours (08:00-16:00), from May to September.

A visual representation of the methodological process is visible in Figure 5.2: Methodology Chapter Process Map

Figure 5.2: Methodology Chapter Process Map



6. Results

This chapter presents the results of the calculations and simulations conducted for the base classroom model and all the individual and combined renovation scenarios.

6.1. Base model

During a normal summer conditions scenario, the base model of the classroom experiences significant overheating. For the adults, out of the total 704 occupied hours, from May to September, the indoor operative temperature exceeds the upper comfort limit by 1°C or more for 230 hours, or 32.67% (Criterion 1). Regarding children, criterion 1 is exceeded by 439 hours out of the total 704, corresponding to 62.35%. This is considerably high since there is overheating if more than 3% of the total occupied hours exceed the upper limit of the representative categories (Category II for the adults, and Category I for the children). The second criterion is well above the limits as well, as the sum of the weighted exceedance for adults reaches 47.59 and 71.36 for the children, while the criterion states the sum should be less than or equal to 6. The third criterion, or the absolute upper temperature limit, is exceeded too. For adults, 74 hours exceed the limit, while for children, it is 213 hours. This is quite high as well, considering that no hours should exceed that limit. The maximum operative temperature reached is 37.2 °C.

With the heatwave scenario, the overheating intensifies. There is a total of 696 occupied hours in this simulation. That is due to different years having different amounts of working days, thus hours. Regarding criterion 1 and adults, 277 hours exceed the upper comfort limit by 1°C or more, corresponding to 39.8% of the occupied period. For the children, it is again higher than in normal conditions, 545 hours or 78.30% of the occupied period. The sum of the weighted exceedance is lower than in the normal condition, with 29.38 for the adults and 53 for the children. Hours above the absolute upper temperature limit are also lower for adults, 74 hours, but higher for children, 213 hours. The maximum operative temperature is 34.52 °C. These unexpected differences between the normal condition and the heatwave results, such as lower weighted exceedance, the absolute upper temperature for adults, and the maximum operative temperature, could be due to different meteorological inputs in the two weather files. The summary can be seen in Table 6.1: Base Model Simulation Result Summary, Normal Summer Conditions and Heatwave Scenario.

Table 6.1: Base Model Simulation Result Summary, Normal Summer Conditions and Heatwave Scenario

Scenario	Occupant	Total Occupied Hrs	Hrs Exceed	He%	Weighted Exc	Max Op Temp	Avg Op Temp	Avg Rm Temp	Crit3 Hrs Exceed
BaseNormal	Adults	704	230	32,67	47,59	37,2	26,71	15,18	74
BaseNormal	Children	704	439	62,35	71,36	37,2	26,71	15,18	213
BaseHeatwave	Adults	696	277	39,80	29,38	34,52	27,57	16,26	52
BaseHeatwave	Children	696	545	78,30	53,00	34,52	27,57	16,26	263

6.2. Improved Envelope

The thicker insulation and new and better windows, in fact, worsen the overheating. During normal summer conditions, for adults, 331 hours, or 47% of the total occupied period, exceed the upper comfort limit by 1°C or more, while with the base model, it is 230 hours or 32.67%. For children, even more, 538 hours or 76.4%, compared to 439 hours or 62.35%.

The sum of the weighted exceedance is higher too, 61.29 for the adults and 85.06 for the children. The hours above the absolute upper temperature limit are quite high as well. For the adults, 159 hours are above the limit, 85 more than in the normal conditions, while for the children, 310 hours are above the limit, 97 hours more than in the normal conditions. The maximum operative temperature reaches an astounding 39.37 °C.

It is even more severe during the heatwave. Out of the total 696 hours, 419 hours exceed the upper comfort limit for adults with the improved envelope, equivalent to 60%, compared to 277 hours or 39.8% in the base model. For children, it is even more critical, 609 hours or 87.51%, compared to 545 hours or 78.30%. Similar to the base model's normal condition and heatwave comparison, the sum of the weighted exceedance is lower, with 41.75 for the adults and 65.37 for the children. Though the exceedance is lower, it is still far above the overheating limit, which is less than or equal to 6. Regarding the adults, 164 hours are above the criterion 3, or the absolute upper temperature limit, while for the children, 393 hours. The maximum operative temperature is lower than during normal summer conditions, but still very high, 36.57 °C. For the improved envelope, the summary is presented in Table 6.2: Improved Envelope Simulation Result Summary, Normal Summer Conditions and Heatwave Scenario.

Table 6.2: Improved Envelope Simulation Result Summary, Normal Summer Conditions and Heatwave Scenario

Scenario	Occupant	Total Occupied Hrs	Hrs exceed	He%	Weighted Exc	Max Op Temp	Avg Op Temp	Avg Rm Temp	Crit3 Hrs Exceed
Envelope Normal	Adults	704	331	47,00	61,29	39,37	28,081	15,22	159
Envelope Normal	Children	704	538	76,40	85,06	39,37	28,081	15,22	310
Envelope Heatwave	Adults	696	419	60,00	41,75	36,57	29,00	16,26	164
Envelope Heatwave	Children	696	609	87,51	65,37	36,57	29,00	16,26	393

6.3. Shading

The addition of external venetian blinds slightly reduces overheating compared to the base model. For the adults, the hours regarding criterion 1 during normal summer conditions decrease from 230 hours in the base model to 216 hours with the addition of shading. Percentage-wise, that is a decrease from 33.38% to 30.67% of the total occupied time for the adults. The hours for the children also decrease slightly, from 442 hours to 430 hours, or from 62.78% to 61.08%. The sum of weighted exceedance has a modest increase, from 47.59 for the adults and 71.36 for the children in the base model, to 48 for the adults and 71.77 for the children with the shading addition. Though hours that exceed the absolute upper limit reduce slightly, they nevertheless remain high. They decrease from 76 hours for adults to 68 hours, and from 213 hours for the children to 202 hours. The maximum operative temperature reached is still a very high 37.2 °C.

The results are similar during a heatwave scenario, as the overheating is only slightly reduced. The hours exceeding the upper comfort limit by 1 °C or more, decrease from 277 hours to 271 hours for the adults, or from 39.8% to 38.94%. Correspondingly, the hours decrease from 540 hours to 536 hours for the children, or from 77.59% to 77%. The weighted exceedance increases from 29.38 for adults in the base model to 29.83 with the shading during the heatwave scenario, and from 53 to 53.45 for the children. Furthermore, there is a slight decrease in the hours above the absolute upper limit. For the adults, from 52 in the base

model's heatwave scenario to 48 with the addition of the external venetian blinds, and for the children, from 263 hours to 258 hours. Lastly, the maximum operative temperature has been minimally reduced by 0.02 °C, now being 34.5 °C. The summary can be seen in Table 6.3: Shading Simulation Result Summary, Normal Summer Conditions and Heatwave Scenario.

Table 6.3: Shading Simulation Result Summary, Normal Summer Conditions and Heatwave Scenario

Scenario	Occupant	Total Occupied Hrs	Hrs Exceed	He %	Weighted Exc	Max Op Temp	Avg Op Temp	Avg Rm Temp	Crit3 Hrs Exceed
Shading Normal	Adults	704	216	30,67	48,00	37,2	26,57	15,22	68
Shading Normal	Children	704	430	61,08	71,77	37,2	26,57	15,22	202
Shading Heatwave	Adults	696	271	38,94	29,83	34,5	27,52	16,26	48
Shading Heatwave	Children	696	536	77,00	53,45	34,5	27,52	16,26	258

6.4. Night Cooling

The night cooling reduces the overheating to some degree. During normal summer conditions and for adults, the hours exceeding the upper comfort limit decline from 230 in the base model to 195, or from 32.67% to 27.7% of the total occupied period. There is a slight reduction for the children too, from 439 hours to 396 hours, or from 62.35% to 56.39%. The sum of weighted exceedance reduces from 47.59 to 38.24 for the adults, and from 71.36 to 62.01 for the children. Hours above the absolute upper limit decrease to 53 hours, from the initial 74 hours in the base model during normal summer conditions. For the children, the hours decrease from 213 to 183. The maximum operative temperature has a very modest reduction, now being 36.28 °C.

The overheating reduces during the heatwave scenario as well. The hours exceeding the upper comfort limit decrease from 277 to 204 for the adults, or from 39.8% to 29.31%. Regarding the children, the hours decrease from 545 to 496, or from 78.3% to 71.25%. The sum of the weighted exceedance is also lower. With the utilisation of night cooling, the sum is 20.53 for the adults, compared to 29.38 in the base model's heatwave scenario, and for the children, 41.71, compared to 53. Among the improved envelope, the addition of shading and the utilisation of night cooling, night cooling demonstrates the highest efficiency regarding criterion 3. The hours above the absolute upper limit decrease from 52 to 26 for the adults, and from 263 to 188 for the children. The maximum operative temperature reaches 33.34 °C. Table 6.4: Night Cooling Simulation Result Summary, Normal Summer Conditions and Heatwave Scenario illustrates the presented results.

Table 6.4: Night Cooling Simulation Result Summary, Normal Summer Conditions and Heatwave Scenario

Scenario	Occupant	Total Occupied Hrs	Hrs Exceed	He%	Weighted Exc	Max Op Temp	Avg Op Temp	Avg Rm Temp	Crit3 Hrs Exceed
Night Cooling Normal	Adults	704	195	27,70	38,24	36,28	26,32	15,22	53
Night Cooling Normal	Children	704	396	56,39	62,01	36,28	26,32	15,22	183
Night Cooling Heatwave	Adults	696	204	29,31	20,53	33,34	26,89	16,26	26
Night Cooling Heatwave	Children	696	496	71,25	41,71	33,34	26,89	16,26	188

6.5. Shading and Night Cooling

Among the renovation cases discussed so far, the combination of shading and night cooling demonstrates the highest efficiency in decreasing overheating. During normal summer conditions, hours regarding criterion 1 for the adults decrease from 230 in the base model to 169 in the shading and night cooling combination model, and from 439 to 357 for the children. Percentage-wise, from 32.67% to 24.01% of the total occupied period for the

adults, and from 62.35% to 50.71% for the children. The sum of the weighted exceedance decreases from 47.59 to 35.12 for the adults and from 71.36 to 58.60 for the children. Although the decrease is substantial, the values remain exceptionally high. The most significant reduction can be seen regarding criterion 3. From 74 hours regarding the adults in the base model, to 38 hours with the combination of shading and night cooling, and regarding children, from 213 hours to 152 hours. The maximum operative temperature has reduced by 1.35 °C, now being 35.85 °C.

In the heatwave scenario, the hours exceeding the upper comfort limit decrease from 277 to 160 for the adults, from 39.80% to 30%, and for the children, from 545 hours or 78.3% to 442 hours or 63.51%. There is also a reduction in the sum of the weighted exceedance. For the adults, the sum with the base model heatwave scenario is 29.38, and with the shading and night cooling combination, 18.69. For the children, it decreases from 53 to 39.45. Similar to the normal summer condition scenario, the most significant reduction is seen regarding criterion 3. The hours above the absolute upper limit decrease from 52 to 15 for the adults, and from 263 to 151 for the children. The maximum operative temperature in this scenario reaches 33.05 °C. The summary is presented in Table 6.5: Shading and Night Cooling Simulation Result Summary, Normal Summer Conditions and Heatwave Scenario.

Table 6.5: Shading and Night Cooling Simulation Result Summary, Normal Summer Conditions and Heatwave Scenario

Scenario	Occupant	Total Occupied Hrs	Hrs Exceed	He%	Weighted Exc	Max Op Temp	Avg Op Temp	Crit3 Hrs Exceed
S+NC Normal	Adults	704	169	24,01	35,12	35,85	25,76	38
S+NC Normal	Children	704	357	50,71	58,60	35,85	25,76	152
S+NC Heatwave	Adults	696	160	30,00	18,69	33,05	26,43	15
S+NC Heatwave	Children	696	442	63,51	39,45	33,05	26,43	151

6.6. Improved Envelope, Shading and Night Cooling

When the improved envelope, which includes the addition of thicker insulation and new triple-glazed windows, is combined with shading and night cooling, overheating is reduced compared to the base model; however, it does not outperform the shading and night cooling scenario demonstrated in Chapter 6.5. During normal summer conditions and in the base model, the adults experience 230 hours exceeding the upper comfort limit by 1°C or more, while in this scenario, 188 hours. It is a decrease from 32.67% to 26.7% of the total occupied hours over the limit. Children experience 380 hours in this scenario, compared to 439 in the base model. That is now 53.98%, compared to the base model's 62.35%. The sum of the weighted exceedance decreases from 47.59 to 37.88 for the adults, and from 71.36 to 61.65 for the children. The hours exceeding the absolute upper limit are also lower than the base model's scenario, but higher than the shading and night cooling scenario, from 74 hours to 50 hours for the adults, and from 213 hours to 169 hours for the children. The maximum operative temperature reaches 36.27 °C.

With the heatwave scenario, this combination results in 191 hours exceeding the upper comfort limit for the adults, compared to the 277 hours in the base model's heatwave scenario. That is now 27.44%, compared to 39.80%. For the children, it decreases from 545 hours to 467 hours. That is an additional 25 hours more compared to just using shading and night cooling. Percentage-wise, it is a decrease from 78.30% to 67.10%. The sum of the

weighted exceedance decreases from 29.38 to 20.47 for the adults and from 53 to 41.58 for the children. The most significant decrease is again with criterion 3, from 52 hours to 25 for the adults, and from 263 hours to 177 hours for the children. The maximum operative temperature with this renovation case during a heatwave is 33.34 °C. Lastly, for the renovation case when the shading and night cooling are combined with the improved envelope, the results are summarised in Table 6.6: Improved Envelope, Shading and Night Cooling Simulation Result Summary, Normal Summer Conditions and Heatwave Scenario.

Table 6.6: Improved Envelope, Shading and Night Cooling Simulation Result Summary, Normal Summer Conditions and Heatwave Scenario.

Scenario	Occupant	Total Occupied Hrs	Hrs exceed	He %	Weighted Exceed	Max Op Temp	Avg Op Temp	Crit3 Hrs Exceed
Impr Env+S+NC Normal	Adults	704	188	26,70	37,88	36,27	26,08	50
Impr Env+S+NC Normal	Children	704	380	53,98	61,65	36,27	26,08	169
Impr Env+S+NC Heatwave	Adults	696	191	27,44	20,47	33,34	26,73	25
Impr Env+S+NC Heatwave	Children	696	467	67,10	41,58	33,34	26,73	177

6.7. In-depth Analysis

For a better understanding of the thermal behaviour of the classroom, multiple plot analyses were developed. Two days were selected to be shown, representing normal summer conditions (August 9, 2013) and a heatwave scenario (July 22, 2054). These days have the highest indoor operative temperatures within their weather files, therefore representing critical conditions for the occupants.

The first analysis compares the indoor operative temperatures of the base model and each renovation scenario, for each hour of the two representative days. Figure 6.1 represents the hourly indoor operative temperatures on August 9, 2013, during normal summer conditions. In this figure, the base model is shown with a dark blue line, which is barely visible since it is overlapped by the shading's green line. The base model has indoor operative temperatures exceeding 37 °C in the afternoon and temperatures that remain above 30 °C in the evening. This results from a combination of high outdoor temperatures, high solar gains, internal loads during occupied hours and the lack of an active cooling system.

The improved envelope, shown in dark red, performs the worst during this day as well. Despite the improved insulation and new, better windows, the maximum operative temperature rises considerably, reaching nearly 40 °C in the early afternoon. This confirms that without a complementary effective heat gain reduction and heat removal solution, better insulation can worsen the overheating by trapping the heat from the sun and the internal loads inside the room.

The shading follows the base model line almost identically, meaning that on the selected day, the external shading does not prove to be effective in reducing the overheating. This could be due to several factors, including lower solar gains that day or high indoor temperatures that external shade cannot compensate for.

With night cooling, shown in pink, a clear improvement compared to the base model can be seen. This renovation strategy lowers the indoor temperatures early in the morning and therefore reduces the overall indoor temperature throughout the day. From 23:00, when the

night cooling starts, until 08:00, when it ends, there is a noticeable drop in the indoor operative temperature compared to the base model.

The combination of shading and night cooling in bright blue shows the most significant improvement among all the renovation cases, even during a single representative day. The maximum operative temperature is nearly 2 °C lower than in the base model and nearly 4 °C lower than with the improved envelope alone. The temperatures are lower both throughout the day and the evening. This highlights the importance of having both heat gain reduction (shading) and a heat removal solution (night cooling).

The fully combined renovation case of an improved envelope, shading and night cooling, offers a clear improvement as well, yet not as effective as shading and night cooling alone. This renovation scenario is shown with an orange line. The indoor operative temperatures are around 0.5 °C higher than without the improved envelope. Although the improved envelope alone worsens the overheating significantly, this combination proves that the particular renovation scenario can be effective when combined with other solutions.

Figure 6.1: Indoor Operative Temperature Comparison, All Renovation Scenarios - Normal Summer Conditions on 09.08.2013

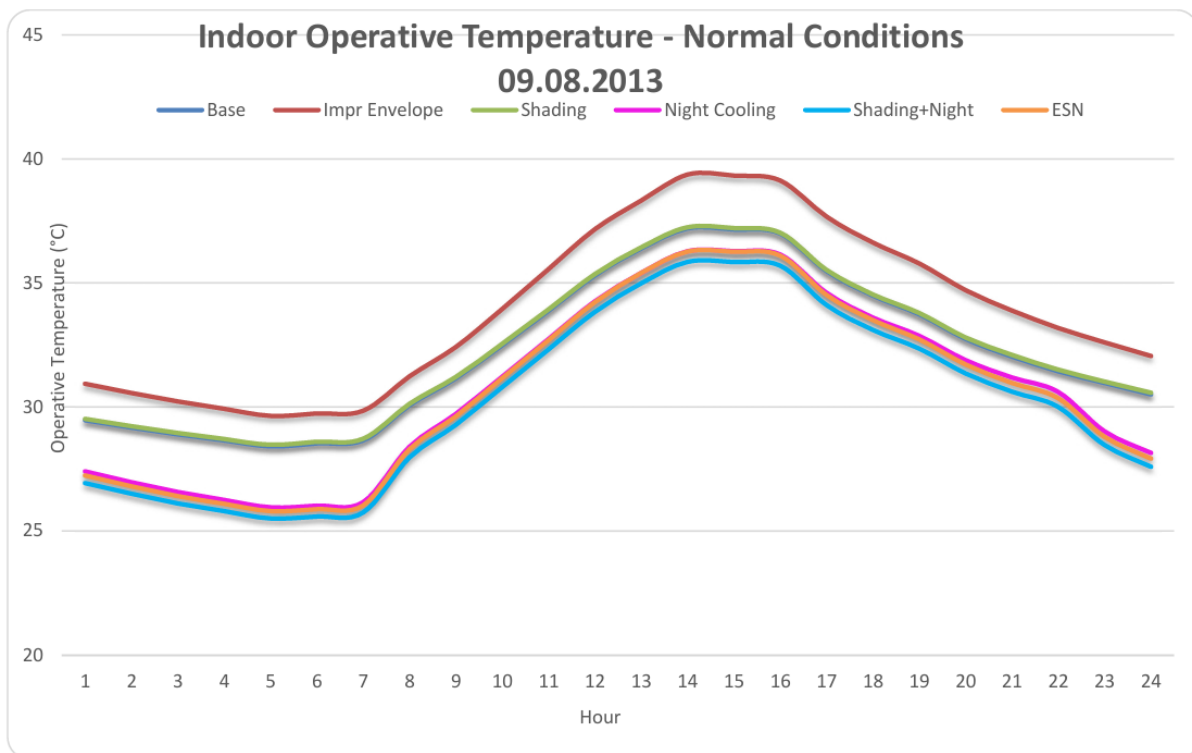


Figure 6.2 presents the indoor operative temperatures on 22. July 2054, representing a critical day during a future heatwave scenario.

Similar to the normal summer condition scenario, the improved envelope worsens the overheating and demonstrates the highest indoor operative temperatures, with the maximum operative temperature being 36.5 °C, 2 °C higher compared to the base model. Once more,

this confirms that, if not combined with other heat gain reduction or heat removal solutions, the improved envelope, alone as a renovation case, traps the heat inside and increases indoor operative temperatures.

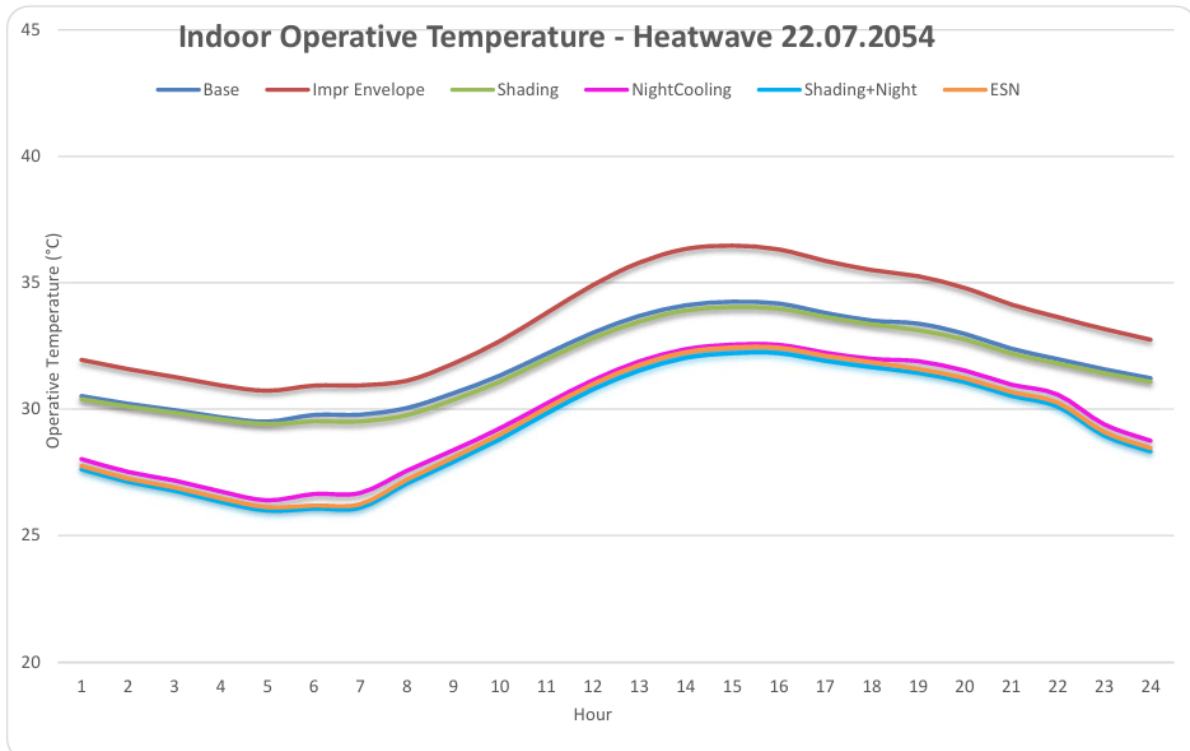
The external shading in this case showcases minimal heat reduction. The line closely follows the base model line, with indoor operative temperatures being 0.1-0.2 °C lower throughout the day.

Night cooling again demonstrates a significant reduction compared to the base model and the shading solution. Just as with normal summer conditions, during a heatwave, the night cooling lowers the indoor operative temperature early in the morning, which reduces the temperature throughout the whole day.

The combined shading and night cooling scenario, shown with a light blue line, remains the most effective solution, lowering the indoor operative temperatures the most. The maximum operative temperature reached is 2 °C lower compared to the base model and more than 4°C lower than with the improved envelope alone.

The fully combined renovation case has the same effect as during normal summer conditions; it reduces the overheating, but it is not as effective as without the improved envelope. Again, the indoor operative temperatures are around 0.5 °C higher than without the improved envelope.

Figure 6.2: Indoor Operative Temperature Comparison, All Renovation Scenarios – Heatwave on 22.07.2054



The representative day analyses reveal the timing of the overheating, which is not visible in the overheating results summaries alone. Peak indoor temperatures occur mid-afternoon, when children are in school. Evening temperatures in both weather scenarios reveal that the classroom cannot effectively get rid of the high temperatures. Furthermore, the analyses visually show how much the improved envelope worsens the overheating, and lastly, they confirm and visually demonstrate that the combined renovation scenarios perform better than individual ones.

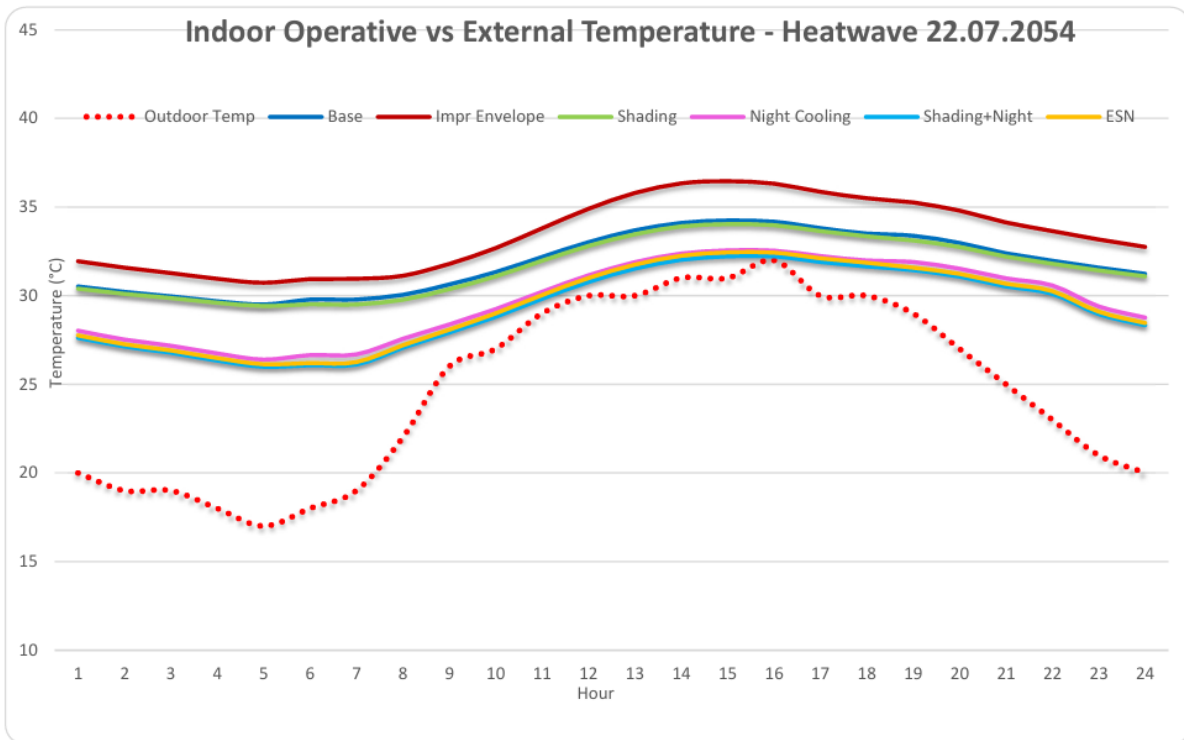
To further investigate how all the renovation cases perform during an overheating weather event, the relationship between the indoor operative temperatures and the external temperature was analysed. 22nd of July 2054 was again chosen as the representative day, as seen in Figure 6.3.

The outdoor temperature reaches 30 °C at noon and exceeds it or stays that way until 18:00. Both the maximum indoor operative and external temperature occur between 15:00 and 16:00. The maximum indoor operative temperature for the base model reached that day is 34.25 °C, while the maximum external temperature is 32 °C.

Despite the external temperatures being the same for each renovation case, the improved envelope shows the highest indoor operative temperatures throughout the entire day. On the other hand, the shading and night cooling scenario shows the lowest indoor operative temperatures.

This analysis shows that during a heatwave, the indoor operative temperatures increase and decrease in relation to external temperatures, but the ability of the building to reduce the overheating depends on its' renovation case. The plot once again demonstrates that individual renovation cases are insufficient in reducing the overheating and that combined scenarios showcase better results.

Figure 6.3: Indoor Operative Temperatures and the External Temperature- Heatwave on 22.07.2054



To evaluate the effectiveness and the consistency of the renovation cases beyond the two representative days, Figures 6.4 and 6.5 show the indoor operative temperature improvements compared to the base model during the entire warm period (May-September). The analysis was made for both normal summer conditions and the future heatwave scenario. Positive values on the x-axis indicate improvements regarding the overheating, thus a decrease in indoor operative temperatures, while negative values indicate an increase in indoor operative temperatures.

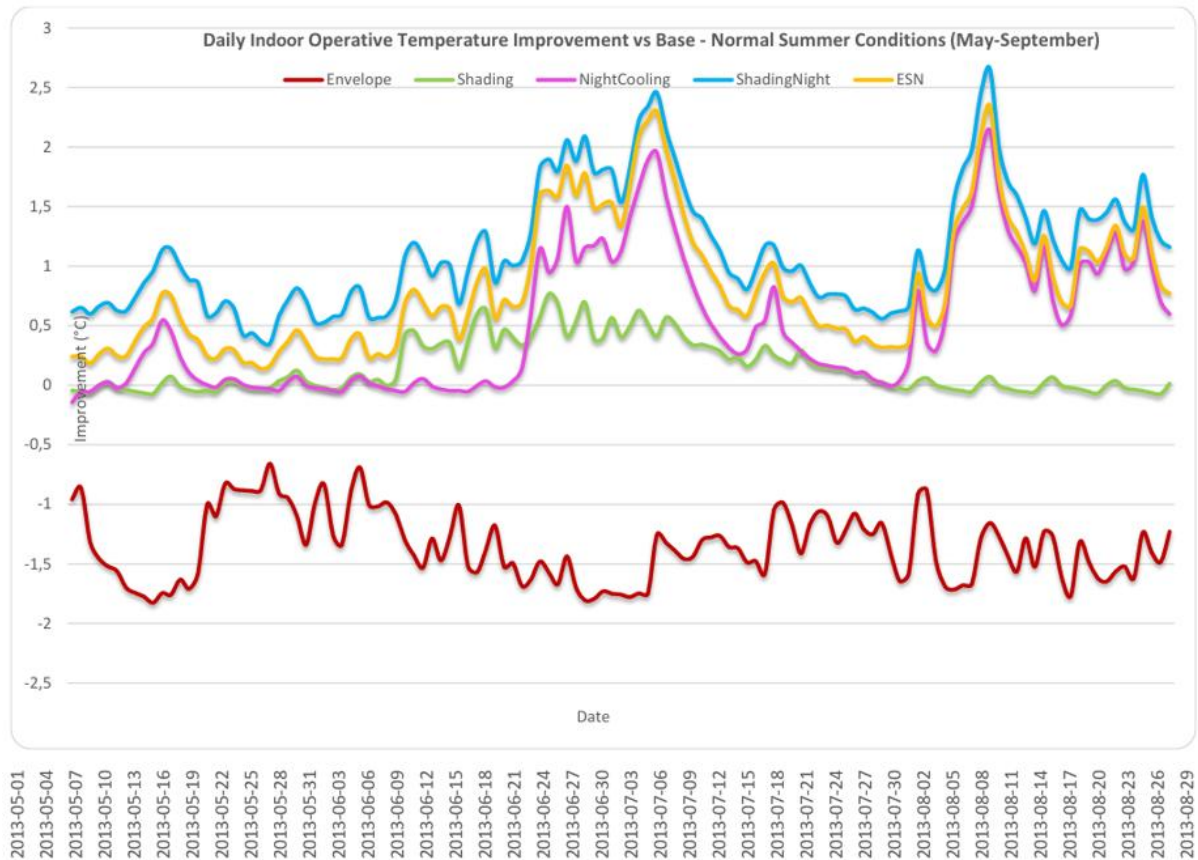
During normal summer conditions, Figure 6.4, the improved envelope, again shown in dark red, continuously demonstrates negative improvements throughout the whole period, confirming that, when not combined with other renovation cases, the reduced heat loss increases the indoor operative temperatures, worsening the indoor thermal conditions.

These plots visibly demonstrate the effectiveness of the shading renovation case, which generally reduces the indoor operative temperatures up to 0.5 °C, with more significant reductions occurring at the end of June and during the first several days of July. This solution is marked with a green line.

The night cooling demonstrates better improvements, particularly during warmer periods such as late June, early July and early August. The variation occurs since the night coolings' effectiveness depends on the diurnal temperature range, with better results occurring when the external temperatures at night are significantly lower than daytime temperatures, allowing more stored heat to be released.

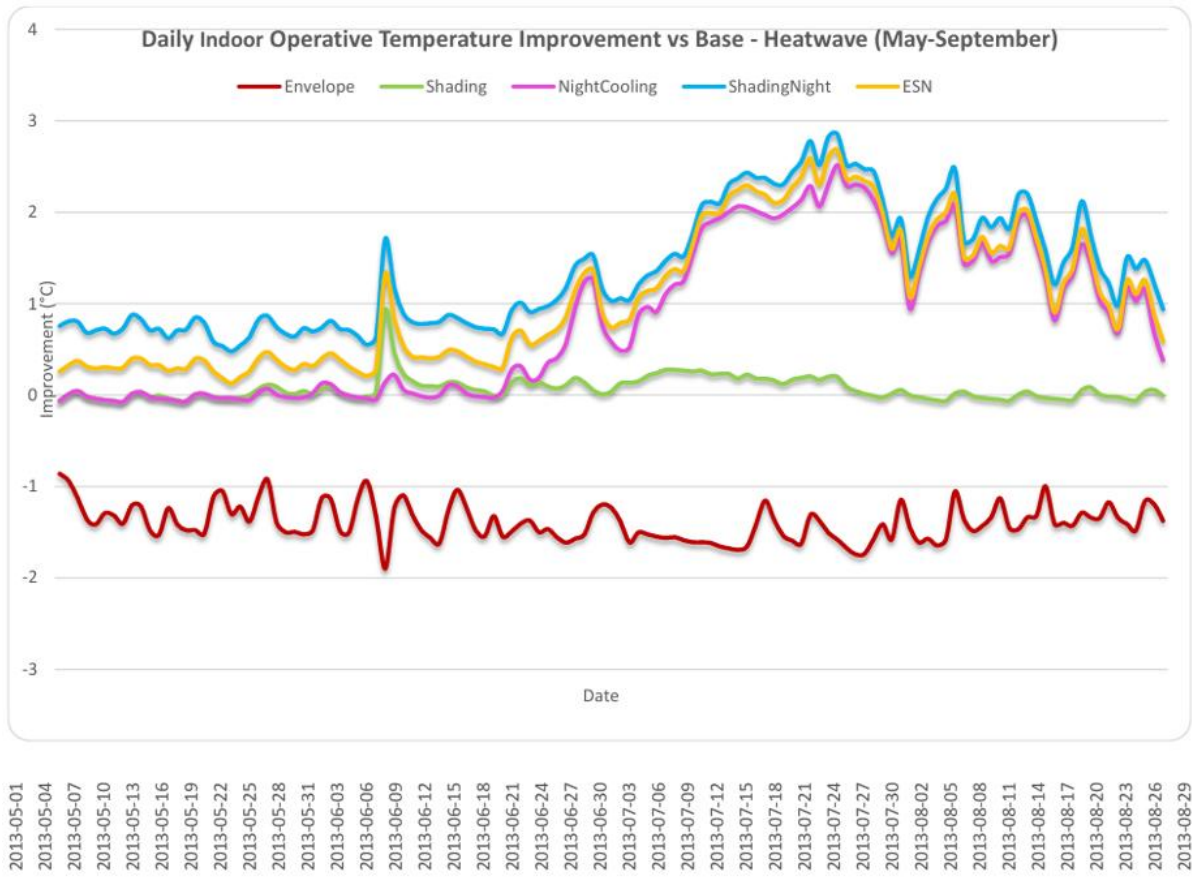
The shading and night cooling combination, marked with light blue, proves to be the most effective solution in reducing the overheating throughout the entire warm period, with the fully combined renovation case, marked with orange, coming close behind, especially during the warmest periods.

Figure 6.4: Daily Indoor Operative Temperature Improvements vs Base - Normal Summer Conditions (May-September)



Regarding the heatwave scenario shown in Figure 6.5, the renovation cases are showing similar effectiveness. The improved envelope again demonstrates negative improvements, while the shading shows marginal improvements. As an individual renovation case, night cooling demonstrates the best result, while the shading and night cooling as a combined renovation scenario remains the best solution.

Figure 6.5: Daily Indoor Operative Temperature Improvements vs Base - Heatwave (May-September)



7. Discussion

This study investigated the thermal comfort of the children in a representative Danish classroom during both typical normal summer conditions and a future heatwave scenario. The discussion chapter focuses on analysing the results regarding the applied thermal comfort models, the simulated renovation cases and the overheating criteria.

7.1. Thermal Comfort Results Analysis

The results indicate that overheating occurs during both weather scenarios and with all renovation cases. However, when the classroom is evaluated with the children's adjusted adaptive thermal comfort model, the exceedances are consistently higher. An expected outcome since the children's model is defined with a lower comfort temperature, and the IEQ expectations are stricter than those of adults. Furthermore, the results support the existing literature showing that children have increased thermal sensitivity, as reflected in lower comfort temperature limits.

A significant conclusion is that, when assessing the overheating with the TM52 criteria, certain acceptable periods with no overheating according to the adult criteria do not regularly correspond to acceptable conditions for the children. For the same operative temperatures, the adult adaptive thermal comfort model shows compliance across multiple scenarios, while the children's adjusted adaptive thermal comfort model exceeds one or more TM52 criteria. This is visible in the frequently higher proportion of exceedance hours (Criterion 1) and the higher number of hours above the absolute limit (Criterion 3) for children across both the base model and all renovation scenarios.

To summarise, even in certain acceptable conditions for adults, but also when they experience thermal discomfort, children are impacted considerably more. The differences in overheating intensity between adults and children in the investigated weather scenarios and renovation cases are summarised in Table 7.1: Comparison of the Overheating Criteria Results for Adults and Children during Normal Summer and Heatwave Conditions. To keep it concise, Criterion 2 was not included in the table, as Criteria 1 and 3 already define the frequency and intensity of overheating.

Table 7.1: Comparison of the Overheating Criteria Results for Adults and Children during Normal Summer and Heatwave Conditions

Scenario	Normal: Adults C1 %	Normal: Children C1 %	Normal: Adults C3 hours	Normal: Children C3 hours	Heatwave: Adults C1 %	Heatwave: Children C1 %	Heatwave: Adults C3 hours	Heatwave: Children C3 hours
Base	32.67	62.35	74	213	39.8	78.3	52	263
Improved Envelope	47	76.4	159	310	60	87.51	164	393
Shading	30.67	61.08	68	202	38.94	77	48	258
Night cooling	27.70	56.39	53	183	29.31	71.25	26	188
Shading + Night cooling	24.00	50.71	38	152	30.00	63.51	15	151
Improved Envelope + Shading + Night cooling	26.70	53.98	50	169	27.44	67.10	25	177

Note: C1= % of occupied hours where $T_{op} > T_{max} + 1$ °C (threshold is 3%)

C3= number of occupied hours where $T_{op} > T_{max} + 4$ °C

7.2. Renovation Cases Effectiveness

7.2.1. Improved Envelope

Not all renovation cases investigated in this study proved to be effective in reducing overheating. The improved envelope worsened the overheating situation for a significant number of hours in both normal summer conditions and the heatwave. This is reflected in the highest operative temperatures, a higher number of overheating hours and the highest criteria 1 and 3 results. This can be explained by the reduced heat losses. During the heating season, it could be beneficial to keep the heat in, but during the warm summer period, and especially during the heatwave, this proves to be inconvenient. With the improved insulation and better windows, but with the absence of an active cooling or a mechanical ventilation system, the internal heat loads and solar heat gains remain in the room, leading to higher operative temperatures and overheating hours.

7.2.2. Shading

The addition of external shading resulted in relatively minor improvements regarding overheating. Though the maximum operative temperatures remained essentially the same, there is a slight decrease in the TM52 overheating criteria during both weather scenarios. While the external venetian shading slightly reduces solar gains, it does not get rid of the internal heat loads within the room. This means that shading alone cannot sufficiently reduce the overheating and, therefore, for better results, should be combined with other renovation solutions. One advantage of this renovation case is its' simplicity and cost-effectiveness, as it takes relatively minimal work compared to other solutions, and can be assembled completely from the exterior.

7.2.3. Night Cooling

While still a very minimal decrease regarding overheating, night cooling has been demonstrated to be the most effective individual renovation case. The results show a decrease in maximum operative temperatures, overall overheating hours and all the overheating criteria during both normal summer conditions and the heatwave scenario. Night cooling is effective since it removes heat which accumulates during the day, with the cool air that enters the room during the night, cooling the building structure and reducing the indoor temperature. Compared to the improved envelope and the shading renovation cases, the night cooling focuses on heat removal, rather than heat gain reduction and prevention. Although night cooling demonstrates a decrease in overheating, relying on it alone as a renovation solution is insufficient.

7.2.4. Shading and Night Cooling

The combination of shading and night cooling is the most effective renovation case evaluated in this study. This scenario resulted in the lowest number of overheating hours, and all three TM52 criteria, outperforming all individual renovation cases during both normal summer conditions and the heatwave scenario. These results highlight the importance of utilising both heat gain reduction (shading) and heat removal (night cooling) simultaneously. Shading reduces solar gains during the day, while night cooling removes accumulated heat during the night, improving the indoor thermal conditions.

7.2.5. Improved Envelope, Shading and Night Cooling

When the improved envelope is added to the combination of shading and night cooling, the results show a worse performance compared to the combination of shading and night cooling alone. Although this case performs better than all the individual renovation cases, it is less effective than one without the improved envelope. This again demonstrates that the improved envelope traps the heat inside, even when other renovation strategies are applied. These results highlight that envelope improvements must be supported by adequate cooling solutions, particularly when buildings rely on natural ventilation.

Although the shading and night cooling combined renovation case is the most effective in reducing the overheating, it does not eliminate it in either of the weather scenarios. This suggests that passive renovation strategies, such as those previously evaluated, may not be sufficient in maintaining acceptable or comfortable indoor thermal environments for vulnerable groups, especially during an extreme weather event in the future, such as a heatwave. Therefore, the results indicate that additional measures, such as a mechanical ventilation system, may be required to ensure sufficient heat removal and acceptable IEQ.

7.3. Weather Scenarios and Heatwave Timing

Comparing the simulation results from the normal summer condition weather file with the heatwave scenario weather file reveals that higher external temperatures do not always lead to higher indoor overheating. On the contrary, with the heatwave weather file, in all the individual and combined renovation cases, the maximum operative temperature reached, the

weighted exceedance and the number of hours exceeding the absolute upper limit are persistently lower than under normal summer conditions.

The lower maximum operative temperatures can be explained by the differences in the climatic variables within the weather files, such as temperature data, solar radiation data, wind, precipitation, humidity and cloud cover data. Although the heatwave weather file represents a prolonged period of extremely warm temperatures, it does not necessarily include the same short-term high temperature peaks as the normal summer condition weather file.

During the heatwave scenario, higher external temperatures increase the running mean temperature, which has a direct impact on the comfort category limits used in the evaluation. Since both adults and children have their acceptable temperature ranges based on the running outdoor mean temperature, the upper comfort limits increase during prolonged warm periods. Consequently, high indoor operative temperatures may exceed the limit by a smaller margin than they would in the normal summer conditions. This clarifies why, in comparison to the normal summer conditions scenario, the heatwave scenario results in lower weighted exceedance and fewer hours exceeding the absolute upper temperature limit. The weighted exceedance depends on both the duration of overheating and the extent to which indoor temperatures are above the comfort threshold. Lastly, regarding the absolute upper temperature limit (criterion 3), since the comfort limits are higher during a heatwave scenario, the criterion's threshold becomes harder to reach, even though indoor operative temperatures are higher.

Even though the children in Denmark usually have summer holidays in July, to evaluate the worst-case scenario, the classroom was assumed to be occupied. An additional analysis excluding July was conducted and showed a decrease in overheating hours and TM52 criteria. A summary of the analysis is shown in Appendix B. Nevertheless, since the timing of a heatwave is unpredictable and can happen during both holidays and the school period, and the fact that the school can be used for different purposes, July was therefore included in this study.

7.4. Delimitations

One significant limitation of this study is that the BSim model, although based on literature, is a fictional representation of a Danish classroom, rather than a validated case with measured indoor climate data. With such models, it is difficult to portray real-world occurrences, such as occupant behaviour, equipment usage and window operation, to name a few. For the aim of this study, the lack of validation does not compromise the results, since all the renovation scenarios are based on the same parameters.

8. Conclusion

This study evaluated the overheating risk in a representative Danish primary school classroom using both adult and children-adjusted adaptive thermal comfort models, during normal summer conditions and a heatwave scenario. Multiple renovation cases were selected, simulated and evaluated to determine their ability to reduce overheating and improve the indoor thermal environment for the children. This was done using BPS in BSim. The overheating was evaluated using the three TM52 overheating criteria.

Answering the First Research Question: How does the overheating risk in a classroom differ when using both adult and children-adjusted adaptive thermal comfort models during normal summer and heatwave conditions?

The results show that overheating hours are continuously higher during both weather scenarios when evaluated with the children-adjusted adaptive thermal comfort model, compared to the adult adaptive thermal comfort model. For the identical indoor operative temperatures, the children-adjusted model resulted in more frequent and severe thermal comfort exceedances and higher values regarding the TM52 overheating criteria. This is due to the lower comfort temperature thresholds specified for the children, which causes overheating to be identified earlier and more frequently.

Answering the Second Research Question: Which renovation cases reduce overheating in the classroom the most and improve children's thermal comfort?

Regarding the individual renovation cases, the night cooling proved to be efficient, though, reducing the overheating marginally. The renovation scenario that reduced overheating the most is the combined case of night cooling and shading. On the other hand, results demonstrated that improving the building's envelope by installing thicker insulation and better windows worsens the overheating risk by a significant amount.

To summarise key findings in this study, overheating is a significant issue in the representative classroom during both normal summer conditions and especially during a heatwave scenario. Depending on the renovation case and the applied thermal comfort model, the frequency and the severity of the overheating changed. With the same indoor operative temperatures, the adjusted adaptive thermal comfort model for children continuously demonstrated a higher number of overheating hours compared to the adult model. Not all renovation cases proved to be effective, as the improved envelope worsened the overheating significantly. The night cooling proved to be effective while the shading had minimal impact. However, the combined renovation case of shading and night cooling emerged as the most effective way of reducing overheating among all assessed cases.

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Appendices

Appendix A - BSim Model and Calculations

Figure A.1: BSim Classroom Model, Front View (Left) and Back View (Right)

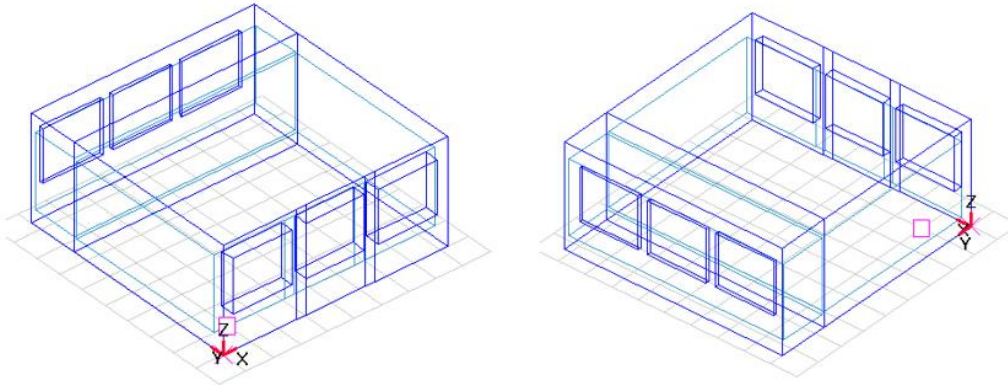


Table A.1: Current Construction Values and BR18 Requirements

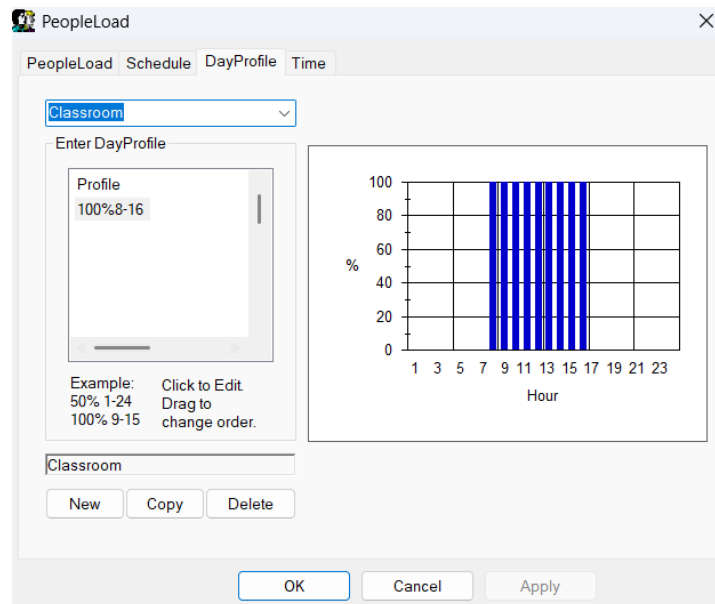
Construction	Current Values	BR18 Requirements
facade infill	$U = 0.50 \text{ W/m}^2\text{K}$	$0.18 \text{ W/m}^2\text{K}$
facade column	$U = 0.92 \text{ W/m}^2\text{K}$	$0.18 \text{ W/m}^2\text{K}$
windows	glazing - $U = 2.7 \text{ W/m}^2\text{K}$, frame - $U = 1.9 \text{ W/m}^2\text{K}$	$\leq 17.0 \text{ kWh/m}^2 \text{ per year}$

As previously mentioned in the main paper, the teacher was characterised as a child, having the same Resting Metabolic Rate (RMR) and Body Surface Area (BSA) characteristics, meaning that in the tool, the final input parameter was 21 children. The people load calculation can be seen in Figure A.25.

Figure A.2: BSim People Load Input

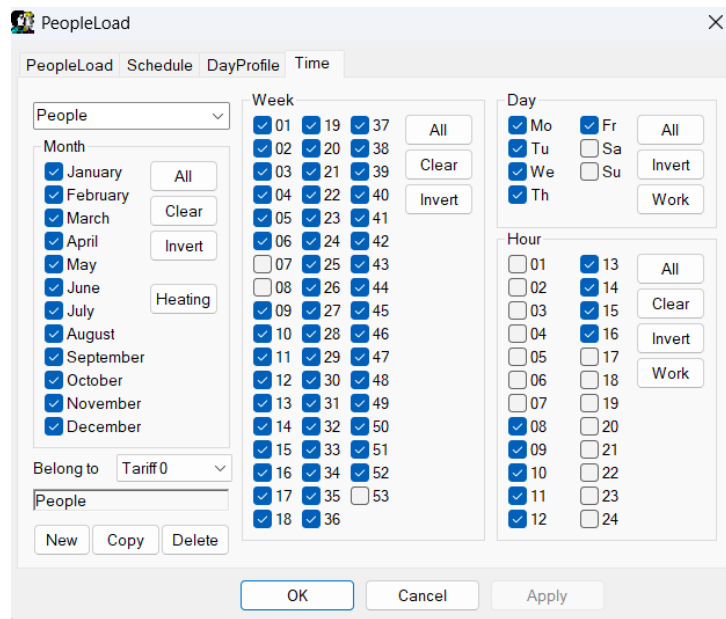
In real life, the classroom occupancy is not 100% throughout the whole occupied period, as both teachers and students (children) have short breaks, a lunch break and use the toilet facilities. However, due to the lack of real-world classroom occupancy data, the occupancy was assumed and set to be 100% for the whole occupied period.

Figure A.3: People Load Day Profile



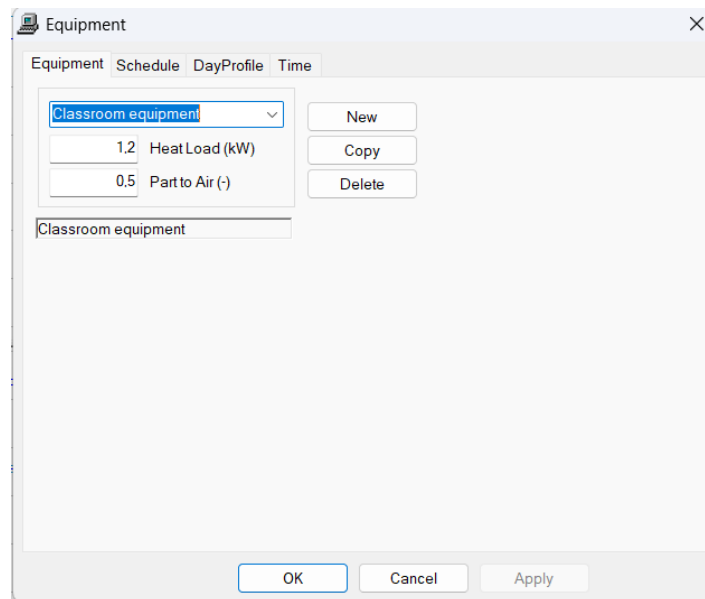
As previously mentioned, during July, the children are usually on summer holiday; however, to represent the worst-case scenario, since the heatwave is happening during that exact period, July was included. Weeks 07 and 08 are Spring Holidays, and Week 53 is the end-of-year holiday. Nonetheless, they do not affect the evaluation since they occur outside the warm period and the heatwave period.

Figure A.4: People Load Time Schedule



The equipment load calculation can be seen in Figure A.25.

Figure A.5: Equipment Load



Similar to the people load, the actual equipment usage varies throughout the day due to periods of inactivity and breaks. However, the same principle is applied for the equipment. Due to the lack of real-world data, the equipment usage is set to 100% for the entire occupied period.

Figure A.6: Equipment Day Profile

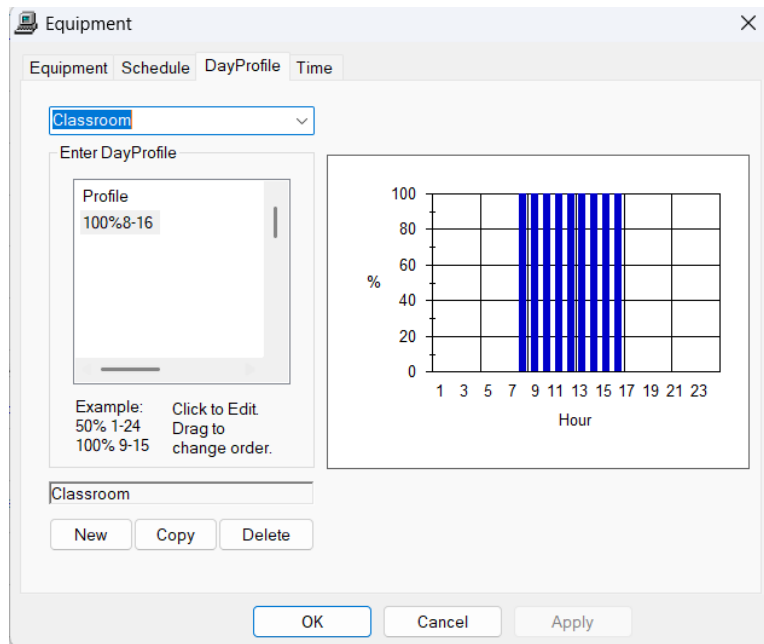


Figure A.7: Equipment Time Schedule

The screenshot shows the 'Equipment Time Schedule' dialog box. The 'Equipment' dropdown is set to 'Equipment'. The 'Month' section has all months selected. The 'Week' section has weeks 01-18 selected. The 'Day' section has Monday, Tuesday, Wednesday, and Thursday selected. The 'Hour' section has hours 13, 14, 15, and 16 selected. Below the 'Month' section, there are buttons for 'All', 'Clear', and 'Invert'. Below the 'Week' section, there are buttons for 'All', 'Clear', and 'Invert'. Below the 'Day' section, there are buttons for 'All', 'Invert', and 'Work'. Below the 'Hour' section, there are buttons for 'All', 'Clear', 'Invert', and 'Work'. At the bottom are 'OK', 'Cancel', and 'Apply' buttons.

Single-sided ventilation was not selected (as it is in the model) because choosing this option would deactivate all the fields above, making them unable to be modified and used. The venting and night cooling were calculated according to SBI Anvisning 213, Section 3.1.3 and 6.4. The calculations are presented in Figure A.26. The rest of the inputs are according to the official BSim user guide.

Figure A.8: Daytime Venting Input

The screenshot shows the 'Venting' dialog box with the 'Daytime venting' profile selected. The settings are as follows:

Parameter	Value	Unit
Basic AirChange	1.6	/h
TmpFactor	0	/h/K
TmpPower	0.5	
WindFactor	0	s/m/h
Max AirChange	5	/h
Max Wind	0	m/s

Additional settings and status:

- Sensor Zone: (Current)
- Natural Ventilation: Combined (Disabled)
- Daytime venting: [Daytime venting]
- Buttons: New, Copy, Delete, OK, Cancel, Apply
- Summary: N4 = 1.6 /h, N10 = 1.6 /h

Figure A.8: Night Cooling Input

The screenshot shows the 'Venting' dialog box with the 'Night cooling' profile selected. The settings are as follows:

Parameter	Value	Unit
Basic AirChange	0.8	/h
TmpFactor	0	/h/K
TmpPower	0.5	
WindFactor	0	s/m/h
Max AirChange	5	/h
Max Wind	0	m/s

Additional settings and status:

- Sensor Zone: (Current)
- Natural Ventilation: Combined (Disabled)
- Daytime venting: [Daytime venting]
- Buttons: New, Copy, Delete, OK, Cancel, Apply
- Summary: N4 = 0.8 /h, N10 = 0.8 /h

For the program to acknowledge when the windows are open, a control input had to be set up. According to SBi Anvvisning 213, Section 3.1.2 Setpunkt for udluftning, windows automatically open only when the operative temperature exceeds 23 degrees Celsius.

Figure A.9: Daytime Venting Control Input

The screenshot shows a dialog box titled "Venting" with a close button (X) in the top right corner. It has four tabs: "Venting", "Schedule", "VentingCtrl", and "Time". The "VentingCtrl" tab is selected. Inside the dialog, there is a dropdown menu currently set to "Daytime". To the right of the dropdown are three buttons: "New", "Copy", and "Delete". Below the dropdown are three input fields: the first contains "23" and is labeled "SetPoint (°C)", the second contains "0" and is labeled "SetP Co2 (ppm)", and the third contains "1" and is labeled "Factor (-)". Below these fields is a text box containing "Daytime". At the bottom of the dialog are three buttons: "OK", "Cancel", and "Apply".

According to SBi Anvisning 213 (BE18), Section 3.1.3 and 6.4, night cooling should be utilised. Therefore, in BSim, the control has been set up so that the windows open when the temperature exceeds 24 degrees Celsius.

Figure A.10: Night Cooling Control Input

The screenshot shows a dialog box titled "Venting" with a close button (X) in the top right corner. It has four tabs: "Venting", "Schedule", "VentingCtrl", and "Time". The "VentingCtrl" tab is selected. Inside the dialog, there is a dropdown menu currently set to "Night cooling". To the right of the dropdown are three buttons: "New", "Copy", and "Delete". Below the dropdown are three input fields: the first contains "24" and is labeled "SetPoint (°C)", the second contains "0" and is labeled "SetP Co2 (ppm)", and the third contains "1" and is labeled "Factor (-)". Below these fields is a text box containing "Daytime". At the bottom of the dialog are three buttons: "OK", "Cancel", and "Apply".

Naturally, both the venting and the night cooling are utilised only during the warm period.

Figure A.11: Daytime Venting Schedule

The screenshot shows the 'Venting' application window with the 'Time' tab selected. The 'venting daytime' dropdown is set to 'venting daytime'. The 'Month' section has checkboxes for January through December, with April, May, June, July, August, and September checked. The 'Week' section has checkboxes for days 01 through 53, with days 01 through 36 checked. The 'Day' section has checkboxes for days of the week: Mo, Tu, We, Th, Fr, Sa, Su, with Mo, Tu, We, and Th checked. The 'Hour' section has checkboxes for hours 01 through 24, with hours 13 through 24 checked. Buttons for 'All', 'Clear', 'Invert', and 'Work' are present for each section. At the bottom are 'OK', 'Cancel', and 'Apply' buttons.

Figure A.12: Night Cooling Time Schedule

The screenshot shows the 'Venting' application window with the 'Time' tab selected. The 'Night cooling' dropdown is set to 'Night cooling'. The 'Month' section has checkboxes for January through December, with April, May, June, July, August, and September checked. The 'Week' section has checkboxes for days 01 through 53, with days 01 through 36 checked. The 'Day' section has checkboxes for days of the week: Mo, Tu, We, Th, Fr, Sa, Su, with Mo, Tu, We, and Th checked. The 'Hour' section has checkboxes for hours 01 through 24, with hours 01 through 24 checked. Buttons for 'All', 'Clear', 'Invert', and 'Work' are present for each section. At the bottom are 'OK', 'Cancel', and 'Apply' buttons.

The infiltration rate was determined according to SBi Anvisning 213 (BE18), Section 6.2, since there were no real-world blower door measurements for the representative building. Since infiltration happens constantly, two schedules were created, one for the occupied period and one for the unoccupied period. During occupied hours, SBi recommended a rate of an ACH of 0.17 for the classroom, and for the unoccupied hours, 0.12 ACH. The rest of the inputs are according to the official BSim user guide.

Figure A.13: Infiltration During Occupied Period

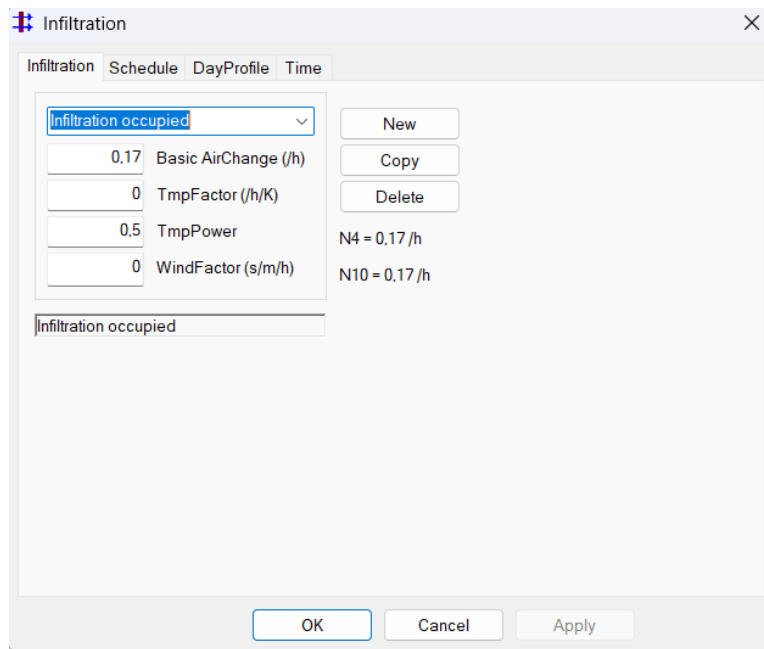


Figure A.14: Infiltration During Unoccupied Period

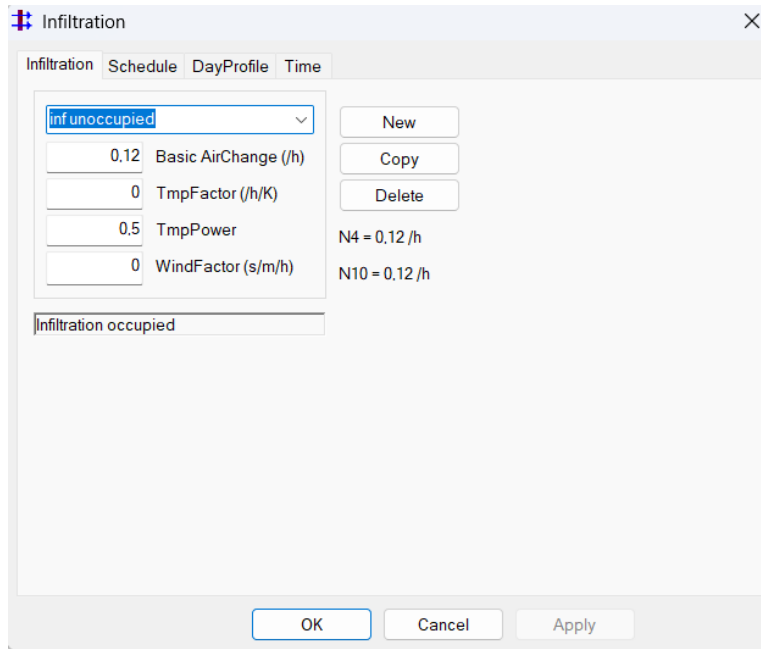


Figure A.15: Infiltration Occupied Period Day Profile

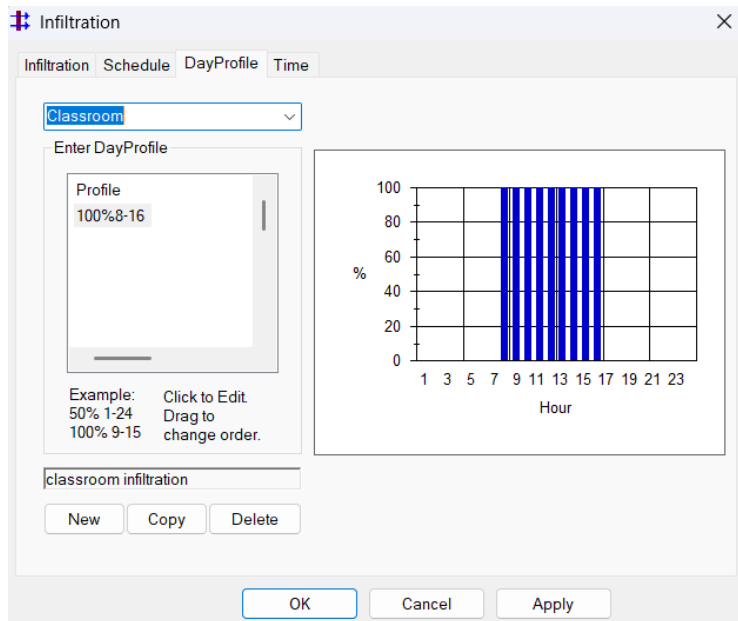


Figure A.16: Infiltration Unoccupied Period Day Profile

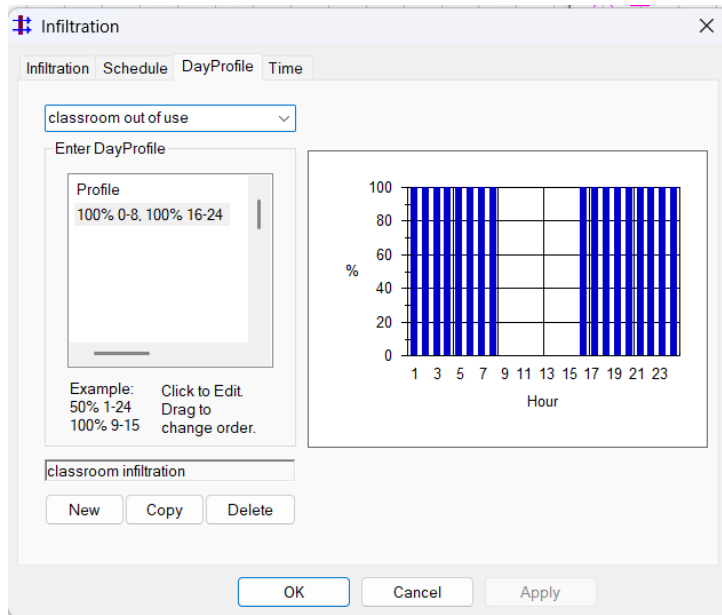


Figure A.17: Infiltration Occupied Period Time Schedule

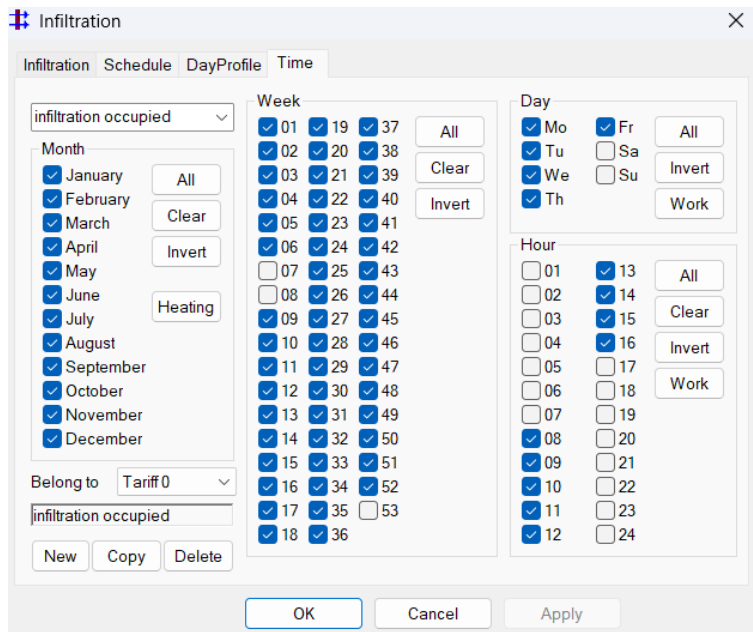
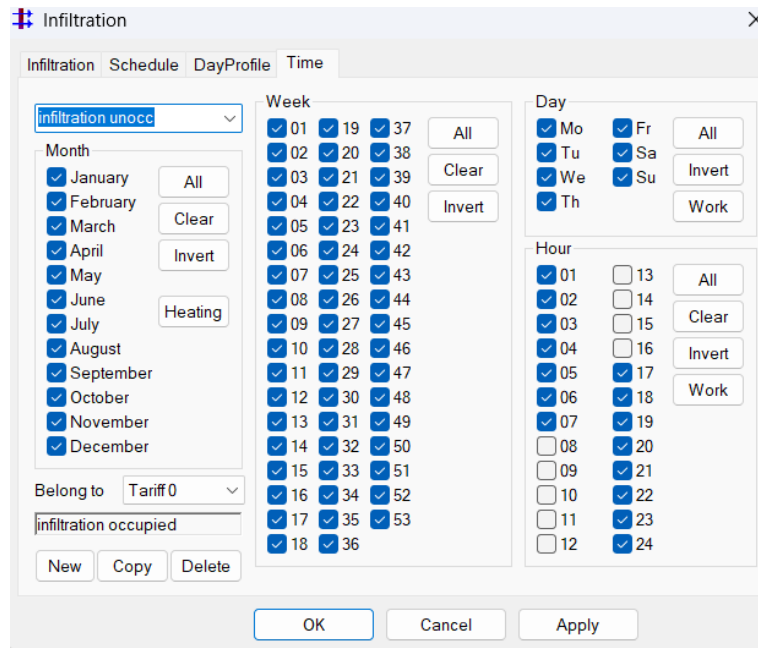


Figure A.18: Infiltration Unoccupied Period Time Schedule



Calculations regarding the classroom lighting are presented in Figure A.28.

Figure A.19: Lighting Input

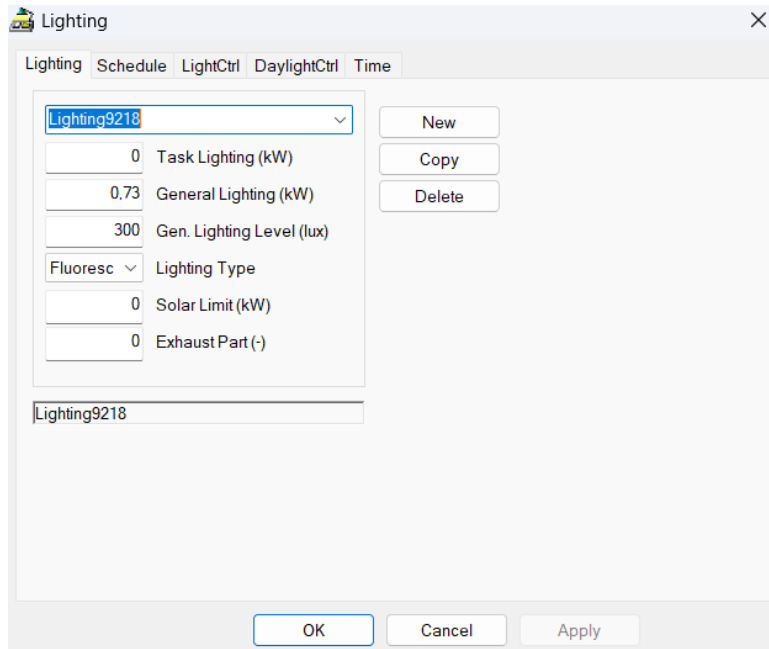


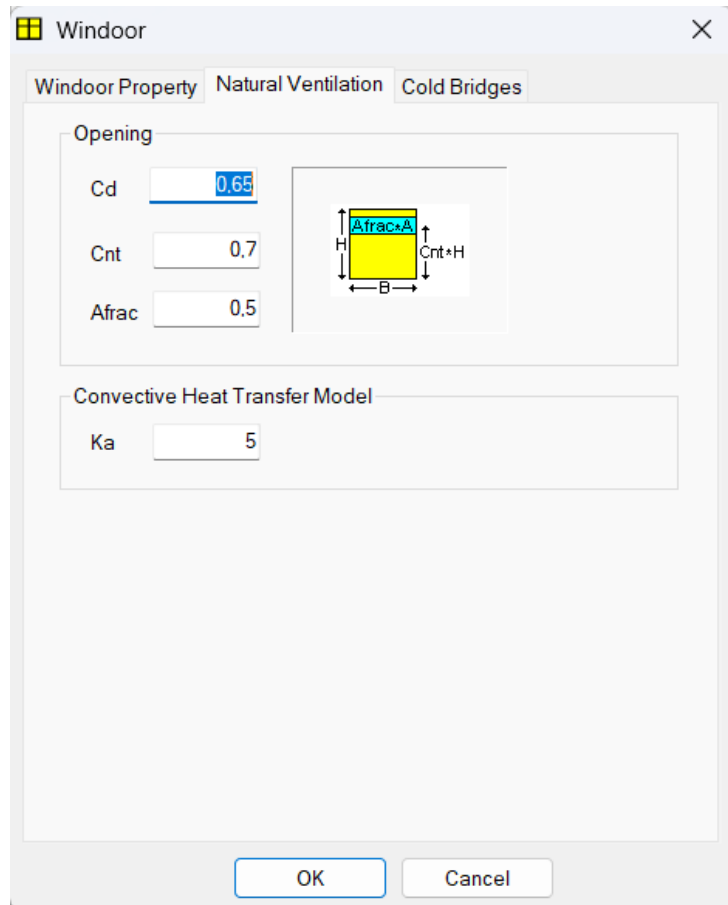
Figure A.20: Lighting Time Schedule

The dialog box 'Lighting' contains the following sections:

- Lighting:** A dropdown menu set to 'Lighting'.
- Month:** A list of months from January to December, each with a checked checkbox. To the right are buttons for 'All', 'Clear', 'Invert', and 'Heating'.
- Week:** A grid of 53 week numbers (01-53) with checked checkboxes. To the right are buttons for 'All', 'Clear', and 'Invert'.
- Day:** A list of days of the week (Mo, Tu, We, Th, Fr, Sa, Su) with checkboxes. 'Mo', 'Fr', and 'Th' are checked. To the right are buttons for 'All', 'Invert', and 'Work'.
- Hour:** A list of hours from 01 to 24 with checkboxes. Hours 13, 14, 15, 16, 17, 07, 08, 09, 10, 11, and 12 are checked. To the right are buttons for 'All', 'Clear', 'Invert', and 'Work'.
- Belong to:** A dropdown menu set to 'Tariff 0'.
- Lighting:** A text input field.
- Buttons:** 'New', 'Copy', 'Delete', 'OK', 'Cancel', and 'Apply'.

To ensure that BSim recognises that windows can be opened, these fields must be filled in. Cd is the discharge coefficient with values typically ranging from 0.62-0.7. Cnt is the geometrical centre of the opening, ranging from 0-1. Since the windows are openable on the top, 0.7 was chosen. Lastly, afrac is part of the window that can be opened. If the value is 0, the window cannot be opened. The selected value was 0.5, meaning half of the window can be opened, in this case, the top half.

Figure A.21: Natural Ventilation - Window Opening Inputs



The inputs regarding the external venetian solar shading and the sensor control are according to the official BSim guide.

Figure A.22: External Shading Inputs

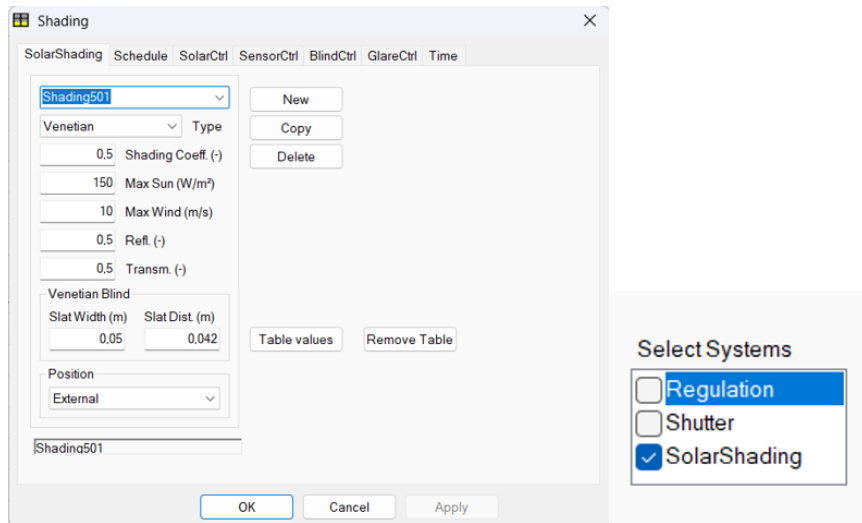


Figure A.23: External Shading Sensor Control

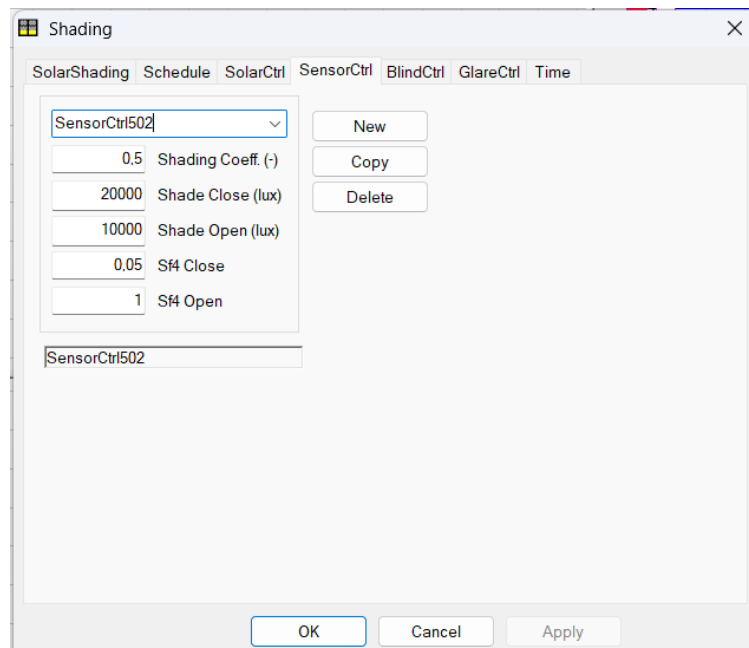


Figure A.24: Improved External Wall U-Value Calculation

Improved External Wall Calculation			
Layer	Thickness [m]	Lambda λ [W/mK]	Resistance R [m ² K/W]
plaster	0,015	0,4	0,0375
aerated concrete	0,18	0,24	0,75
mineral wool	0,24	0,05	4,8
clinker bricks	0,12	0,81	0,15
TOTAL (incl. Rsi=0.13, Rse=0.04)			5,9
U-value [W/m ² K]			0,17

Figure A.25: People Load and Equipment Calculation

Students + teacher =21	
People load – Classroom	
Inputs	
Number of children	20
Number of teachers (in BSim same as children)	1
Total occupants	21
Metabolic rate for children	48.4 W/m ² (resting)
Body surface area per child	1.14 m ²
Assumed schedule	Mon-Fri 08:00-16:00, none during Holidays
Results	
Heat per child	55.2 W
Heat per child (kW)	0.055 kW
Total heat all occupants (kW)	21 × 0.055 = 1.159 kW
BSim heat input (kW/person)	0.055 kW
Equipment load	
Equipment selected	- one desktop PC 49W
	- one monitor 36W
	- an interactive whiteboard 200W
	- a projector 210 W
	-a laptop 35W per person (35 × 20) =700W
Total heat load	1200W = 1.2 kW
Assumed schedule	Mon-Fri 08:00-16:00, none during Holidays

Figure A.26: Venting Calculation

Venting Calculation	
<i>Providing fresh air in a building by in this case opening windows</i>	
Floor area A	50.0 m² (8 m x 6.25 m)
Room height	2.7 m
Volume V = A × h	135.0 m ³
Occupied period - day time and manually opening windows	
Total flow	1.2 × 50 = 60 l/s = 0.06 m³/s
In m ³ /h	0.06 × 3600 = 216 m³/h
Air changes	216 / 135 = 1.6 h/1
Venting Schedule	top >24°C
Unoccupied period (Night cooling)	
Total flow	0.6 × 50 = 30 l/s = 0.03 m³/s
In m ³ /h	0.03 × 3600 = 108 m³/h
Air changes	08 / 135 = 0.8 h/1

Figure A.27: Infiltration Calculation

Based on SBi Anvisning 213 (no q50 available)	
Infiltration Calculation	
<i>leakage of outdoor air into a building through cracks, openings, and gaps in the building envelope</i>	
Floor area A	50 m ²
Room height h (m)	2.7 m
Volume V = A × h (m ³)	135 m ³
Occupied period	
Infiltration rate I	0,13 (L/s·m ²)
Airflow Q use	0.13 x 50 =6.5 (L/s)
Airflow Q use	6.5 x 3.6 = 23,4 m ³ /h
ACH	23.4 / 165 =0.173 1/h
Unoccupied period	
Infiltration rate I	0,09 (L/s·m ²)
Airflow Q	4,50
Airflow Q	16,2
ACH	0,12

Figure A.28: Lighting Calculation

Lighting load – Classroom	
Floor area A	50.0 m²
Lighting power	14.5 W/m ² (fluorescent tubes)
Total lighting power P	14.5 × 50 =725 W
BSim 'General Lighting' input	0.725 kW = 0.73 kW
Assumed schedule	ON: Mon–Fri 07:00–17:00, other time: OFF

Appendix B – Results

An additional evaluation, excluding July, was carried out to create a more realistic scenario in which the children are on summer holiday. The results indicate that the risk of overheating is not higher than during normal summer conditions, mainly since the heatwave occurs in July. Again, it is important to emphasise that heatwaves can happen at any moment, both during school holidays and when classes are in progress.

Table B.1: Base Model Overheating Results July Excluded

Scenario	Occupant	Total Occupied Hrs	Hrs Exceed	He%	Weighted Exc	Max Op Temp	Avg Op Temp	Avg Rm Temp	Crit3 Hrs Exceed
BaseNormal	Adults	520	213	40,97	47,59	37,2	26,5	15,3	76
BaseNormal	Children	520	357	68,65	71,36	37,2	26,5	15,3	192
BaseHeatwave	Adults	512	187	36,52	29,38	34,52	26,85	16,2	44
BaseHeatwave	Children	512	370	72,65	53	34,52	25,85	16,2	170