Master's Thesis

Evaluation of Control Strategies for Ventilation, Night Cooling in AAU Campus

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Abstract:

This thesis examines the night cooling performance of several rooms in the AAU BUILD facility during warm summer periods. By analysing measured temperature data, the study evaluates how ventilation type, airflow conditions, thermal mass, and internal heat gains influence the ability of each room to cool down overnight. The results show clear differences between cross-ventilated and single-sided rooms, with cross-ventilated spaces achieving faster and deeper cooling. Weekend periods also demonstrate lower starting temperatures due to reduced internal loads. Overall, the findings highlight the importance of effective airflow paths and thermal mass in reducing overheating risk and improving morning thermal conditions.

Contents

Preface

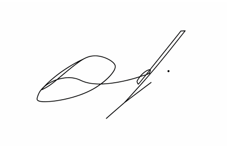
This report is the result of my fourth semester Master's thesis, carried out as part of the MSc programme at Aalborg University, Department of the Built Environment. The thesis was conducted during the spring and summer of 2025 and represents the final requirement for completing my Master's degree.

The project focuses on the evaluation of night time cooling and indoor thermal conditions in selected office rooms at Aalborg University. The study is based on measured data from the Building Management System (BMS) and investigates how different ventilation strategies influence indoor temperatures during warm periods.

During this project, I was responsible for data collection, data processing, analysis of results, and writing of the report. The work combines theoretical knowledge from the Master's programme with practical analysis of a real building.

I would like to thank my supervisors for their guidance and feedback throughout the project. I also thank Aalborg University for providing access to the building and the measurement data used in this study.

Aalborg University, January 5, 2026



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Abbreviation / Symbol	Full Form / Description	Unit
AAU	Aalborg University	–
AAU BUILD	Department of the Built Environment, Aalborg University	–
TMV23	Building 23 (AAU BUILD facility)	–
BMS	Building Management System	–
HVAC	Heating, Ventilation and Air Conditioning	–
NV	Natural Ventilation	–
MV	Mechanical Ventilation	–
VAV	Variable Air Volume	–
IAQ	Indoor Air Quality	–
BR18	Danish Building Regulations 2018	–
DS 469	Danish Standard for Thermal Indoor Climate	–
DS 418	Danish Standard for Energy Calculation in Buildings	–
EN 16798-1	Indoor Environmental Input Parameters for Building Design	–
ISO 7730	Thermal Comfort – PMV/PPD Method	–
CIBSE AM10	Natural Ventilation in Non-Domestic Buildings	–
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers	–
SBi 202	Danish Guideline for Natural Ventilation	–
SBi 213	Danish Guideline for Thermal Indoor Climate	–
CO_2	Carbon Dioxide Concentration	ppm
T	Air Temperature	°C
T_{in}	Indoor Air Temperature	°C
T_{out}	Outdoor Air Temperature	°C
T_{min}	Minimum Night-time Indoor Temperature	°C
$\overline{T}_{\text{night}}$	Average Night-time Indoor Temperature	°C
ΔT_{20-08}	Full-night Temperature Reduction (20:00–08:00)	°C
ΔT_{20-23}	Early-night Temperature Reduction (20:00–23:00)	°C
$\Delta T_{\text{relative}}$	Relative Night-time Temperature Difference (reference: Room 1325)	°C
CR	Cooling Rate	$°\text{C}\,\text{h}^{-1}$
t_1, t_2	Time instants used in cooling rate calculation	h
N	Number of samples in averaging period	–
v	Outdoor Wind Speed	$\text{m}\,\text{s}^{-1}$
$\dot{V}$	Airflow Rate	$\text{L}\,\text{s}^{-1}$
ACH	Air Changes per Hour	h^{-1}
A	Opening Area (window or skylight)	m^2
Δp	Pressure Difference Across Opening	Pa
Q	Stored or Released Thermal Energy	J
Q_{int}	Internal Heat Gains	W
c_p	Specific Heat Capacity of Air	$\text{J}\,\text{kg}^{-1}\,\text{K}^{-1}$
ρ	Air Density	$\text{kg}\,\text{m}^{-3}$
n_{50}	Air Leakage Rate at 50 Pa	h^{-1}
U-value	Thermal Transmittance	$\text{W}\,\text{m}^{-2}\,\text{K}^{-1}$

Table 1: List of Abbreviations and Symbols used in the thesis

Chapter 1

Introduction

This thesis focuses on analyzing and improving the performance of the Building Management System (BMS) in the new research and teaching building of the Department of the Built Environment at Aalborg University. The building is located in the western expansion area of the university (Campus Vest) and represents a modern low-energy facility developed under the supervision of the Danish Building and Property Agency (Bygningsstyrelsen), with architectural and engineering contributions from Rambøll, Kjaer & Richter, and Møller & Grønborg. The total floor area of the building is approximately 9,000 m^2, distributed over five levels and a partial basement. It contains several types of spaces such as laboratories, project halls, classrooms, offices, and common study areas. The architectural design emphasizes openness, flexibility, and sustainability, and includes a central multi-storey atrium that enhances daylight access, natural ventilation, and interaction between students, researchers, and staff members. [17] One of the main intentions behind this project is to create a "living laboratory"a building that can be continuously monitored and analyzed to support research on energy performance, thermal comfort, and environmental control. The integrated systems, including heating, cooling, ventilation, and solar shading, are all connected through the BMS platform, which enables real time monitoring and optimization of building operations.

In this study, the main focus is on evaluating the **night cooling strategy**, which uses natural outdoor air during the night to remove the heat accumulated in the building's thermal mass. This passive approach helps reduce the need for mechanical cooling during the daytime and improves indoor comfort conditions in an energy efficient way. The analysis is based on BMS data collected from rooms **1315,1317,1319,1321,1323,1325,1327**, which include measurements of indoor air temperature, outdoor conditions, airflow rates, and skylight opening states. These rooms were selected because they provide different orientations and occupancy patterns, making them suitable for understanding how night cooling performs under varying conditions.

The main objectives of this thesis are:

- To analyze the current performance of the night cooling system in selected rooms of the building.
- To identify the main factors influencing the efficiency of night cooling, such as airflow rate, temperature difference.

- Result-based operational implications rather than design proposals.

The findings of this study are expected to contribute to a better understanding of passive and hybrid cooling methods in educational buildings. Moreover, the results can help improve the use of BMS data for energy optimization and support future design decisions in low-energy university facilities.

Figure 1.1: Aerial view of the BUILD Department of the Built Environment at Aalborg University. [14].

1.1 Description of selected rooms

For this study, seven rooms located along the southern facade of the building (1315, 1317, 1319, 1321, 1323, 1325, and 1327) were selected for analysis. These rooms were chosen because they have almost the same geometry and layout. This makes them suitable for comparing how the night cooling strategy performs under slightly different boundary conditions while keeping other parameters similar.

During daytime (08:00–16:30), the selected rooms are primarily ventilated through mechanical ventilation; however, one of the rooms operates under a hybrid ventilation strategy, meaning that its airflow conditions are not fully comparable to those of the mechanically ventilated rooms. During nighttime (16:30–08:00), mechanical ventilation is disabled in all rooms, and the building relies solely on natural ventilation, which leads to varying ventilation conditions between rooms. Rooms 1315 and 1327 have single sided openings, while 1319 and 1323 include cross-ventilation that allows higher airflow rates. Room 1321 has cross ventilation during daytime but stays closed during the night, which makes it useful for comparing the effect of ventilation type on temperature reduction.

In terms of solar shading, all rooms are connected to the BMS for automated shading control. However, rooms 1315, 1317, and 1319 are operated using an enhanced control algorithm that overrules the standard BMS logic applied in the remaining rooms.

The number of Ultralink sensors varies between rooms, reflecting differences in ventilation strategies. This variation does not reduce data quality; rather, each room is equipped with the number of sensors required for its specific ventilation setup. Although all rooms have nearly the same area (around 18.8 m²), small differences in internal load and control setup lead to slightly different thermal responses. These variations help to understand how airflow, solar gains, and night ventilation interact in practice.Windows and Doors were adjusted manually twice a day in the morning and in the evening to make sure the systems operated consistently throughout the monitoring period.

Overall, these rooms represent realistic conditions in the building and provide a solid basis for evaluating the night cooling strategy and its impact on indoor comfort and temperature stability.

Figure 1.2: selected rooms (1315–1327) along the southern facade of the building [23].

1.2 Study Scope and Assumptions

This study focuses on the performance and evaluation of the night cooling strategy in a limited part of the BUILD department at Aalborg University, specifically in rooms 1315–1327 located along the southern facade. The analysis is based on data collected from the Building Management System (BMS) during the monitoring period from July 14th to August 21st, 2025.

The scope of the work is limited to thermal performance and energy related parameters such as indoor temperature, airflow, and shading control. Factors such as lighting control, occupant comfort surveys, and acoustic or air quality measurements are not included in this study. The results and conclusions are therefore valid only for the analyzed rooms and for the mentioned monitoring period, and cannot be generalized to the entire building or to other seasons of operation. Seasonal variations and long term effects are beyond the scope of this thesis. Additionally, the focus of this study is mainly on data analysis and interpretation, without including new design proposals or simulation work. However, the results can serve as a useful reference for future optimization or simulation based validation studies.

Use of AI-Based Tools Artificial intelligence based tools were used in a supportive role during this project. Their use was limited to Python code debugging and minor language editing. All scientific analysis, methodological decisions, data processing steps, and conclusions were produced by the author.

Chapter 2

Theory

2.1 Introduction

A clear theoretical foundation is necessary for assessing indoor environmental conditions, thermal comfort, and the thermal behaviour of buildings. This chapter outlines the regulatory and scientific background relevant to the performance analysis carried out in this thesis. The discussion integrates Danish building legislation, international comfort standards, and the physical mechanisms that determine how indoor environments respond to ventilation, solar exposure, and thermal storage.

The chapter begins with the Danish Building Regulations (BR18), which define mandatory requirements for ventilation, indoor climate, overheating limits, and moisture control in buildings [22]. These regulations establish the boundary conditions within which building designers and engineers must operate. They also provide the criteria used to evaluate acceptable indoor air quality and thermal conditions in practice, making them fundamental to the assessment of the rooms investigated in this study.

In addition to national regulations, relevant international standards are introduced to frame the thermal comfort methodologies applied in building research. ISO 7730 [11] and EN 16798 [10] specify definitions, comfort categories and evaluation procedures for indoor environments. While ISO 7730 provides the classical comfort framework, EN 16798 is widely used in European practice and focuses on classification of indoor climate conditions, including local discomfort criteria such as draught and vertical temperature differences, which are more relevant for naturally and mix ventilated buildings like the one analysed here. The remainder of this chapter focuses on the physical and operational principles that govern the indoor climate in such buildings. Key topics include thermal comfort mechanisms, the influence of local discomfort factors, the role of thermal mass in regulating temperature fluctuations, and the effect of night-time ventilation on removing excess heat stored in the building structure. The chapter also examines the impact of solar shading on reducing heat gains and stabilising indoor conditions, as well as the functions of the Building Management System (BMS), which provides continuous measurements and controls ventilation and shading strategies in the TMV23 building.

Together, these theoretical components provide a coherent basis for interpreting the indoor climate data collected from the rooms analysed in this thesis and for understanding the mechanisms that drive their thermal behaviour.

2.2 Danish Building Regulations (BR18)

The Danish Building Regulations 2018 (BR18) constitute the legal framework governing the energy performance and indoor environment of buildings in Denmark [22]. The regulation applies to new buildings, major renovations, and changes in building use. BR18 ensures that buildings provide adequate ventilation, acceptable indoor climate, safe moisture conditions, and efficient use of energy.

2.2.1 Ventilation Requirements

BR18 stipulates that all occupied spaces must receive sufficient outdoor air to ensure good indoor air quality (IAQ), prevent excessive moisture buildup, and maintain healthy conditions for occupants. The regulation specifies minimum airflow rates and performance criteria for both mechanical and hybrid ventilation systems.

Table 2.1: Key ventilation requirements from BR18 (interpreted from official guidelines).

Requirement	Description
Outdoor air supply	Must ensure healthy IAQ and limit CO_2 levels
Minimum ventilation rate	Typically 0.3–0.5 ACH (higher for offices and schools)
Moisture control	Prevents condensation, mould growth, and poor IAQ
Filter requirements	Mechanical systems must include adequate filtration
Heat recovery (HRU)	Required for most mechanical systems to reduce energy loss
System balancing	Mechanical ventilation must be balanced and calibrated

2.2.2 Energy Performance Requirements

BR18 includes strict energy performance requirements to ensure efficient building operation. The regulation defines limits for total energy use, thermal transmittance (U-values), airtightness, and the performance of mechanical systems.

Table 2.2: Typical BR18 building envelope requirements (general overview).

Component	Regulatory parameter	Purpose
Walls / Roof / Floors	Thermal transmittance (U-value)	Limit conductive heat transfer through opaque building elements
Windows / Doors	Thermal transmittance (U-value)	Reduce conductive heat loss through transparent building elements
Airtightness	Air leakage rate (n_{50})	Limit uncontrolled air infiltration and exfiltration
Thermal bridges	Thermal bridge reduction	Reduce local heat losses and risk of surface condensation

2.2.3 Indoor Climate Requirements

Although BR18 is not a dedicated comfort standard, it contains provisions related to indoor climate, including:

- Minimum ventilation rates for IAQ
- Moisture protection requirements
- Temperature limitations to avoid overheating
- Requirements for controlling solar gain (e.g., shading)

These regulatory requirements directly influence the thermal comfort strategies applied in buildings especially those involving night cooling, shading control, or dynamic operation via BMS.

2.2.4 Overheating Criteria in BR18

BR18 defines explicit limits for indoor temperature exceedance to minimise thermal discomfort and protect occupants during warm periods [22]. The regulation allows the following annual exceedances:

- Up to 100 hours per year above 26°C,
- Up to 25 hours per year above 27°C.

Exceeding these thresholds indicates insufficient thermal control, inadequate shading, limited night cooling, or excessive internal or solar gains. These overheating limits provide operational guidance that complements analytical comfort.

2.3 International Indoor Climate Standards

2.3.1 Thermal Comfort Standards in Denmark: DS469 and BR18

Thermal comfort requirements in Danish office buildings are primarily defined by the national standard DS469 and the Danish Building Regulations (BR18). DS469 specifies recommended indoor temperature ranges to ensure acceptable comfort under normal operation. The standard states that indoor temperatures in office environments should generally remain within the range of 20–26 °C, with temperatures above 26 °C only permissible for limited periods. Furthermore, DS469 acknowledges that measured indoor temperature profiles may be used as a practical method for assessing thermal comfort and evaluating the effectiveness of ventilation strategies such as night cooling.

BR18 introduces explicit overheating criteria to ensure that indoor environments do not exceed acceptable temperature limits during warm periods. According to BR18, indoor temperatures may exceed 26 °C for no more than 100 hours per year and may exceed 27 °C for no more than 25 hours per year. These criteria serve as regulatory reference thresholds and were used in this study to evaluate the thermal performance of the monitored rooms.

Table 2.3: Summary of thermal comfort criteria in DS469 and BR18

Standard	**Criteria / Requirements**	**Purpose**
DS469	Indoor temperature range: 20–26 °C. Limited tolerance for temperatures above 26 °C. Supports assessment based on indoor temperature profiles.	Defines recommended thermal comfort conditions
BR18	Overheating limits: maximum 100 hours per year above 26 °C and maximum 25 hours per year above 27 °C.	Regulatory requirement for overheating control

2.4 Thermal Comfort Theory

Thermal comfort refers to the degree to which occupants feel satisfied with the thermal conditions in an indoor environment. According to ISO 7730 [11], comfort is experienced when the surrounding environment allows the body to maintain thermal balance without feeling too warm or too cold. Although thermal comfort can seem subjective, it is primarily shaped by factors such as air temperature, radiant temperature, air movement, and humidity, all of which influence how heat is exchanged between the human body and the environment. In buildings that operate with hybrid ventilation and are exposed to varying solar gainssuch as the rooms analysed in this project the indoor thermal conditions fluctuate throughout the day due to changing airflow patterns, shading behaviour, and nighttime cooling performance. Because of these dynamics, whole body comfort metrics are not always the most accurate way to evaluate how occupants actually experience the space.

For this reason, Danish regulation and European standards (Br18 and EN 16798) emphasise the importance of evaluating local thermal discomfort, particularly draught and vertical air temperature differences [10, 22]. These two parameters are especially relevant in naturally or hybrid ventilated rooms, where airflow speed and temperature stratification can change rapidly depending on window use, external weather, and internal heat gains.

2.5 Local Thermal Discomfort

even if the overall indoor temperature seems acceptable. This usually happens when thermal conditions are not uniform throughout the space. In practice, occupants often react more strongly to these local variations than to the general room temperature.

According to [11], several mechanisms can cause local discomfort, but in the type of building investigated in this project where airflow patterns are influenced by window opening, mechanical ventilation, solar gains and night cooling the two most relevant mechanisms are draught and vertical air temperature differences. These are also emphasised in European and Danish indoor climate standards, including EN 16798 [10] and BR18 [22], because they frequently occur in spaces where ventilation is not constant or uniform.

2.6 Thermal Mass

Thermal mass plays a significant role in shaping the thermal behaviour of indoor spaces, particularly in buildings that rely on natural or hybrid ventilation and night cooling strategies. In the context of this project, thermal mass is especially relevant because it determines how indoor temperatures respond to solar gains, external fluctuations, and the ability of the building to dissipate stored heat during nighttime ventilation.

Thermal mass describes the capacity of a material to absorb, store, and later release heat. Materials with high density and high specific heat capacity such as concrete, brick, stone, and other heavy construction elementsare capable of retaining substantial amounts of thermal energy throughout the day when exposed to solar radiation or elevated indoor temperatures [13]. This stored heat is then gradually released when temperatures decrease, moderating diurnal temperature swings and contributing to improved thermal stability [15].

The heat storage capability of a material or building component is commonly expressed by:

$$Q = \rho \, c_p \, V \, \Delta T$$

[15]

where:

- Q is the amount of heat stored or released [J],
- ρ is the material density [kg/m^3],
- c_p is the specific heat capacity [J/(kg K)],

- V is the material volume [m^3],
- ΔT is the change in temperature of the material [K].

This relationship illustrates that both material properties and the magnitude of the temperature variation govern the overall thermal buffering potential of the building fabric [15].

In rooms exposed to substantial solar gains similar to those analysed in this project hermal mass helps delay (time lag) and reduce (damping) peak indoor temperatures. Heavier building elements slow down heat transfer, resulting in peak temperatures occurring later in the day compared to lightweight structures, thereby reducing overheating risk and improving comfort during warm periods [19]. However, the effectiveness of thermal mass is highly dependent on the availability of sufficient nighttime ventilation. During the day, heat accumulates within the mass. If adequate airflow is supplied at night, this stored heat can be flushed from the building, preparing the mass to absorb heat again the following day. Insufficient night cooling results in progressively warmer thermal mass, which can amplify indoor overheating over consecutive days a phenomenon well documented in passive cooling literature [19].

Practically, thermal mass behaves as a thermal battery: it charges during daytime and must be discharged during nighttime. When combined with effective shading and night ventilation, it significantly stabilises indoor temperatures and reduces cooling needs [3]. In this project, evaluating the interaction between thermal mass, solar gains, and nighttime ventilation is essential for explaining the observed temperature trends and the variation in overheating levels between the studied rooms.

2.7 Night Cooling

Night cooling is widely applied in Danish buildings as a simple and effective way to lower indoor temperatures without the use of mechanical cooling. As described in SBi-anvisning 202 [20] and 213 [21] , the method relies on allowing cooler outdoor air to enter the building during the night so that the heat stored in the building's thermal mass during the day can be released. When nighttime outdoor temperatures drop sufficiently, the indoor temperature can be reduced before occupancy begins the following morning [20, 21].

The basic cooling potential can be estimated using the standard ventilation heat balance formula from DS418:

$$\Phi_{vent} = \rho\, c_p\, \dot{V}\, (T_{in} - T_{out}),$$

where $\dot{V}$ is the airflow rate and $(T_{in} - T_{out})$ represents the driving temperature difference. A larger temperature difference increases the amount of heat that can be removed through ventilation.

To assess how effectively night cooling reduces indoor temperatures, SBi 213 suggests evaluating the hourly cooling rate:

$$CR = \frac{T_{in}(t_2) - T_{in}(t_1)}{t_2 - t_1},$$

where a negative value indicates cooling. This simple metric is useful for comparing the performance of different rooms.

For naturally ventilated buildings, the airflow through an open window depends on wind pressure and thermal buoyancy. SBi-anvisning 202 describes this using the following general expression:

$$\dot{V} = C_d A \sqrt{\frac{2\Delta p}{\rho}},$$

where A is the opening area and Δp is the pressure difference across the opening. This relationship is commonly used in Danish practice when estimating ventilation potential.

Effective night cooling helps reduce the risk of overheating, which is regulated by BR18. According to BR18, indoor temperatures may exceed 26 °C for a maximum of 100 hours per year and may only exceed 27 °C for up to 25 hours [22]. These limits make night-time ventilation an important strategy for ensuring acceptable indoor climate conditions in buildings without mechanical cooling.

2.8 Solar Shading

Solar shading systems play an essential role in regulating indoor thermal conditions, particularly in buildings exposed to high levels of solar radiation. In this project, shading is a key strategy for reducing daytime solar gains and limiting overheating in the analysed rooms. By controlling the amount of direct and diffuse solar radiation entering the space, shading systems influence both the operative temperature and the mean radiant temperature, which are fundamental parameters of thermal comfort.

Shading devices can generally be classified into:

- **External shading**: such as external blinds, louvres or overhangs, which block solar radiation before it reaches the glazing.
- **Internal shading**: including roller blinds or curtains, primarily used for glare control and visual comfort.
- **Dynamic shading**: BMS-controlled systems that adjust their position based on sunlight intensity, indoor temperature or occupancy.

External shading is typically the most effective for reducing thermal loads because it prevents solar heat from entering the building envelope. Internal shading, while useful for reducing glare, has limited impact on thermal performance since radiation has already passed through the glazing.

The primary function of solar shading is to reduce solar heat gains and thereby minimise indoor temperature rise during peak sunlight hours. This leads to lower operative temperatures, reduced overheating risk and decreased cooling demand. Effective shading also enhances the performance of night cooling and thermal mass, as less heat needs to be removed during the night.

Shading further contributes to visual comfort by controlling glare and limiting excessive brightness contrasts. In hybrid ventilation buildings, shading may also indirectly influence natural airflow, since solar-driven temperature differences affect buoyancy forces and pressure gradients.

Overall, solar shading operates as a passive cooling measure that complements thermal mass and night ventilation. By moderating solar gains and altering radiant temperature fields, shading systems help stabilise indoor thermal conditions and improve thermal comfort in the rooms studied in this project.

2.9 Building Management Systems (BMS)

The Building Management System (BMS) plays a central role in the operation and monitoring of the rooms investigated in this project. It provides continuous high-resolution measurements of the indoor environment, forming the basis for analysing thermal comfort, ventilation performance and the interaction between natural and mechanical ventilation strategies.

The BMS records key variables such as indoor air temperature, CO_2 levels, VAV damper positions, lighting signals, occupancy-related information and window states. These data points are essential for understanding how indoor conditions change in response to solar gains, outdoor conditions and occupant behaviour. Since the rooms operate under hybrid ventilation conditions, the BMS also documents transitions between mechanical and natural ventilation modes. From a control perspective, the BMS regulates the VAV dampers for supply and extract air based on CO_2 concentrations, temperature boundaries and occupancy patterns. Window opening behaviour is also monitored, which is particularly relevant for hybrid ventilation, as it directly influences airflow patterns and night cooling potential.

In this project, BMS data are used to evaluate:

- daytime temperature rise under solar exposure,
- nighttime cooling effectiveness,
- ventilation performance as reflected by CO_2 levels,
- airflow changes due to window openings,
- the combined impact of shading and external climate conditions.

Overall, the BMS functions both as a measurement infrastructure and as a control system that governs the interaction between mechanical ventilation, natural airflow and occupant behaviour. This makes it a critical component for assessing overheating risks, comfort variations and the overall thermal performance of the rooms analysed in this project.

Data Acquisition

For this project, the Building Management System (BMS) serves as the primary source of information about how the indoor environment evolves throughout the day. The system continuously collects operational and environmental data from each room, with new values recorded every thirty minutes. This frequency is sufficient to capture the overall trends in temperature development, ventilation behaviour and changes related to occupancy and external conditions.

The signals registered by the BMS include indoor air temperature, CO_2 levels, the opening positions of the supply and extract VAV dampers, lighting status and the window state. Together, these measurements give a detailed picture of how the rooms respond to solar exposure, shading, natural ventilation and mechanical airflow. They also make it possible to trace how specific events such as an opened window or an increase in CO_2 influence the room's thermal conditions.

All data streams are time aligned, which allows different parameters to be compared directly. This is important when analysing hybrid ventilation, since the interaction between outdoor air, mechanical ventilation and internal heat gains can change throughout the day. The structure of the dataset makes it possible to link these changes to the resulting temperature patterns, which is essential for understanding the causes of overheating and evaluating the effectiveness of night cooling.

Indoor Climate Variables

The indoor climate in the analysed rooms is shaped by several different variables that are monitored through the control system. Each signal represents a specific aspect of how the room behaves thermally or how the ventilation system responds to changing conditions. Although the measurements are simple on their own, they provide useful insight when viewed together. Temperature is the most direct indicator of the room's thermal state and reflects the combined influence of solar gains, heat storage in the building materials and the effectiveness of ventilation or shading. CO_2 concentration is used as an indirect measure of occupancy and ventilation demand; when values rise, it usually indicates either increased activity in the room or insufficient airflow.

The supply and extract damper positions show how the mechanical ventilation system modulates the airflow. When the dampers open further, more air is delivered to the space, which can influence both cooling potential and perceived comfort. Lighting status is included as well, since artificial lighting contributes to internal heat gains and may affect the temperature profile during occupied hours.

Finally, the window signal indicates whether the window is open or closed. This parameter is particularly important in buildings with hybrid ventilation, as even a small window opening can change airflow direction, cooling capacity and the overall behaviour of the indoor environment.

By combining these variables, it becomes possible to understand why the rooms warm up or cool down at certain times of the day, and how different factors such as shading, occupancy or natural ventilation shape the thermal conditions observed in the project.

Ventilation Control Logic

The ventilation system in the building operates in a way that continuously adjusts the airflow based on the conditions inside each room. Rather than supplying a fixed amount of air, the system increases or decreases the airflow depending on how the indoor environment changes throughout the day. This makes it possible to respond to varying levels of activity, external weather conditions and the thermal load created by solar exposure.

Temperature also plays a role in how the ventilation is regulated. When the indoor temperature climbs above a defined comfort range, the system increases the airflow to help remove excess heat. This effect is especially noticeable during sunny periods, when solar gains cause the room to warm up even if occupancy is low. The extract airflow generally follows the behaviour of the supply side to maintain a balanced flow pattern. This prevents unwanted pressure differences in the room and helps ensure that fresh air reaches the occupied zone effectively.

Natural ventilation adds another layer of complexity. When a window is opened, the airflow in the room changes immediately, and the mechanical system reduces its output to avoid counteracting the natural driving forces. In some cases, the mechanical airflow may drop significantly, depending on how much outside air enters through the window.

Overall, the control logic is designed to provide the minimum amount of mechanical ventilation needed while still maintaining acceptable indoor air quality and supporting thermal comfort. This dynamic behaviour is essential for understanding how the rooms cool down at night, how quickly they heat up during the day and why ventilation patterns sometimes shift abruptly.

Ventilation System Operation

The central ventilation system supplies fresh air to the different rooms in the building and removes stale air through a coordinated extract system. Although the system is controlled automatically, its behaviour can be understood by looking at how it responds to the varying conditions inside the building throughout the day.

Fresh air is drawn in from outdoors, filtered, and then distributed to the rooms through a network of ducts. The amount of air delivered is not constant; it changes continuously depending on the ventilation demand signalled by the individual rooms. When one or more rooms require more airflow typically due to higher temperatures or elevated CO_2 levels the central system increases the supply volume accordingly.As fresh air enters the rooms, an equal amount of air is removed through the extract side of the system. This balanced approach prevents pressure differences and helps maintain steady airflow patterns. The extract airflow also adapts to the room conditions, which allows the system to efficiently remove warm air and indoor pollutants when necessary.A heat recovery component is included in the system to reduce energy losses. When the building releases warm indoor air, some of this heat is transferred to the incoming fresh air without the two air streams mixing. This process helps stabilise indoor temperatures, particularly during cooler periods of the year, while still providing adequate ventilation.

The supply air temperature is kept within a defined range so that ventilation can support comfort without introducing additional discomfort. Although the ventilation system is not designed as a primary cooling system, the temperature of the incoming air can contribute to reducing indoor temperatures, especially when combined with night-time ventilation strategies.

In hybrid ventilation conditions, the behaviour of the central system changes when windows are opened. As outdoor air enters naturally, the mechanical system reduces its output to avoid unnecessary airflow and to make use of the natural cooling potential. This interaction between the natural and mechanical systems is essential for understanding the temperature trends observed in the analysed rooms.

Window Interaction

Window opening plays a significant role in how the indoor environment develops, especially in buildings that rely on a combination of natural and mechanical ventilation. Even a small opening can change the airflow pattern in the room and influence both temperature and perceived comfort.

When a window is opened, outdoor air enters the room based on wind pressure and temperature differences between indoors and outdoors. This natural flow often becomes the dominant source of ventilation, and the mechanical system reacts by reducing its air supply. As a result, the balance between supply and extract airflow shifts, and the room may begin to operate primarily through natural ventilation rather than mechanical control.

This change in airflow can have several effects. On warm days, an open window may help release accumulated heat, allowing the room to cool more quickly. On the other hand, if the outdoor air is cooler than expected or enters the room at high speed, occupants may experience draught or uneven temperature distribution.

The behavior of the room during night-time ventilation is also strongly affected by window openings. When windows are left partially open at night, cooler outdoor air can remove heat stored in the building materials, improving the conditions for the following day. The effectiveness of this process depends on how long the window is open, the outside temperature, and how the mechanical system adjusts its airflow.window interaction is one of the most influential factors shaping the thermal conditions in the analysed rooms. It directly affects ventilation rate, cooling potential and the level of thermal comfort experienced during both day and night.

Sensor Accuracy

Since the analysis in this project relies heavily on measurements from the building's control system, it is important to consider the accuracy and limitations of the sensors used. Each measurement carries a certain degree of uncertainty, and this can influence how the indoor climate is interpreted, especially when analysing small temperature differences or rapid changes in ventilation behaviour.

The temperature sensors generally provide reliable readings within a narrow tolerance, which is sufficient for studying daily temperature trends and identifying overheating hours. However, when examining parameters such as vertical temperature differences or the cooling effect of night ventilation, even small deviations should be taken into account.

The feedback signals from the supply and extract dampers also have a margin of uncertainty. While they reflect the general behaviour of the ventilation system, the exact damper position may not always correspond perfectly to the actual airflow delivered to the room.

Window status sensors, which simply indicate whether a window is open or closed, are less sensitive to measurement noise but can still introduce uncertainty if the opening angle varies or if the window is not fully latched.

Understanding these measurement limitations is important when interpreting the indoor climate data. It ensures that observed variations in temperature, airflow are evaluated with an awareness of the potential uncertainty in the underlying signals.

Occupancy Detection

Understanding occupancy patterns is an important part of interpreting the indoor climate data, since many of the variables measured by the control system are directly influenced by how the rooms are used. Occupancy affects the amount of heat generated internally, the level of CO_2 released into the space and the ventilation demand required to maintain acceptable air quality.

In this project, occupancy information is derived indirectly through several signals. Changes in CO_2 concentration, variations in lighting status and shifts in damper positions all provide indications of whether a room is in use. These signals are not perfect representations of occupancy on their own, but together they form a pattern that makes it possible to identify when the room is likely occupied and how this influences the thermal behaviour.

The presence of people tends to increase CO_2 levels and raise the internal heat load. As a result, the ventilation system responds by adjusting the airflow, which in turn affects the temperature development throughout the day. When a room becomes unoccupied, the CO_2 levels typically fall, and the mechanical airflow may reduce, allowing the thermal conditions to stabilise or cool down depending on outdoor temperatures.Although occupancy is not measured with dedicated sensors, the available signals offer enough information to link indoor climate variations to changes in room usage. This helps explain several patterns observed in the data, such as sudden increases in airflow, short-term temperature fluctuations or periods of improved night-time cooling.

Chapter 3

Methodology

3.1 Overview of Methodology

This chapter describes the methodology used to evaluate the performance of the night cooling strategy in the BUILD department at Aalborg University. The study is based on data obtained from the Building Management System (BMS), together with manual observations and onsite actions performed during the monitoring period from July 14th to August 21st, 2025. Since the main goal was to analyze the real operation of the system, different sensors, devices, and control settings were used to simulate realistic internal loads and environmental conditions.

3.2 Case Description

The analysis was conducted in seven rooms (1315, 1317, 1319, 1321, 1323, 1325, and 1327), all located on the southern facade of the BUILD department [23]. During daytime, most rooms operated with mechanical ventilation, while one room applied a hybrid ventilation strategy combining mechanical supply with natural airflow. During nighttime, the mechanical ventilation system was switched off in all rooms, leaving natural driving forces as the only source of air exchange. As a result, the nighttime airflow depended on window openings and room-specific boundary conditions.

The windows were not connected to the BMS and therefore required manual operation twice per day: between 08:00 and 08:30 in the morning and again around 16:30 in the afternoon. Each morning, the windows were manually closed and the heaters were switched on to simulate internal heat loads. Activating the heaters corresponded to the room being occupied by approximately nine people using nine laptops.

The estimation of internal heat gains is based on the Danish national standards for internal loads, following the design values provided in DS 418 and the Branchevejledning for Energiberegning af Bygninger (BvB) [4, 8]. In this study, it was assumed that each room accommodates nine occupants working simultaneously, each using a laptop, in addition to one centrally positioned 40-inch screen. This assumption reflects the typical occupancy pattern and equipment layout observed in the TMV23 office rooms during normal operation, where workstations are arranged to support full-capacity use during peak daytime hours.

Standard internal load values of 100 W per person, 60 W per laptop, and 70 W for a 40-inch screen were applied. With nine occupants and nine laptops present in each room, the total internal heat gains amount to approximately 1.5 kW per room. These assumptions are aligned with commonly applied design practices in Danish office building energy assessments and comply with national calculation methodologies.

3.3 Data Collection

The main data used for the analysis were collected from the BMS, which continuously records indoor and outdoor environmental parameters. The following variables were included in the study:

- Indoor air temperature (°C)
- Outdoor air temperature (°C)
- Solar radiation (W/m^2)
- Skylight position (open/close)
- CO_2 concentration (ppm)
- A wind speed sensor located on the nearby building FIB11 to provide outdoor wind data

Additional monitoring equipment was also used to expand the measurement capabilities and ensure better control accuracy:

- Raspberry Pi units for shading control
- Airflow rate (L/s)
- Ultralink sensors for measuring airflow and temperature at inlets
- Cameras for detecting the shading position (up/down status)

Because the TMV23 building did not have its own outdoor wind sensor, the wind data from the FIB11 building were used instead. FIB11 is the closest building on campus with a wind sensor connected to the BMS, making it the most practical and reliable source for outdoor wind measurements. Although small local differences may exist, the general wind conditions are similar across the campus, so the FIB11 sensor provides a reasonable estimate of the outdoor wind speed during the measurement period. The Ultralink system was connected to rooms with single and cross ventilation setups to monitor inlet air temperature and air flow. For skylights, BMS signals were used, and shading control signals were verified through both the Raspberry Pi system and camera observations.

3.4 Control Strategies

The building's BMS manages heating, ventilation, and skylight shading systems. The control logics applied during the monitoring period are summarized below.

3.4.1 Solar Shading Control Strategy

The solar shading in TMV23 is controlled automatically through the BMS following a prioritized sequence of signals. The control logic responds first to wind speed, where a value above 8 m/s triggers an up signal for safety. If wind speed remains below this threshold, shading is then controlled by a combination of room temperature and solar radiation. When the room temperature exceeds 24 °C and solar radiation is above 180 W/m^2, a down signal is issued. Conversely, if the room temperature falls below 23 °C or solar radiation drops below 120 W/m^2, an up signal is activated. If none of these conditions are met, no new shading signal is applied, following the prioritized logic below:

1. Wind speed > 8 m/s → Up signal
2. Room temperature > 24°C and solar radiation > 180 W/m^2 → Down signal
3. Room temperature < 23°C or solar radiation < 120 W/m^2 → Up signal
4. If none of the above conditions are met → No new signal

The shading control operation was validated using the Raspberry Pi log data and the camera recordings, which clearly showed the moments when the blinds were raised or lowered according to the logic above.

3.4.2 Window Operation Strategy

The seven test rooms in TMV23 exhibited different natural ventilation potentials due to variations in window operability and facade configuration. Since the windows were not connected to the BMS, their operation had to be performed manually and differed between rooms. Consequently, each room had a distinct ventilation pattern during daytime (08:00–16:30), nighttime (16:30–08:00), and weekends. These differences also resulted in different ventilation modes, including single-sided ventilation, cross-ventilation, or no natural ventilation. A summary of the ventilation characteristics of each room is provided in Table 3.1.

Table 3.1: Natural Ventilation mode and availability for each test room in TMV23

Room	Ventilation Mode	Daytime (08–16:30)	Nighttime (16:30–08)
1315	Single-sided	None	NV available
1317	None	None	None
1319	Cross	None	NV available
1321	Cross	NV available	None
1323	Cross	None	NV available
1325	None	None	None
1327	Single-sided	None	NV available

These variations in window operation and ventilation mode created meaningful differences in the natural ventilation potential across the rooms. This allowed for direct comparison between single sided ventilation, cross ventilation, and no natural ventilation, thereby providing insight into how different boundary conditions influence indoor climate performance.

3.5 Data Processing and Analysis

All collected data (from both BMS and external devices) were processed and analyzed using Microsoft Excel and Python (Spyder). The main steps included:

1. **Filtering and cleaning BMS data:** The raw BMS data contained missing timestamps, sensor dropouts, and occasional outliers caused by communication delays. A pre-processing script was used to remove invalid readings (e.g., negative temperatures, frozen values, and repeated timestamps). Linear interpolation was applied only for gaps shorter than five minutes to avoid distorting the thermal trends. Larger gaps were excluded from the analysis. This step ensured that all further calculations were based on reliable measurements, although the limitation remains that sensor noise could not be completely eliminated.

2. **Synchronizing time-series data:** Data from different sensors (temperature, CO_2, shading position, and weather data) were originally logged at different intervals. All datasets were resampled to a consistent one-minute resolution, and timestamps were aligned to a common time base. This allowed direct comparison between variables. A limitation of this approach is that resampling cannot fully compensate for asynchronous logging frequencies in the BMS.

3. **Comparing indoor and outdoor temperature trends:** For each day, indoor temperatures were plotted alongside outdoor temperatures from the FIB11 weather station. This visual comparison helped identify the effect of nighttime cooling and internal loads. The reasoning behind this method is that temperature differences between inside and outside offer a simple and robust indicator of ventilation effectiveness. However, the limitation is that outdoor temperature alone cannot explain all variations, as solar gains and internal loads also contribute.

4. **Evaluating the impact of window operation during nighttime:** The manually documented window schedules were combined with nighttime temperature curves to assess whether open windows contributed to measurable cooling. The analysis focused on temperature reduction rates (°C/hour). The method is useful because window status is the dominant driver of natural ventilation in TMV23. Nevertheless, the limitation is that varying outdoor wind conditions and different window geometries create uncertainty in quantifying the exact airflow rate.

5. **Verifying shading control behavior using Raspberry Pi camera data:** Time-lapse images recorded by the Raspberry Pi camera were compared with BMS shading position logs to verify whether the shading responded according to the programmed priority rules. This cross-validation ensured that unexpected shading movements could be detected. The method is effective because it provides a visual confirmation independent of the BMS; however, camera visibility was sometimes limited by lighting conditions and reflections.

6. **Comparing results with comfort criteria from DS469 and BR18:** Temperature profiles were evaluated against the allowable comfort ranges specified in DS469 and the overheating criteria in BR18 [9, 22]. This comparison enabled an assessment of how well each room performed in relation to regulatory requirements. The limitation is

that only temperature was evaluated; other comfort parameters such as air velocity or radiant temperature were not measured.

All temperature, airflow, and shading signals were plotted in time-series graphs to visually identify how effectively the night cooling strategy reduced indoor temperatures across different rooms.

In summary, this chapter explained the experimental setup and methodology applied to evaluate the night cooling strategy. The combination of BMS data, Raspberry Pi observations, and manual window operation provided valuable insight into the real behavior of the system. The next chapter presents the results and discusses the overall performance of the analyzed rooms.

Figure 3.1: Supply air duct serving Room 1.323, illustrating the ventilation configuration.

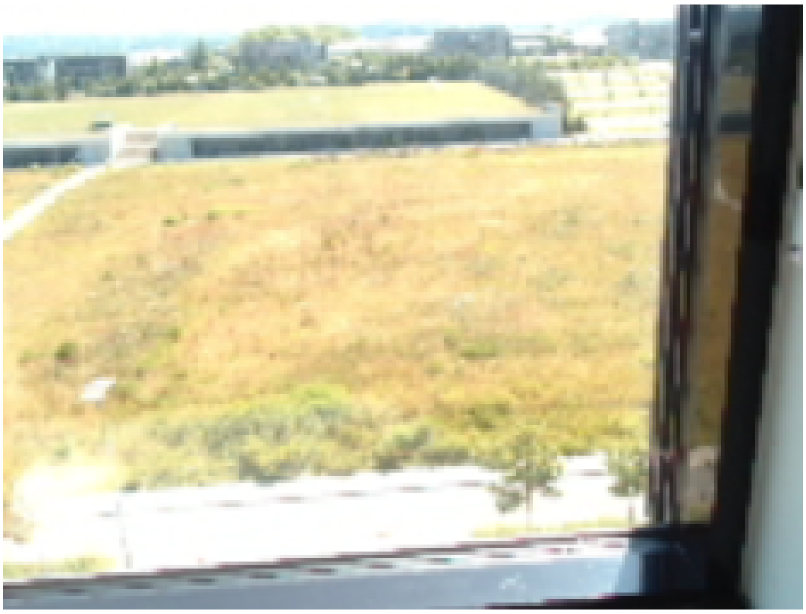

Figure 3.2: Camera based shading control system used to monitor and control external shading.

Chapter 4

Results

4.1 Overview of the Dataset and Analysis Approach

The results presented in this chapter are based on measured data obtained from the building management system (BMS) in the analysed section of the TMV23 building. The available dataset covers a continuous summer period from late July to early September, which includes several warm weeks with elevated indoor temperatures and multiple instances where night ventilation and shading systems were active. This period is particularly suitable for evaluating overheating tendencies, night-time cooling behaviour and the performance of hybrid ventilation.

The data used in the analysis consist of:

- indoor air temperature for each room (30-minute resolution),
- CO_2 concentration as an indicator of occupancy and ventilation demand,
- damper positions for both supply and extract airflow,
- window opening signals for rooms with hybrid or natural ventilation,
- shading activation status (binary signal),
- global horizontal solar radiation and outdoor temperature.

Before the analysis, the dataset was pre processed to remove faulty readings, disconnected sensors and short periods where the system reset or produced non-physical spikes. Missing values were handled using forward–backward interpolation only when the gap was sufficiently small; longer missing intervals were excluded from the analysis to avoid biasing the results.

All time series were aligned to a common 30 minute timestamp to ensure synchronisation across temperature, CO_2, damper positions, window status and solar radiation. This step was essential for interpreting causal relations, for example linking shading activation to changes in indoor temperature or relating night cooling performance to window operation and outdoor conditions.

The analysis presented in the following sections is structured according to the key mechanisms influencing indoor thermal performance. Weekly mean temperatures highlight overall differences between rooms, daily temperature profiles reveal typical daytime and night time behaviour, and night cooling efficiency is evaluated using temperature reduction and cooling rate metrics. CO_2 development and ventilation response are used to interpret occupancy dependent variations and system reactions, while shading operation is examined to assess its contribution to limiting solar gains.

Together, these components provide a comprehensive view of the indoor climate conditions and the performance of the ventilation and shading strategies in the studied part of the building.

4.1.1 Outdoor Climate Conditions

Figure 4.1 illustrates the outdoor air temperature measured during the analysis period (Weeks 30–34). The data are aggregated to an hourly resolution to provide a clearer view of the diurnal temperature patterns that influence night-time ventilation performance in the TMV23 building.

A repeated daily cycle is evident across the entire period: temperatures typically rise rapidly during the morning, reach their peak in the early afternoon, and gradually decline towards the evening. These fluctuations are important because the effectiveness of night cooling depends strongly on the outdoor,indoor temperature difference, especially during late evening and early morning hours when natural ventilation or hybrid systems can operate with minimal thermal penalty.

The shaded regions in the figure correspond to weekends and night time hours (17:00–08:00). These intervals are non-occupied periods in which indoor temperatures are not directly influenced by internal heat gains from occupants or equipment. Highlighting these periods makes it easier to assess the cooling potential available to the building when mechanical ventilation is inactive and the system relies solely on natural airflow through operable windows.

Overall, the figure shows a gradual decline in outdoor temperature from late July to early August, followed by slight fluctuations later in the period. This general trend provides favourable conditions for night cooling, especially during the cooler nights where the temperature difference between indoor and outdoor air becomes sufficiently large to remove accumulated daytime heat from the building's thermal mass.

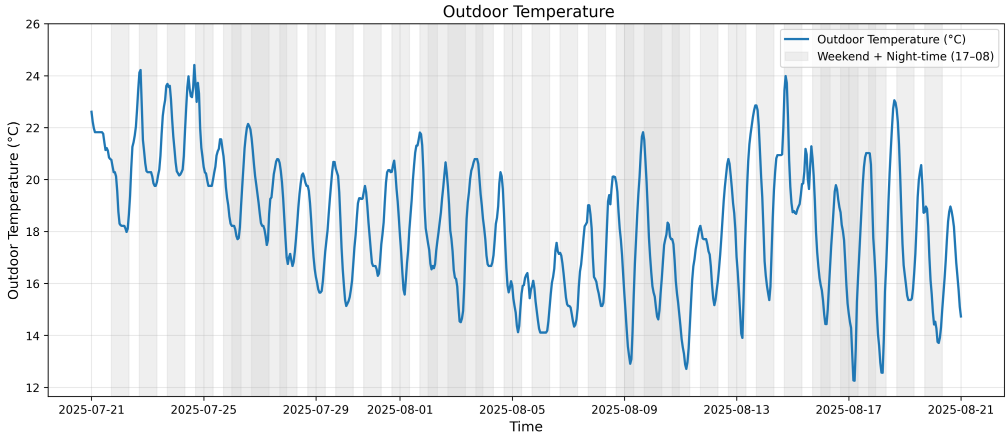

Figure 4.1: outdoor temperature profile for Weeks 30–34, including shaded periods representing weekends and night time hours (17:00–08:00). The shading helps visualise non occupied periods and highlights the temperature dynamics during daytime, which are relevant for assessing overheating risks and ventilation performance.

4.2 Weekly Mean Indoor Temperature

To provide an aggregated overview of the thermal development in the monitored rooms, the weekly mean indoor temperature was calculated for each room during Weeks 30–34. Weekly averaging is a useful approach for identifying broader thermal patterns, as it reduces short term fluctuations caused by transient occupancy, window operation, shading adjustments or momentary ventilation changes.

The analysed rooms differ in their ventilation configurations, including cross ventilation, single-sided ventilation and mechanically ventilated rooms without night-time natural ventilation. These functional differences contribute to the variation in indoor temperature levels observed across the monitoring period.

Table 4.1 summarises the weekly mean temperature for all seven rooms. All rooms follow a similar overall trend that reflects the outdoor conditions: a gradual decrease in indoor temperatures from Week 30 to Week 32, followed by an increase during Weeks 33 and 34 as outdoor temperatures rose again. While the general pattern is shared across the rooms, the absolute temperature levels vary, indicating differences in ventilation effectiveness, orientation and thermal characteristics.

Table 4.1: Weekly mean indoor temperatures for Rooms 1315–1327 during Weeks 30–34

Week	1315	1317	1319	1321	1323	1325	1327
30	29.6	30.6	29.9	29.1	30.0	30.2	29.7
31	28.4	29.5	28.4	28.0	28.7	29.0	28.1
32	26.2	27.8	26.6	25.8	26.8	27.2	26.0
33	27.9	29.0	28.1	27.3	28.3	28.4	27.4
34	28.1	29.1	27.8	27.4	28.1	28.7	27.8

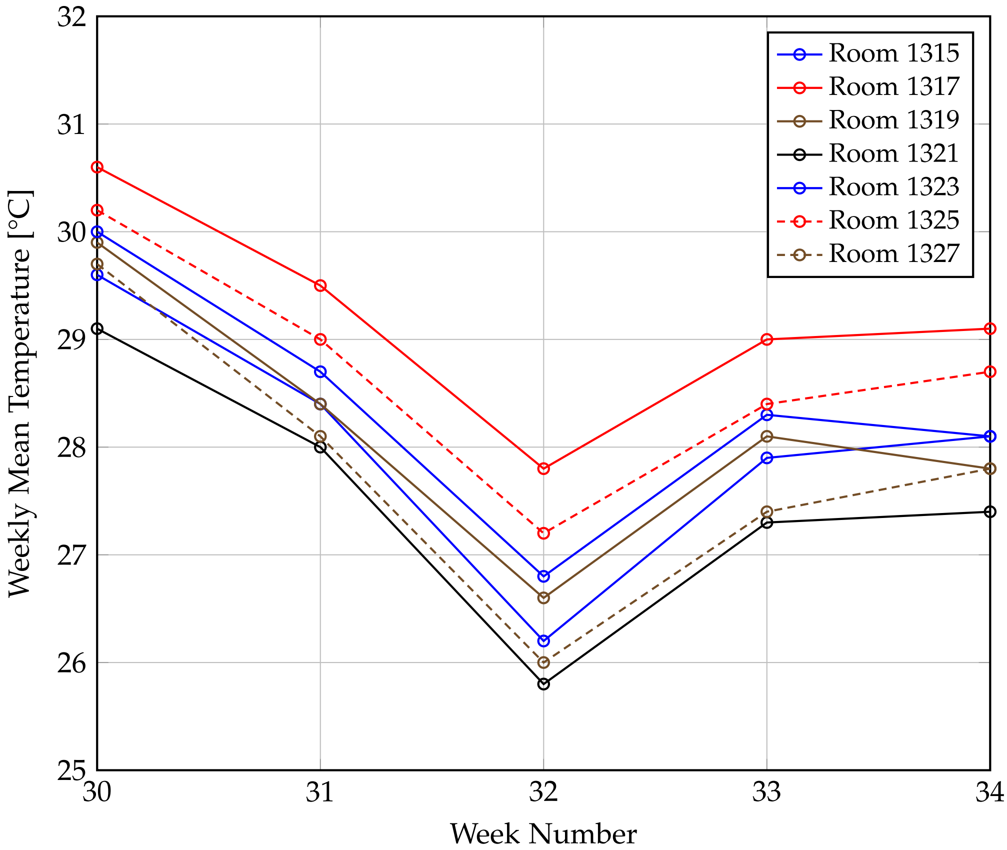

Figure 4.2: Weekly mean indoor temperature for Rooms 1315–1327 during Weeks 30–34.

4.2.1 Comparison Between Rooms

To better understand the relative thermal behaviour of the monitored rooms, the weekly mean indoor temperatures were compared against Room 1325, which is used as the reference space due to its representative mechanical ventilation configuration and its central position within the corridor. Positive deviations indicate rooms that were warmer than the reference, while negative deviations indicate cooler conditions.

It should be noted that the weekly means and the resulting comparison presented here include only weekday data. Weekend periods were excluded from the analysis because the building is largely unoccupied, mechanical ventilation operates at reduced levels, and internal gains differ significantly from typical weekday conditions. Including weekends would therefore distort the comparison and weaken the interpretation of ventilation related thermal differences between rooms.

Table 4.2 summarises the temperature differences for Weeks 30–34. A consistent pattern emerges across all weeks. Room 1317 is the warmest room, remaining approximately 0.3–0.6 °C above the reference. This behaviour reflects the fact that the room relies solely on mechanical ventilation and has limited capacity for night-time heat removal.

Room 1321 is consistently the coolest room, with temperatures 1.0–1.4 °C below the reference. The room benefits from effective cross ventilation, which enables higher airflow rates and more efficient removal of stored heat, especially during the late afternoon and night.

Rooms 1315, 1319, 1323 and 1327 generally remain slightly cooler than the reference room, with deviations typically within 0.3–0.9 °C below the baseline. These differences are consistent with their ventilation characteristics, which include limited natural ventilation potential or single sided window openings that provide some cooling but not to the same extent as the cross ventilated Room 1321.

Overall, Room 1317 demonstrates the weakest thermal performance, while Room 1321 shows the strongest passive cooling capability. These differences highlight the impact of ventilation strategy, airflow pathways and exposure on the indoor thermal environment.

Table 4.2: Weekly indoor temperature difference (°C) relative to Room 1325 for Weeks 30–34.

Week	1315	1317	1319	1321	1323	1327
30	-0.6	+0.4	-0.3	-1.1	-0.3	-0.59
31	-0.6	+0.6	-0.5	-1.0	-0.3	-0.91
32	-1.0	+0.6	-0.6	-1.4	-0.4	-1.12
33	-0.5	+0.6	-0.4	-1.1	-0.1	-1.00
34	-0.6	+0.3	-0.9	-1.3	-0.7	-0.98

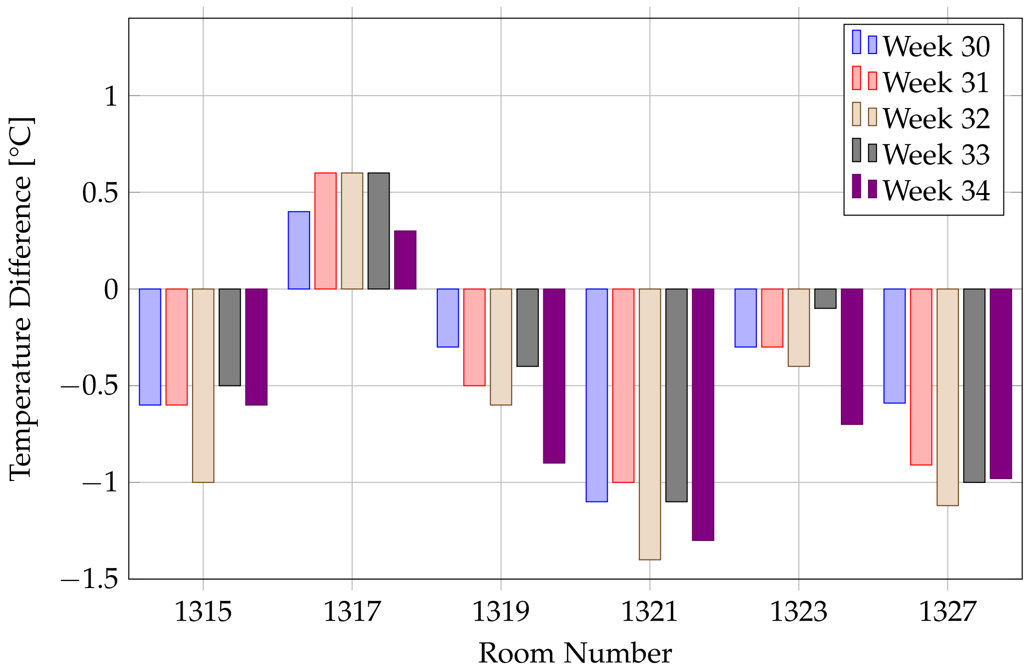

Figure 4.3: Weekly temperature deviation relative to Room 1325 for Weeks 30–34.

4.3 Weekly Temperature Ranking

In order to establish a clear and consistent thermal context for the interpretation of the measured results, I ranked the monitored weeks from the warmest to the coolest based on the mean indoor air temperatures during occupied weekday hours (08:00–17:00). This time window was selected because it represents the primary period of building use, during which indoor temperatures are most strongly influenced by internal heat gains, solar gains, and the applied ventilation strategy.

Weekend data were deliberately excluded from this analysis. During weekends, the building operates under reduced or altered ventilation schedules and experiences minimal occupancy, resulting in indoor temperature profiles that are not representative of normal operational conditions. Including weekend data would therefore distort the weekly averages and obscure meaningful comparisons between weeks.

Table 4.3 presents the resulting temperature ranking for all analysed rooms. Week 30 was identified as the warmest period of the monitoring campaign, consistently exhibiting the highest mean indoor temperatures across all rooms. This indicates a combination of elevated outdoor temperatures and significant internal and solar heat gains during this period. Week 31 followed as the second warmest week, showing a similar but slightly reduced thermal load. Week 34 also exhibited relatively high indoor temperatures, although it remained marginally cooler than Weeks 30 and 31. Week 33 represented moderate thermal conditions, while Week 32 was clearly the coolest week of the monitoring period, coinciding with lower outdoor temperatures and reduced thermal stress on the building.

This ranking is not presented merely as a descriptive summary of temperature levels, but serves as an essential reference framework for the subsequent analyses. By clearly distinguishing between warmer and cooler weeks, the ranking allows observed differences in indoor temperature behaviour to be interpreted in relation to external boundary conditions rather than random variability. It provides a structured basis for comparing overheating occurrence, daytime thermal stability, and night-time cooling performance under different climatic and operational conditions.

In particular, the identification of Week 30 as the warmest period provides a justified reference for the detailed evaluation of night cooling effectiveness presented in the following sections. Analysing night cooling performance during the most thermally demanding conditions ensures that the assessed cooling potential reflects a realistic worst-case scenario. Conversely, the cooler weeks serve as a comparative baseline, allowing the influence of outdoor temperature variations on indoor thermal response to be clearly distinguished from the effects of ventilation strategy and building operation.

Table 4.3: Weekly temperature ranking based on weekday mean indoor temperatures (08:00–17:00).

Week	1315	1317	1319	1321	1323	1325	1327
30	29.6	30.6	29.9	29.1	30.0	30.2	29.7
31	28.4	29.5	28.4	28.0	28.7	29.0	28.1
34	28.1	29.1	27.8	27.4	28.1	28.7	27.8
33	27.9	29.0	28.1	27.3	28.3	28.4	27.4
32	26.2	27.8	26.6	25.8	26.8	27.2	26.0

4.4 Daily Temperature Profiles

The daily temperature profiles presented in this section are based exclusively on weekday data and only during the core occupied hours (08:00–17:00). Weekend periods were not included in the analysis because the building experiences minimal occupancy and reduced mechanical ventilation during these days, which results in thermal behaviour that does not reflect typical overheating conditions. Focusing on weekdays and daytime hours ensures that the analysis captures the period in which overheating is most likely to occur, driven by solar gains, internal loads and normal operational schedules. This filtering approach provides a more representative and comparable basis for evaluating daytime temperature patterns and identifying peak overheating events.

4.4.1 Daily Temperature Profiles

In order to obtain a clear understanding of how indoor temperatures evolve during the occupied period of the day, daily temperature profiles were generated for all monitored rooms using the measurements collected between 08:00 and 17:00. Week 29 was removed from the analysis because several days contained incomplete or missing data. Weekend days were not included in the evaluation of indoor temperature trends, although they were preserved in the time axis to maintain the continuity of the dataset. To ensure that these non-occupied periods would not interfere with the visual interpretation of the results, Saturdays and Sundays were shaded in grey in the final plot, while the temperature curves were intentionally interrupted across these days. This approach makes it possible to distinguish between the behaviour of the building during operational hours and the periods during which no natural or mechanical ventilation was expected to take place.

The general pattern across the monitored rooms shows that the temperature during early morning hours begins at a noticeably lower level and gradually increases as the day progresses. This progression corresponds closely with the expected increase in solar gains and internal loads throughout the occupied period. In many of the warmer weeks, the temperature in several rooms reaches values in the range of approximately thirty to thirty-three degrees in the middle of the day, whereas the early morning conditions remain several degrees lower. This characteristic daily rise highlights the considerable heat stress imposed on the building during the summer period and emphasises the need to evaluate the effectiveness of ventilation strategies and thermal mass utilisation.

Although the overall shape of the daily temperature curves is similar among the rooms, the absolute temperature levels show clear differences. Rooms 1317 and 1323 frequently record the highest temperatures during the afternoon. This behaviour may be influenced by their orientation, exposure to solar radiation or differences in the operation of windows and shading devices. In contrast, Rooms 1319 and 1321 consistently appear as the cooler rooms within the group. Their lower afternoon temperatures suggest that they either receive less direct solar input or that the ventilation pathways in these rooms are more effective at removing accumulated heat. Room 1325, which has been used as the baseline reference, typically remains close to the median of the group.

The presence of weekend gaps in the figure provides a valuable insight into the behaviour of the building at the beginning of each week. Since no daytime ventilation or occupancy occurs during Saturdays and Sundays, the conditions observed on Mondays reflect the residual heat stored within the spaces. In several weeks, the temperature on Monday mornings is slightly higher than on the following weekdays, indicating that night-time ventilation alone may not always be sufficient to fully discharge the thermal mass of the building before the start of the working week. This observation will be relevant for the subsequent analysis of night cooling performance and the discussion of thermal mass behaviour in Sectionthermalmass

The synchronised shape of the temperature curves across all rooms demonstrates that the dataset is well aligned in time and that the rooms respond to outdoor conditions in a broadly comparable manner. Nevertheless, the variability in their absolute values indicates that local physical characteristics, such as glazing area, orientation and internal thermal mass, as well as differences in cross-ventilation potential, play a substantial role in defining how quickly each space heats up during the day.

Overall, the daily temperature profiles provide a clear overview of the building's thermal behaviour under summer conditions. They reveal consistent overheating tendencies during peak hours, highlight the influence of room-specific characteristics on temperature levels and illustrate the extent to which non occupied periods affect the thermal conditions observed at the start of each week. These findings form a crucial basis for the analyses presented later in this chapter, including the evaluation of night cooling, thermal mass response and the role of solar shading in moderating indoor temperatures.

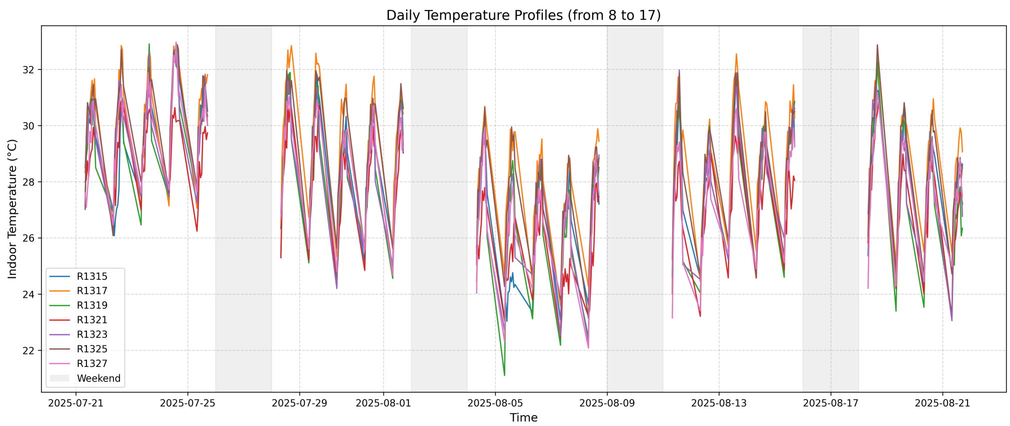

Figure 4.4: Daily temperature profiles for all monitored rooms during weekdays (08:00–17:00) .

4.5 Representative Hot Week Analysis (Week 30)

To better understand how the rooms responded during the hottest period of the monitoring campaign, Week 30 was selected as a representative hot week. This week consistently showed the highest indoor temperatures across the full monitoring period and therefore provides a clear basis for comparing the influence of ventilation type, solar exposure, and room geometry on overheating behaviour.

The following subsections present the temperature profiles of all seven rooms during Week 30. Only daytime hours (08:00–17:00) are shown, as these correspond to the period in which overheating is most relevant for occupied spaces. Each profile has been examined individually to understand how the rooms behave relative to each other and relative to the baseline room (Room 1325).

4.5.1 Room 1315

Room 1315 generally maintained moderate temperature levels throughout Week 30. Although the room is single-sided ventilated, it still showed slightly lower peak temperatures compared with several other rooms. This indicates that the external boundary conditions (such as solar exposure and shading position) had a noticeable effect on limiting heat accumulation.

During most days, temperatures increased rapidly after 10:00, reaching daily peaks in the range of approximately 30–31 °C. Compared with the baseline (Room 1325), Room 1315 remained consistently cooler, suggesting that its ventilation performance and solar gain profile were more favourable. Even though overheating still occurred, the magnitude was lower than in rooms with higher solar exposure, such as Room 1317 and Room 1319.

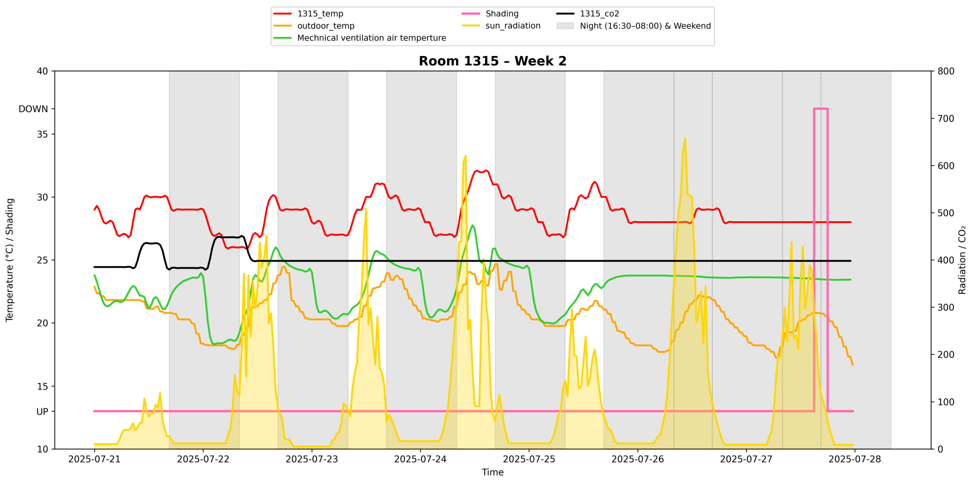

Figure 4.5: Indoor temperature profile for Room 1315 during Week 30 .

4.5.2 Room 1317

Room 1317 consistently showed some of the highest temperatures of all rooms during Week 30, often exceeding 31–32 °C in the early afternoon. This room is also single sided ventilated, but compared to Room 1315 it appears to be more exposed to solar gains, which contributed to higher indoor temperatures.The temperature rise during the morning hours was noticeably sharper, indicating that the room heats up quickly once solar radiation is present. Relative to the baseline room, Room 1317 was consistently warmer across the week. This behaviour aligns well with the comparative results presented earlier, where Room 1317 appeared as one of the warmest rooms in the set.

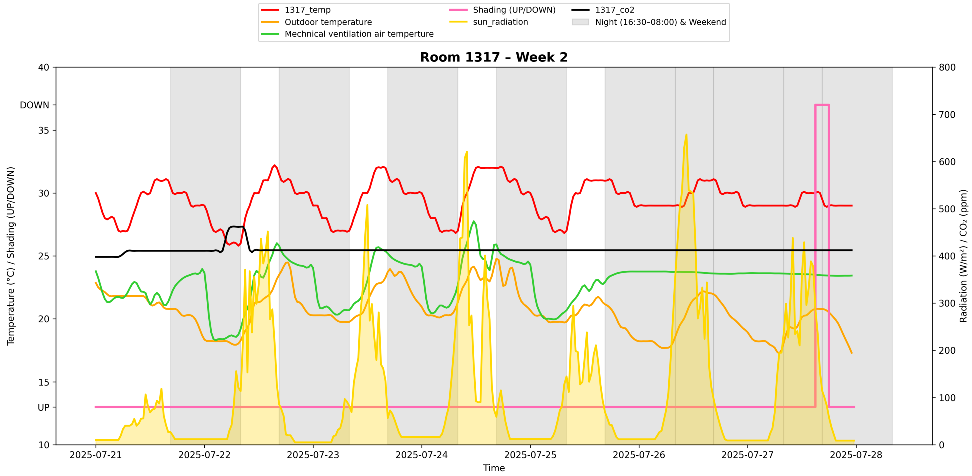

Figure 4.6: Indoor temperature profile for Room 1317 during Week 30

4.5.3 Room 1319

Room 1319 showed a temperature pattern similar to Room 1317, with relatively high afternoon temperatures and a quick increase after mid morning. The room frequently exceeded 30 °C, particularly on the warmest days of the week.

Despite being single sided ventilated, its behaviour suggests that ventilation alone was not sufficient to offset the solar gains. Compared with the baseline room, Room 1319 still tended to be warmer, although the difference was slightly smaller than for Room 1317. Overall, the room demonstrates limited cooling potential under hot conditions, mainly due to internal heat storage and insufficient natural airflow.

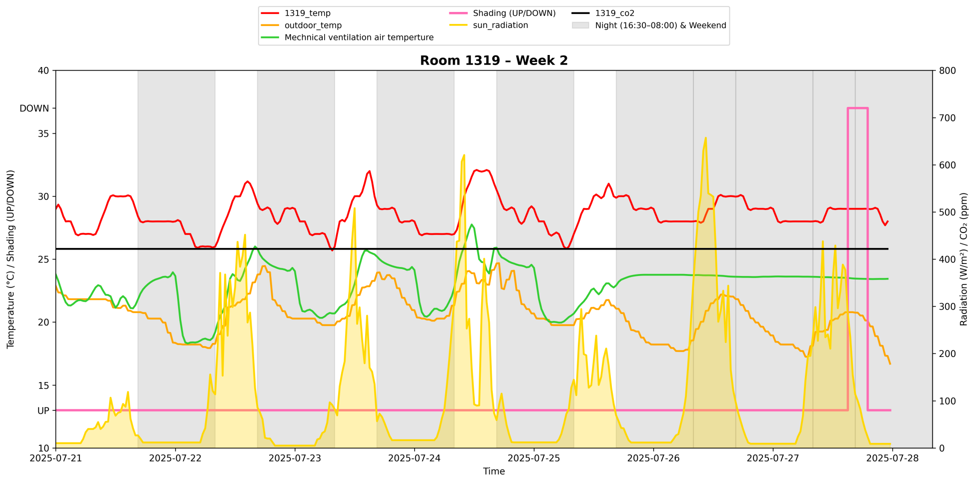

Figure 4.7: Indoor temperature profile for Room 1319 during Week 30 .

4.5.4 Room 1321

Room 1321 was the best performing room during Week 30. Its temperature remained consistently lower than all other monitored rooms, and noticeably below the baseline room. This strong performance is attributed to the presence of cross ventilation, which provides higher airflow rates and improves heat removal. Even during the hottest hours of the week, Room 1321 typically remained 1–2 °C cooler than Room 1325. The morning warm-up was also slower, indicating enhanced night time flushing and better utilisation of the building's thermal mass.

These observations confirm the importance of ventilation configuration on indoor thermal conditions during extreme weather periods.

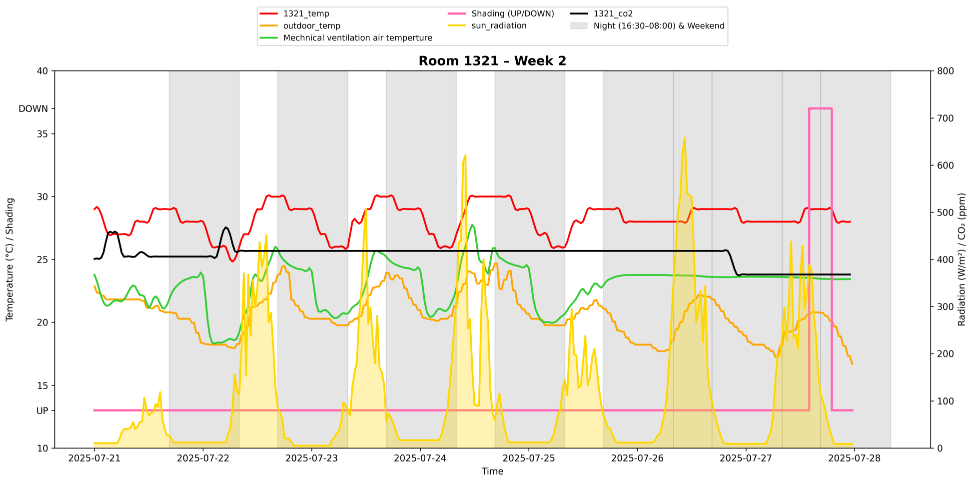

Figure 4.8: Indoor temperature profile for Room 1321 during Week 30

4.5.5 Room 1323

Room 1323 exhibited moderate overheating behaviour. Daily temperature peaks were typically within the range of 30–31 °C, but the room remained slightly cooler than the baseline across most of the week. This suggests reduced solar gains or a more favourable ventilation pattern compared with the warmest rooms.

Although not performing as well as the cross ventilated Room 1321, the room still showed a more stable thermal behaviour than Rooms 1317 and 1319.

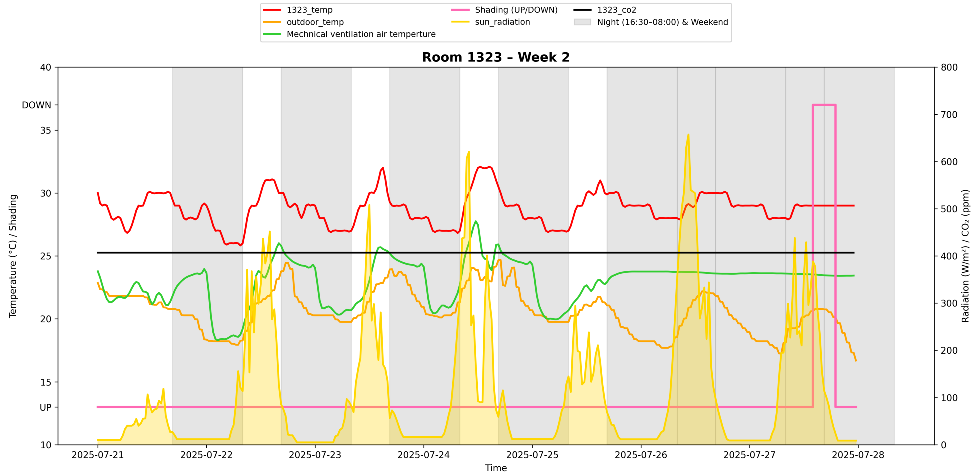

Figure 4.9: Indoor temperature profile for Room 1323 during Week 30

4.5.6 Room 1325 (Baseline Room)

Room 1325 served as the internal reference throughout the thermal comparison analysis. Its temperature profile during Week 30 showed consistently high values, with several daily peaks around 31–32 °C. The room warmed rapidly during the morning and cooled relatively slowly in the afternoon, indicating a limited natural ventilation effect.

Because the room reflects the typical behaviour of this corridor segment, using it as a baseline allowed meaningful comparison of ventilation effectiveness and solar gains across the other rooms.

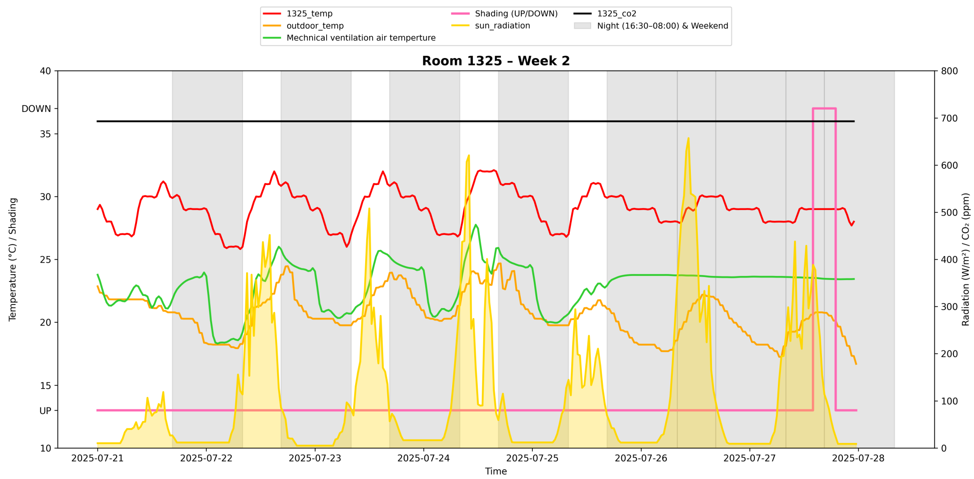

Figure 4.10: Indoor temperature profile for Room 1325 (baseline) during Week 30

4.5.7 Room 1327

Room 1327 showed a temperature pattern comparable to the baseline room but with slightly lower peaks on several days. Although the room still reached temperatures above 30 °C, the overall overheating magnitude was somewhat reduced compared with the baseline.

The slower cooling rate in the afternoon indicates limited ventilation and the presence of thermal storage that delays temperature reduction. Nevertheless, its performance was more favourable than the hottest rooms (1317 and 1319).

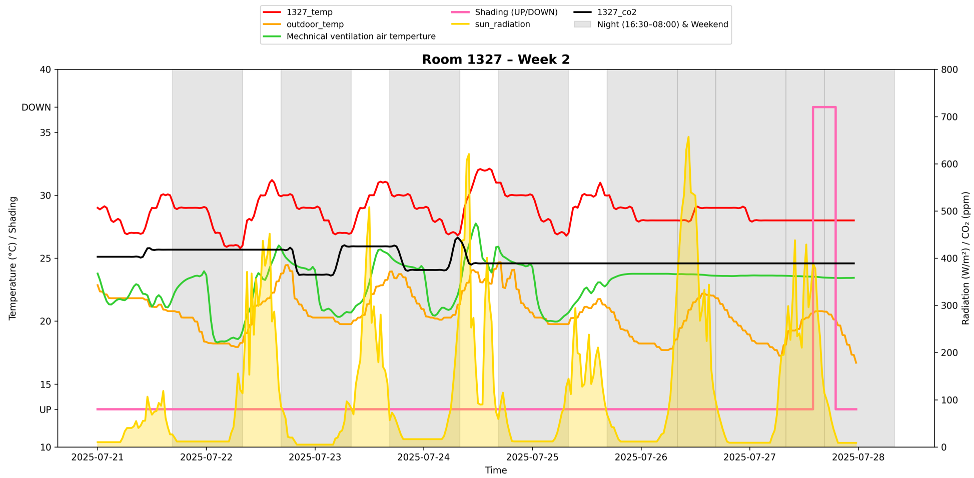

Figure 4.11: Indoor temperature profile for Room 1327 during Week 30

4.5.8 Rooms Performance Summary for Week 30

The results from all seven monitored rooms during the hottest week of the measured period provide a clear picture of how ventilation configuration, solar exposure, and thermal storage influence indoor temperature development under extreme outdoor conditions.

Across the week, a consistent ranking pattern emerges. Room 1321 demonstrates the most favourable thermal behaviour, remaining noticeably cooler than the baseline room. Its cross-ventilation strategy appears to be the decisive factor, enabling more effective heat removal during both daytime and night time periods. The slower morning warm up and lower peak temperatures suggest that night flushing combined with usable thermal mass helped maintain a more stable indoor environment.

At the opposite end of the spectrum, Room 1317 shows the highest temperature peaks and the steepest morning temperature rise. These results align with the earlier weekly comparisons and confirm that the room accumulates heat more rapidly than the rest of the corridor. The limited effect of night cooling and the persistent temperature elevation throughout the day indicate a combination of strong solar gains and insufficient natural airflow.

Rooms 1319 and 1325 form a second group with similar performance. Both rooms exhibit significant overheating during the afternoon, and their cooling rates remain modest.

Since Room 1325 serves as the internal reference, its behaviour establishes the baseline against which the other rooms are evaluated. Room 1319 typically performs slightly worse, which suggests more pronounced heat accumulation.

Rooms 1315, 1323, and 1327 perform in an intermediate range. They reach temperatures above 30 °C during several days but remain slightly cooler than the baseline. Their behaviour indicates reduced radiant exposure or more favourable facade conditions, though the ventilation pattern is not sufficient to avoid overheating entirely.

Overall, Week 30 clearly demonstrates how strongly the indoor thermal environment is shaped by ventilation strategy, orientation, and the ability of the room to dissipate heat during the night. The cross-ventilated Room 1321 stands out as the most resilient space under high external loads, while Rooms 1317 and 1319 show the greatest overheating risk. These differences highlight the importance of integrating natural ventilation potential, solar control, and thermal mass considerations in the design and operation of similar buildings.

Overheating Profile During Occupancy Hours (08:00–17:00)

To evaluate short term overheating behaviour during the hottest monitored period, a detailed hour by hour exceedance analysis was conducted for Week 30. This week represents the most thermally demanding conditions in the dataset, and the assessment focuses specifically on occupancy hours between 08:00 and 17:00. Weekend days were excluded to ensure that the results reflect typical operating conditions.

for each room and each hour of the day, the number of days in Week 30 during which indoor temperatures exceeded thresholds ranging from 25°C to 32°C. Since Week 30 contains seven weekdays, the maximum possible value in each cell is seven.

A clear pattern emerges across all rooms: indoor temperatures were already above 25°C in nearly all rooms at 08:00, indicating residual heat accumulation from the previous day. As the day progressed, exceedances increased sharply, with the most severe conditions observed between 12:00 and 15:00. This period aligns with peak outdoor temperatures and maximum solar exposure.

- **Room 1317** shows the highest overheating severity, reaching 29–31°C more frequently and more persistently than any other room. This confirms its status as the warmest-performing room.
- **Room 1321** remains the coolest room, with minimal exceedances above 28°C and no occurrences above 30°C. This behaviour correlates with its strong night cooling performance.
- **Rooms 1315, 1319, 1323, and 1327** show moderate overheating. Temperatures above 27°C are frequent, but extreme overheating (above 30°C) is limited to short periods.
- **The baseline Room 1325** shows stable but noticeable overheating behaviour. While exceedances above 27°C occur daily, temperatures above 30°C remain relatively rare.

These results illustrate how differently the rooms respond to identical external conditions. The exceedance patterns are visualised further in the heatmap shown in Figure **??**, which highlights the progression of overheating severity throughout the day and across rooms.

4.6 Night Cooling

Night cooling is an established passive cooling strategy that utilises the natural temperature difference between indoor spaces and the outdoor environment during night-time hours. When outdoor temperatures fall below the indoor air and thermal mass temperature, increased ventilation can be used to remove accumulated heat and reduce the following day's cooling demand. This process is particularly effective in buildings with moderate to high thermal mass, where the heat capacity of the structure allows significant energy storage and subsequent release during the night.

In the context of summer comfort and overheating risk mitigation, night cooling plays an important role by lowering the initial morning temperatures and consequently reducing the likelihood of exceeding the comfort thresholds defined in standards such as EN 16798 and DS 474. The efficiency of the strategy depends on several factors, including the outdoor climate, ventilation configuration (single sided or cross ventilation), internal heat gains, and the responsiveness of the building's thermal mass.

This section presents a detailed evaluation of the night cooling performance in the studied zones of the AAU BUILD facility. Temperature measurements were analysed for multiple rooms with different ventilation configurations to investigate how effectively the night cooling strategy reduces indoor air temperatures during selected warm periods. The analysis focuses on the rate of night-time cooling, differences between room types, the influence of weekend versus weekday operational conditions, and the resulting impact on morning start temperatures.

The following subsections provide a systematic assessment of the night cooling behaviour during representative warm weeks, beginning with Week 30, which was selected due to its elevated outdoor temperatures and clear night-time cooling potential. The presented results form an essential basis for understanding the thermal dynamics of the building and evaluating the effectiveness of the implemented ventilation strategy in reducing overheating.

4.6.1 Night Cooling Performance During Week 30

Figure 4.12 illustrates the night-time temperature development in Rooms 1315, 1317, 1319, 1321, 1323, 1325 and 1327 during Week 30. Only the period between 17:00 and 08:00 is shown in order to isolate the behaviour of the night cooling strategy from the daytime load conditions. All daytime hours (08:00–17:00) are intentionally removed from the plot and appear as gaps. Weekend periods are highlighted with grey shading to distinguish them from regular weekdays.

Across all seven days of Week 30, a consistent cooling trend is observed. Indoor air temperatures in all rooms start between 29 °C and 31 °C shortly after 17:00. These values represent the accumulated heat load originating from solar gains, internal loads, and mechanical ventilation limitations during daytime operation. Once the night cooling strategy is activated, temperatures decline rapidly. The steepest cooling occurs during the early night hours (approximately 17:00–23:00), indicating strong heat rejection due to favourable indoor–outdoor temperature gradients and increased air exchange.

After midnight, the cooling rate becomes less pronounced. This change in slope reflects the reduction in temperature difference between indoors and outdoors and the fact thatOutdoor temperatures reach their lowest values during this period, which creates favourable conditions for night-time cooling. The observed behaviour is therefore consistent with well established physical expectations for night cooling in buildings with significant thermal mass, where stored heat can be effectively released during cooler night hours [20, 21].

A clear difference can be observed between single sided and cross ventilated rooms. Rooms 1319, 1321, and 1323, which are equipped with cross ventilation, generally exhibit lower indoor temperatures and steeper cooling gradients compared to single-sided rooms such as 1315 and 1327. This behaviour reflects the theoretical advantage of cross ventilation, as it provides more effective airflow paths and enhances convective heat removal from the space [20]. Room 1325, used as the baseline reference, shows a more moderate cooling behaviour, positioned between the fastest and slowest cooling responses.The weekend period (25–27 July), highlighted in grey, shows a slightly different cooling pattern. Due to reduced occupancy and lower internal heat gains, the starting temperatures at the beginning of weekend nights are marginally lower than during weekdays. As a result,the minimum temperatures reached overnight are also slightly reduced, indicating that the effect of night cooling becomes more pronounced when internal heat disturbances are limited [21].

Overall, the results demonstrate that the night cooling strategy performs effectively throughout Week 30. All rooms show a consistent decrease in indoor temperature during the night, confirming that the building's thermal mass is actively involved in storing and releasing heat. This contributes to lower indoor temperatures in the morning and reduces the risk of exceeding Category II thermal comfort limits during the following day, in line with Danish guidelines for indoor climate and overheating prevention [9, 22].

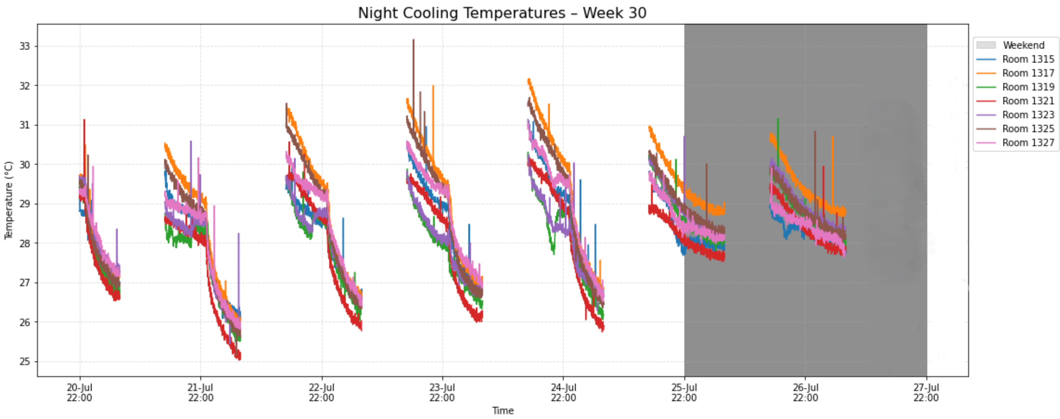

Figure 4.12: Night-time temperature development (17:00–08:00) for Rooms 1315, 1317, 1319, 1321, 1323, 1325 and 1327 during Week 30. Daytime hours (08:00–17:00) are removed for clarity. Weekend periods are highlighted in grey.

4.6.2 Night-time Temperature Drop (T_{night})

To evaluate the effectiveness of night cooling in each room, the average temperature during the night-time period (17:00–08:00) was calculated. This time window is commonly used in night ventilation studies, as documented in CIBSE AM10, where night hours are considered the main period for passive and mechanical night cooling [6].

The mean night time temperature for each room was computed using:

$$\overline{T}_{\text{night}} = \frac{1}{N}\sum_{i=1}^{N} T_{i,\text{night}} \tag{4.1}$$

[2, 16]

This equation represents the standard arithmetic average, which is the recommended method for analysing time-series environmental data in thermal comfort and building performance studies.

To compare the rooms, Room 1325 was selected as the baseline reference. The temperature difference relative to the baseline was calculated as:

$$\Delta T_{\text{relative}} = \overline{T}_{\text{night,room}} - \overline{T}_{\text{night,1325}} \tag{4.2}$$

[5]

A negative value of $\Delta T_{relative}$ indicates that the room cooled more effectively than the baseline, while a positive value indicates weaker cooling performance.

Table 4.4 summarises the results:

Room	**Mean Night Temp (°C)**	**Baseline 1325 (°C)**	$\Delta T_{relative}$ **(°C)**
1315	26.40	27.17	-0.77
1317	27.60	27.17	+0.42
1319	26.08	27.17	-1.10
1321	26.54	27.17	-0.63
1323	26.47	27.17	-0.70
1325	27.17	27.17	0.00
1327	26.26	27.17	-0.92

Table 4.4: Night-time mean temperatures and relative differences compared with the baseline room.

To visualise the results, a bar chart was also created (Figure 4.13). Rooms with negative values clearly show stronger night cooling performance. Among them, Room 1319 exhibits the largest cooling effect with a relative drop of $-1.10\ C$, followed by Rooms 1327, 1315, 1323 and 1321. Room 1317, on the other hand, performs weaker than the baseline with a positive value of $+0.42\ C$, meaning that its cooling during the night was less effective.

These results align well with the general understanding of night cooling effectiveness as described in the literature: rooms with better ventilation pathways and lower internal loads tend to achieve lower night-time temperatures and steeper cooling profiles. The consistency between the numerical results and the observed temperature curves strengthens the validity of the chosen evaluation method. In addition to the mean night time temperatures and the relative differences presented above, a more detailed assessment of the cooling behaviour during Week 30 was carried out by analysing three complementary indicators: the early-night temperature reduction, the full-night cooling across the entire night period, and the minimum temperature reached during night-time hours. These indicators provide a broader understanding of the thermal response of each room and allow comparison of how effectively heat was removed once night cooling was activated.

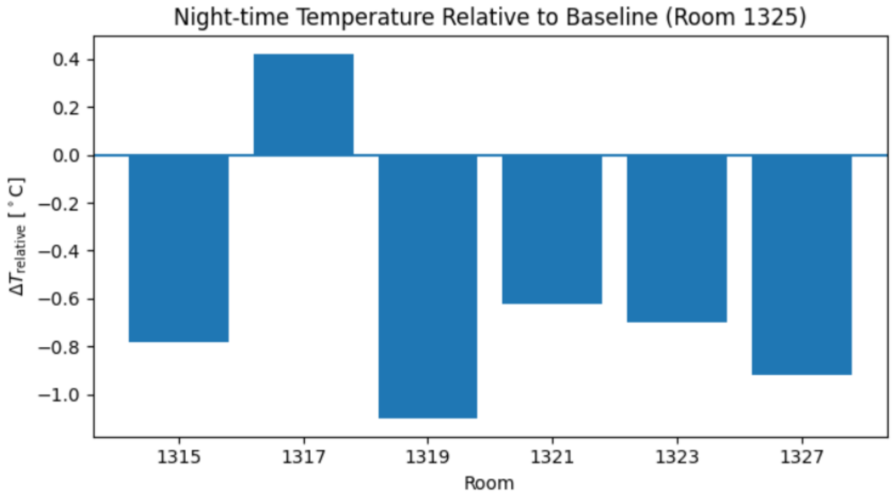

Figure 4.13: Relative night-time temperature drop for each room compared to the baseline (Room 1325). Negative values indicate better cooling performance.

Early-night temperature reduction (20:00–23:00)

The first indicator examines the initial temperature drop shortly after the onset of night cooling. This period is characterised by the largest indoor–outdoor temperature gradient, making it a critical phase for heat rejection. The temperature reduction was calculated as:

$$\Delta T_{20-23} = T_{20:00} - T_{23:00} \tag{4.3}$$

[6]

Figure 4.14 illustrates the results for all rooms. Rooms 1317, 1325, and 1321 show the steepest initial cooling, confirming a strong heat loss potential during the early hours of the night. In contrast, Rooms 1319 and 1323 exhibit weaker reductions, which is consistent with the smaller indoor, outdoor driving temperature difference and potentially less favourable airflow paths present in those rooms.

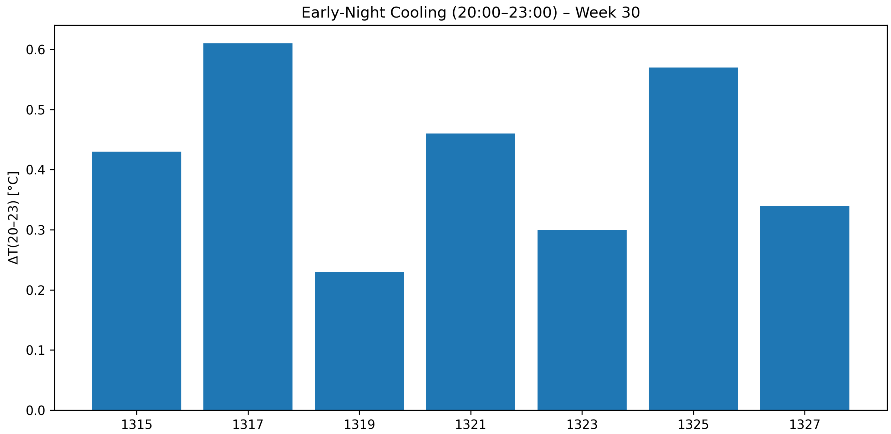

Figure 4.14: Early-night temperature drop ΔT_{20-23} for Rooms 1315–1327 during Week 30. Larger values indicate stronger initial cooling performance.

Full-night temperature reduction (20:00–08:00)

To quantify the cumulative effect of night cooling, the temperature reduction across the entire night period was evaluated.This indicator describes how effectively the thermal mass of the rooms was able to release stored heat throughout the night. The calculation follows:

$$\Delta T_{20-08} = T_{20:00} - T_{08:00} \tag{4.4}$$

[10]

Figure 4.15 presents the full-night cooling values. Rooms 1317, 1325, and 1321 achieve the highest overall temperature reductions, confirming that these rooms benefit from favourable ventilation configurations and effective interaction with thermal mass. Rooms 1319 and 1323 show the smallest night long reductions, indicating slower heat-release dynamics.

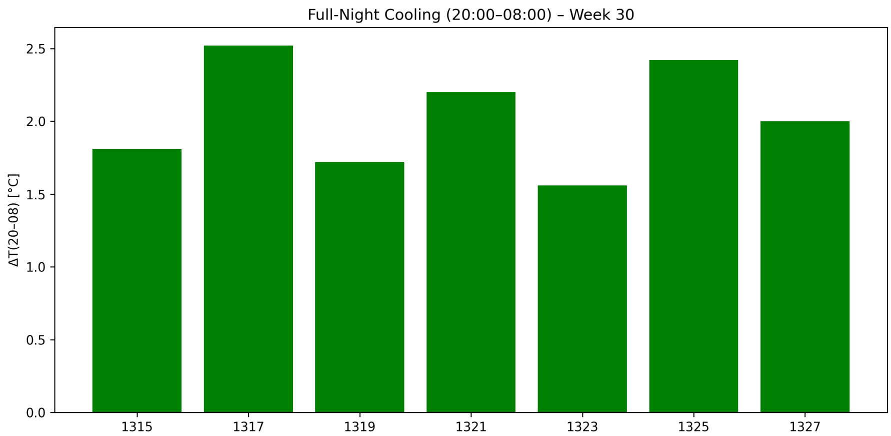

Figure 4.15: Full-night temperature reduction ΔT_{20-08} for all monitored rooms during Week 30. Higher values indicate stronger overall night cooling performance.

Minimum night-time temperature

As a third performance indicator, the minimum indoor temperature reached during the entire night-time period was extracted for each room. This indicator reflects the ability of the building's thermal mass to discharge stored heat during the night and to reset thermal conditions before the start of the following occupied day. Lower minimum night time temperatures are therefore associated with a reduced risk of overheating during daytime hours, a relationship also emphasised in EN 16798 and DS 474.

Figure 4.16 presents the minimum night time indoor temperatures, T_{min}, for all analysed rooms during Week 30, shown in a ranked format to support direct comparison between spaces. The results indicate clear differences in night time thermal resetting performance. Rooms 1321 and 1325 reach the lowest minimum temperatures, approximately 25,$^\circ$C, suggesting that these rooms were able to discharge a larger fraction of accumulated heat during the night. This behaviour indicates more effective night-time cooling and improved thermal preparation prior to morning occupancy.

In contrast, Rooms 1317 and 1327 maintain the highest minimum night-time temperatures, close to 26,$^\circ$C. The elevated minima observed in these rooms suggest a slower thermal response or reduced effectiveness of the applied ventilation strategy during the later hours of the night. As a result, these rooms begin the following day from a less favourable thermal state, which may contribute to an increased susceptibility to overheating during occupied hours.

Overall, the ranked representation in Figure 4.16 highlights relative differences in night-time cooling performance between rooms and provides additional insight into the effectiveness of thermal mass utilisation and ventilation driven heat removal during the

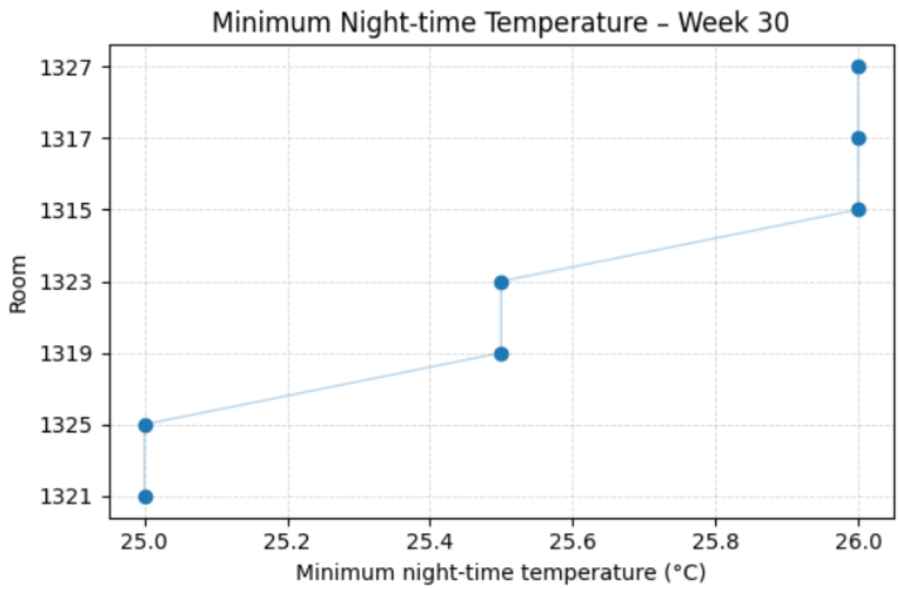

Figure 4.16: Minimum night-time temperature T_{min} (17:00–08:00) for Rooms 1315–1327 during Week 30. Lower values indicate stronger cooling potential and improved thermal resetting.

Summary of night-time cooling behaviour

When the three indicators early night cooling rate, total night time temperature reduction, and minimum night time temperature are considered together, a clear overall pattern can be observed. Rooms 1317, 1321, and 1325 consistently show stronger night-time cooling performance compared to the other rooms. These rooms cool down more rapidly in the early part of the night, achieve a larger overall temperature reduction, and reach lower minimum temperatures by the morning.

In contrast, Rooms 1319 and 1323 show weaker cooling performance during the night. This behaviour is likely related to limited effectiveness of night-time ventilation or differences in how thermal mass is utilised in these spaces.

Overall, the observed trends are in line with the expected influence of ventilation availability and thermal mass on night time cooling performance, and they support the reliability of the evaluation approach applied in this study.

4.6.3 Night-time Cooling Rate

In addition to the mean night-time temperature reduction, it is also important to assess the *rate* at which cooling occurs during the early night period. The cooling rate describes how fast the indoor air temperature decreases once night ventilation becomes dominant, and it provides valuable insight into the thermal response of the rooms and the effectiveness of their ventilation paths.

For this analysis, the interval between 21:00 and 23:00 was selected. During these hours solar gains are close to zero and internal loads are significantly reduced, meaning that the indoor outdoor temperature gradient is the primary driver of heat removal. The cooling rate was estimated using a simplified linear approximation of the temperature decay:

$$\text{Cooling Rate} = \frac{T(t_1) - T(t_2)}{t_2 - t_1} \tag{4.5}$$

[2]

Here, $T(t_1)$ and $T(t_2)$ represent the indoor air temperature at the beginning and end of the selected period, and the resulting value expresses the hourly rate of temperature reduction. A higher absolute cooling rate indicates a steeper temperature decrease and therefore a more effective early night cooling performance.

Table 4.5 summarises the computed cooling rates for all monitored rooms during Week 30. Considerable differences are observed between rooms, which reflect their ventilation configuration, airflow efficiency, and interaction with thermal mass.

Room	Cooling Rate (°C/hour)
1315	0.130
1317	0.211
1319	0.044
1321	0.205
1323	0.078
1325	0.196
1327	0.123

Table 4.5: Calculated earlynight cooling rates (21:00–23:00) during Week 30.

Figure 4.17 illustrates the same results graphically. Rooms 1317, 1321 and 1325 show the steepest cooling rates, meaning that these spaces are able to reject heat more quickly once night ventilation is initiated. This behaviour is consistent with the strong airflow pathways observed in their temperature development curves.

In contrast, Room 1319 shows the lowest cooling rate, suggesting a slower thermal response, likely due to airflow limitations or higher surface heat storage. The remaining rooms fall in between these two categories and demonstrate moderate cooling behaviour.

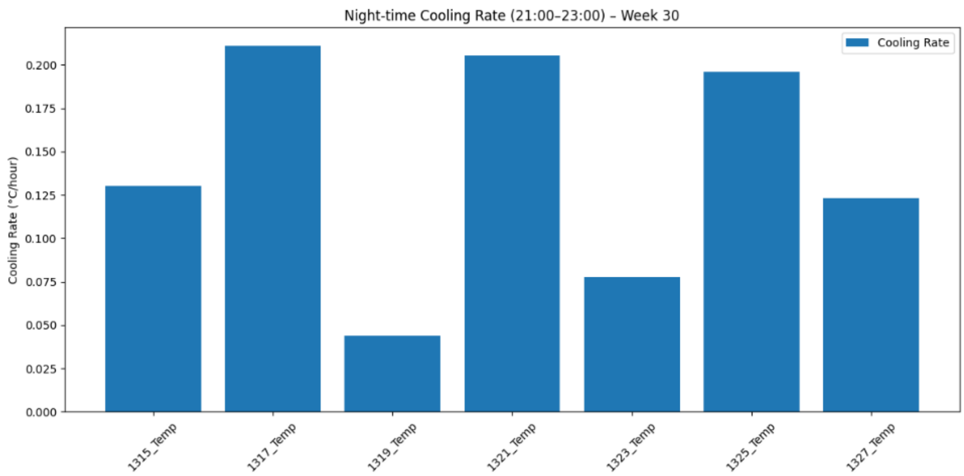

Figure 4.17: Night-time cooling rate (21:00–23:00) for Rooms 1315–1327 during Week 30. Higher values represent steeper temperature reduction.

Overall, the cooling rate analysis confirms the trends identified in the previous sections: rooms with more effective ventilation geometries and better exposure to airflow paths achieve faster cooling during the early night hours. This performance subsequently contributes to lower minimum night-time temperatures and improved morning thermal conditions.

4.6.4 Comparison Between Rooms

Analysis of the night cooling performance across all monitored rooms shows clear and consistent differences in how each space responds to night time ventilation. Although all rooms exhibit a general reduction in temperature during the night hours, the magnitude and speed of this reduction vary notably depending on the room's ventilation configuration, exposure to airflow, thermal mass interaction, and internal heat retention.

Rooms equipped with cross-ventilation particularly Rooms 1319, 1321, and 1323 demonstrate the strongest night cooling behaviour across all indicators. These rooms not only show lower average night time temperatures but also display steeper early night cooling gradients and higher cooling rates between 21:00 and 23:00. Such performance aligns with the expected advantages of cross ventilation, where improved airflow pathways enhance convective heat removal and allow the room surfaces to release stored heat more effectively.

In contrast, single sided rooms such as 1315 and 1327 exhibit weaker cooling performance. Their night-time mean temperatures remain higher, the cooling rate is noticeably lower, and the full night temperature drop is smaller compared to the cross ventilated rooms. This behaviour is consistent with known limitations of single sided ventilation, where reduced air exchange inhibits effective heat release, especially during periods with lower pressure driven flow.Room 1325 used as the baseline reference shows intermediate behaviour. Its performance consistently falls between the faster cooling cross ventilated rooms and the slower cooling single sided rooms. This makes it a suitable benchmark for evaluating relative cooling effectiveness across the building.

The comparison also highlights the influence of occupancy patterns and internal gains. During weekends, where internal loads are minimal, the starting temperature of each night is slightly reduced, and the minimum temperatures achieved are correspondingly lower. The contrast between weekday and weekend behaviour is most visible in rooms with higher internal heat storage, suggesting that residual heat from equipment or occupancy plays a noticeable role in determining cooling effectiveness.

Overall, the comparative analysis confirms that ventilation configuration is the dominant factor governing night cooling performance in Week 30. Cross ventilated rooms consistently outperform single sided rooms in every metric: mean night time temperature, night-time temperature drop, earlynight cooling, and cooling rate. Rooms with optimal airflow pathways not only cool faster but also achieve lower absolute temperatures by early morning, thereby reducing the risk of overheating during the following day.

These findings reinforce the importance of effective night ventilation design in buildings of similar typology. Ensuring adequate cross flow potential, minimising internal heat accumulation, and leveraging available thermal mass can significantly enhance night cooling performance and contribute to maintaining acceptable thermal comfort levels under warm summer conditions.

4.7 Skylight Operation and Solar Radiation

The circulation corridor above the monitored rooms is equipped with a large skylight that has the capacity to influence both solar gains and natural ventilation. Because all seven rooms are aligned along the same corridor and are equally exposed to the skylight, this element represents a shared boundary condition that can meaningfully affect indoor thermal behaviour. Understanding the skylight's operational pattern is therefore essential for interpreting the temperature development, night cooling efficiency, and overheating risk across the monitored rooms.

Solar radiation is a primary driver of heat gains in lightweight and moderately insulated buildings [11]. When transmitted through large transparent or translucent surfaces, it increases the temperature of corridor air and surrounding surfaces, thereby elevating the baseline temperature from which individual rooms must dissipate heat. The skylight above the TMV23 rooms functions both as a potential ventilation opening and as a source of solar gain; however, its real behaviour depends entirely on the building management system (BMS), which automatically operates the opening mechanism.

4.7.1 Observed Skylight Behaviour During Week 30

Figure 4.18 illustrates the skylight open/close signal alongside hourly solar radiation during Week 30 the hottest week in the measurement period. Solar radiation exceeds 600–700 W/m^2 during several midday periods, consistent with typical peak summer conditions in Denmark [7].

In principle, such high radiation levels would justify extended opening of the skylight to promote buoyancy driven ventilation and relieve accumulated heat, particularly during the late morning and early afternoon. However, the measured data reveal a distinctly irregular opening pattern: the skylight repeatedly transitions between open and closed states during the same day, with several closures occurring precisely during the hours when solar gains are highest. This behaviour cannot be explained by thermal logic or a radiation-based control strategy.

4.7.2 Impact of Rainfall on Skylight Control

The irregular operating pattern is largely explained by the presence of multiple short rainfall events during Week 30. The skylight is equipped with a standard automatic rain sensor common in European BMS-controlled operable roof windows which immediately commands closure when precipitation is detected and maintains the closed state until the sensor registers fully dry conditions [18].Because rainfall during this week was intermittent and often brief, the skylight oscillated frequently between open and closed states. Even short rain showers, lasting only a few minutes, resulted in prolonged closure periods due to the sensor's conservative drying time. As a result, the periods when the skylight was most needed to enhance natural ventilation coincided with enforced closures driven by weather conditions rather than thermal requirements.

This behaviour significantly limits the skylight's contribution to thermal relief. In building physics literature, natural ventilation openings located at high elevation are widely recognised as highly effective for removing accumulated warm air and promoting stack ventilation [1, 12]. When such openings are unavailable during peak solar gain periods, indoor spaces rely primarily on mechanical ventilation and thermal mass for temperature control.

4.7.3 Implications for Thermal Conditions in the TMV23 Rooms

The combined effect of high solar gains and restricted skylight operation results in a higher thermal baseline within the corridor zone. Since the corridor acts as a buffer space between the facade and the mechanically ventilated rooms, elevated corridor temperatures increase the temperature of the supply air distributed into the rooms and reduce the overall cooling potential of mechanical and natural ventilation systems.

The consequences can be summarised as follows:

- **Reduced potential for buoyancy-driven heat removal.** With the skylight frequently closed during warm hours, warm air accumulating near the upper corridor ceiling cannot escape, reducing the effectiveness of stack driven ventilation.
- **Increased corridor and surface temperatures.** Solar gains absorbed by corridor surfaces elevate the thermal mass temperature. This reduces night cooling effectiveness, as surfaces begin each night from a higher temperature level [**ThermalMassCooling**].
- **Stronger dependency on mechanical ventilation.** During Week 30, the rooms were forced to depend almost entirely on mechanical ventilation for cooling during occupancy hours, which explains the limited temperature spread between rooms with different orientations.
- **Potential contribution to overheating risk.** Elevated corridor temperatures and reduced ventilation openings contribute to longer daily durations above 26–27°C—the thresholds referenced in BR18 overheating criteria [22].

4.7.4 Correlation Between Skylight State and Solar Radiation

A time-series comparison shows the following patterns:

- The skylight remains closed for substantial periods during radiation peaks;
- Opening events often occur during early morning or late afternoon, when the cooling potential is lower due to reduced temperature gradients;
- Short opening periods do not provide sufficient time for meaningful heat removal from the corridor thermal mass;
- Rain-triggered closures overwrite all thermal control signals.

This behaviour demonstrates that the skylight operates primarily as a *weather-protection device* rather than a *ventilation asset*. Consequently, the thermal dynamics observed in the rooms during Week 30 cannot be interpreted as a reflection of optimal natural ventilation potential; rather, they represent a restricted ventilation scenario imposed by frequent weather driven closures.

4.7.5 Conclusion on Skylight Performance

Although the skylight has the potential to enhance natural ventilation and reduce heat accumulation under warm summer conditions, its actual operation during Week 30 was dominated by rain-protection behaviour. As a result, corridor air temperatures remained elevated, thermal mass discharge was limited, and the indoor temperature profiles of the rooms exhibit characteristics consistent with high solar load and restricted night cooling. This contextual understanding is essential for interpreting the differences between the monitored rooms and for assessing the impact of ventilation strategies and shading systems in later sections of this report.

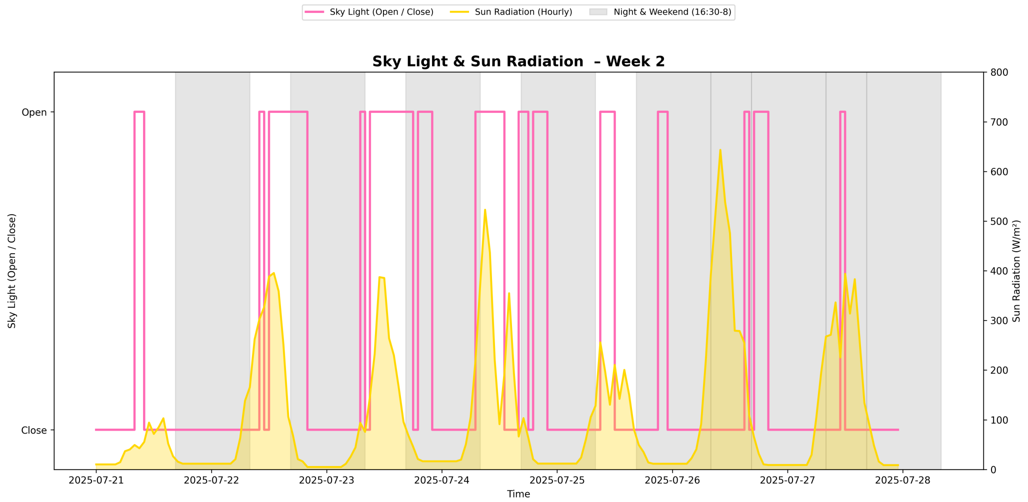

Figure 4.18: skylight and solar radiation during Week 30.

4.8 Comparison Between Room Types

This section compares the night-time cooling performance of the analysed rooms by grouping them according to their dominant ventilation strategy. The comparison is based on two complementary metrics: the early night-time cooling rate calculated between 21:00 and 23:00, and the total night-time temperature reduction, ΔT_{night}, calculated between 20:00 and 08:00 during Week 30. Using both metrics allows the initial thermal response and the overall night cooling effectiveness to be evaluated separately.

4.8.1 Early Night time Cooling Rate

The cooling rate is defined as the absolute value of the hourly indoor temperature reduction. Expressing the cooling rate as an absolute value enables a direct quantitative comparison between rooms operating under different ventilation strategies.

Table 4.6 summarises the cooling rate for each analysed room during the early night-time period between 21:00 and 23:00.

Mechanically ventilated rooms (Rooms 1317 and 1325), together with the Room 1321, exhibit the highest cooling rates during the early night hours, with values close to 0.20 °C/h. In contrast, the cross-ventilated rooms (Rooms 1319 and 1323) show considerably lower cooling rates during the same period.

Table 4.6: Night-time cooling rate for individual rooms during Week 30 (21:00–23:00)

Room	Cooling Rate [°C/h]	Ventilation Type
1315	0.13	Single-sided (night)
1317	0.21	Mechanical-only
1319	0.04	Cross-ventilated (night)
1321	0.21	Mechanical-only (no night ventilation)
1323	0.08	Cross-ventilated (night)
1325	0.20	Mechanical-only (baseline)
1327	0.12	Single-sided (night)

4.8.2 Total Night-time Temperature Reduction

To evaluate the overall effectiveness of night cooling, the total night-time temperature reduction, ΔT_{night}, was calculated for each room between 20:00 and 08:00. This metric represents the cumulative cooling effect achieved over the full night and is therefore more representative of the ability to discharge heat stored in the building's thermal mass.

Table 4.7 presents the calculated ΔT_{night} values for all analysed rooms.

Table 4.7: Total night-time temperature reduction ΔT_{night} during Week 30 (20:00–08:00)

Room	ΔT_{night} [°C]	Ventilation Type
1315	1.81	Single-sided (night)
1317	2.52	Mechanical-only
1319	1.72	Cross-ventilated (night)
1321	2.20	Mechanical-only (no night ventilation)
1323	1.56	Cross-ventilated (night)
1325	2.42	Mechanical-only (baseline)
1327	2.00	Single-sided (night)

4.8.3 Comparison by Room Type

For a systematic comparison, the rooms were grouped according to their ventilation strategy, and mean values were calculated for room types represented by more than one room. The aggregated results are presented in Table 4.8.

Table 4.8: Comparison of early cooling rate and total night-time temperature reduction by room type (Week 30)

Room Type	Mean Cooling Rate [°C/h]	Mean ΔT_{night} [°C]
Mechanical-only (1317, 1321, 1325)	0.21	2.38
Cross-ventilated (1319, 1323)	0.06	1.64
Single-sided (1315, 1327)	0.13	1.91

The results show that there is a noticeable difference between how quickly the rooms cool down in the early part of the night and how much they cool over the entire night. Rooms without night-time natural ventilation tend to cool down faster shortly after night time ventilation starts, with average cooling rates of around 0.20 °C/h. These rooms also show the largest overall temperature reduction by the morning, indicating a strong initial cooling response.

Rooms with cross ventilation behave differently. Their cooling rate during the early evening hours is lower, but cooling continues more steadily throughout the night. As a result, the total temperature reduction over the full night is still significant. This suggests that cooling in these rooms is driven more by sustained airflow and gradual heat removal rather than a rapid temperature drop at the beginning of the night.

Overall, the comparison makes it clear that looking only at the early night-time cooling rate does not fully describe the night cooling performance of the rooms. Both the cooling rate and the total night-time temperature reduction need to be considered to properly understand how different night-time ventilation conditions affect indoor thermal behaviour.

Chapter 5

Discussion and Conclusion

This chapter discusses the results presented in Chapter 4 and places them in the context of the theoretical framework introduced in Chapter 2. The focus is on interpreting the observed thermal behaviour of the analysed rooms, explaining the differences between ventilation strategies, and evaluating the effectiveness of night cooling as a passive measure for overheating mitigation. Finally, the main conclusions are summarised, and practical, result based recommendations for future improvement are proposed.

5.1 Discussion of Results

5.1.1 Overall Night Cooling Performance

The results demonstrate that night cooling has a measurable impact on reducing indoor temperatures in all analysed rooms. Both the early night-time cooling rate and the total night-time temperature reduction indicate that the indoor thermal response is strongly influenced by the applied ventilation strategy. However, the two metrics capture different aspects of the cooling process and therefore must be interpreted together.

The early night-time cooling rate reflects the short-term thermal response immediately after the end of occupancy, when internal heat gains are removed and the indoor air volume reacts rapidly to changes in ventilation conditions. In contrast, the total night-time temperature reduction represents the cumulative cooling effect achieved over the full night, which is primarily associated with the discharge of heat stored in the building's thermal mass. The results show that a high initial cooling rate does not necessarily imply superior overall night cooling effectiveness. Rooms with rapid early temperature drops may still exhibit limited cumulative cooling if sustained airflow during the night is insufficient.

5.1.2 Comparison Between Ventilation Strategies

Clear differences are observed between cross ventilated, single sided ventilated, and mechanically ventilated rooms. These differences can be explained by the physical mechanisms governing airflow and heat removal.

Cross-ventilated rooms exhibit a relatively moderate temperature decrease during the early evening hours but achieve a stable and sustained cooling effect throughout the night. This behaviour is consistent with night cooling theory, where pressure driven airflow and buoyancy forces become more effective as the outdoor,indoor temperature difference increases during the night. The sustained airflow allows effective discharge of heat stored in the building's thermal mass, resulting in lower indoor temperatures at the start of the following day.

Single-sided ventilated rooms show intermediate performance. Although natural ventilation is available during night time, the airflow is limited due to the absence of a clear pressure differential across the room. As a result, both the cooling rate and the total night-time temperature reduction remain lower than those observed in cross ventilated rooms. This confirms the limited capacity of single sided ventilation to provide deep night time cooling under otherwise similar boundary conditions.

Mechanically ventilated rooms display relatively high cooling rates during the early night time perid. This rapid initial temperature reduction is mainly driven by short term thermal effects, such as the sudden removal of internal heat gains and the fast thermal response of the indoor air volume. However, mechanical ventilation alone provides limited capacity for sustained night-time heat removal, confirming that it is not designed to function as an effective standalone night cooling strategy.

5.1.3 Relation to Thermal Comfort and Overheating Criteria

The observed temperature reductions directly influence the risk of overheating as defined by BR18. Rooms with more effective night cooling start the following day at lower indoor temperatures, which reduces the likelihood of exceeding the overheating thresholds during occupied hours.

This relationship confirms that night cooling is a relevant and effective passive strategy for mitigating overheating in low-energy educational buildings, particularly when combined with appropriate ventilation paths and effective utilisation of the building's thermal mass. Although thermal comfort is assessed indirectly through temperature-based indicators in this study, the results demonstrate a clear link between ventilation strategy, night-time cooling performance, and improved daytime thermal conditions.

5.2 Limitations of the Study

While the analysis provides valuable insight into night cooling performance, several limitations should be acknowledged:

- **No direct airflow measurement during night-time:** The study relies on temperature-based indicators to evaluate cooling performance. Although this approach captures the thermal response of the rooms, the absence of direct airflow measurements introduces uncertainty regarding the actual ventilation rates during night-time operation.
- **Manual window operation:** Window opening and closing were performed manually according to predefined schedules. Small variations in opening angle or timing may have influenced airflow patterns and cooling effectiveness, particularly in naturally ventilated rooms.

- **Single summer monitoring period:** The analysis is limited to one summer period and does not include seasonal comparison. Consequently, the results cannot be directly generalised to other seasons or climatic conditions.

These limitations do not invalidate the observed trends but should be considered when interpreting the quantitative magnitude of the results.

5.3 Proposed Improvements and Future Work

The following proposals focus on practical improvements related to operation and control rather than major design changes.

Firstly, night-time window operation could be automated through the Building Management System. This would allow better control of when windows are opened and closed, making it easier to use suitable outdoor conditions for night cooling and improving overall cooling effectiveness.

Secondly, ventilation strategies could be adjusted according to room type. Rooms with cross ventilation or single sided natural ventilation may benefit from longer ventilation periods, while mechanically ventilated rooms may require different control approaches. Applying room specific control strategies could help improve thermal performance across the analysed spaces.

Thirdly, simple night cooling performance indicators, such as the total night time temperature reduction, could be used to support control decisions. By monitoring whether sufficient cooling has been achieved during the night, the system could adjust its operation in a more informed way.

Finally, extending the monitoring period to cover additional seasons would provide a broader understanding of night cooling behaviour. This would help identify seasonal differences and support future improvements in ventilation control strategies.

5.4 Conclusion

This thesis evaluated the performance of night cooling in selected rooms of the TMV23 building at Aalborg University using measured indoor temperature data from the Building Management System. The results show that the applied ventilation strategy has a clear influence on both the short term temperature response and the overall night cooling performance.Rooms with cross ventilation demonstrate the most consistent night cooling behaviour, with effective heat removal maintained throughout the night. Single sided ventilated rooms provide a smaller but still noticeable cooling effect. In contrast, mechanically ventilated rooms show rapid temperature reductions during the early night hours, but limited cooling over the full night period.

Overall, the findings indicate that night cooling can be an effective passive measure for reducing overheating risk in low energy educational buildings when suitable ventilation strategies and thermal mass are utilised. The results also highlight the potential for further improvement through optimisation of BMS based night cooling control and continued investigation of ventilation performance under different conditions.

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Chapter 6

Appendix-A-Sky light and Sun radiation

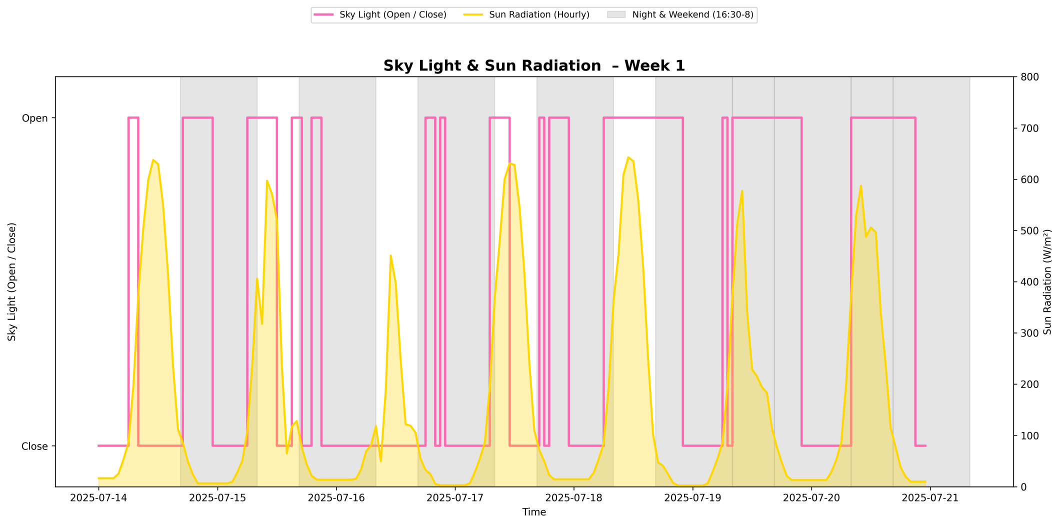


Figure 6.1: Hourly solar radiation and skylight opening state during the first monitoring week. The yellow curve represents measured solar radiation, while the binary skylight signal indicates open and closed states. Grey shaded areas night-time and weekend periods (16:30–08:00), during which night cooling is active.

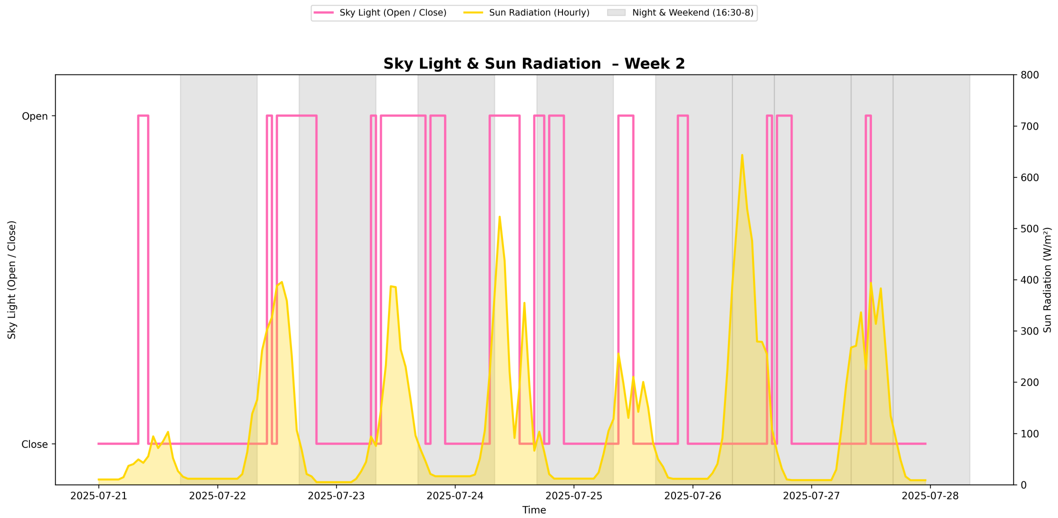


Figure 6.2: Hourly solar radiation and skylight opening state during the first monitoring week. The yellow curve represents measured solar radiation, while the binary skylight signal indicates open and closed states. Grey shaded areas night-time and weekend periods (16:30–08:00), during which night cooling is active.

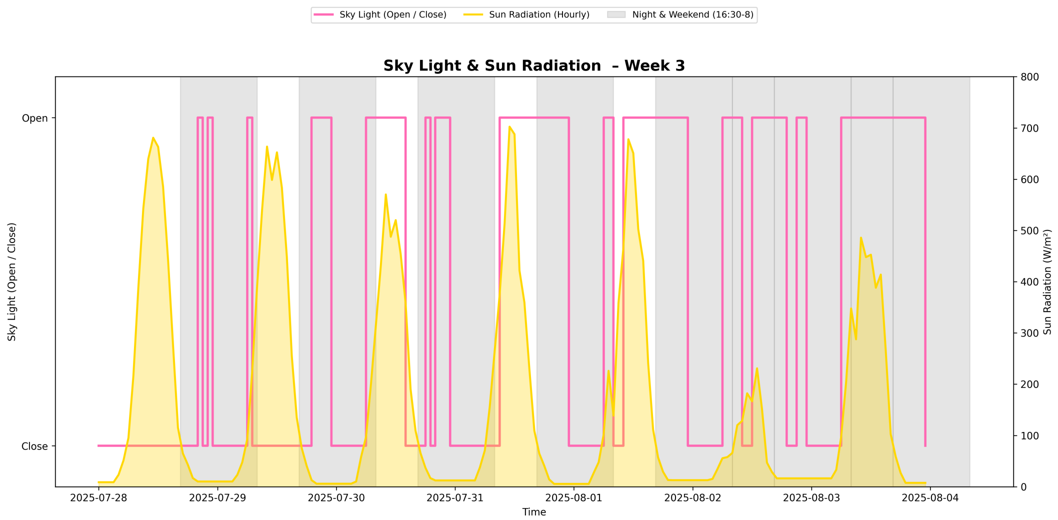


Figure 6.3: Hourly solar radiation and skylight opening state during the first monitoring week. The yellow curve represents measured solar radiation, while the binary skylight signal indicates open and closed states. Grey shaded areas night-time and weekend periods (16:30–08:00), during which night cooling is active.

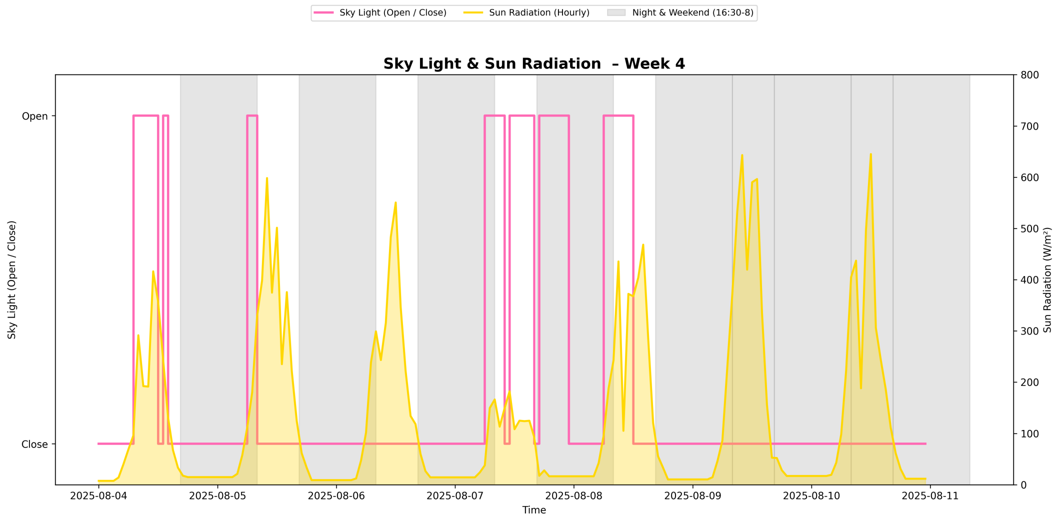


Figure 6.4: Hourly solar radiation and skylight opening state during the first monitoring week. The yellow curve represents measured solar radiation, while the binary skylight signal indicates open and closed states. Grey shaded areas night-time and weekend periods (16:30–08:00), during which night cooling is active.

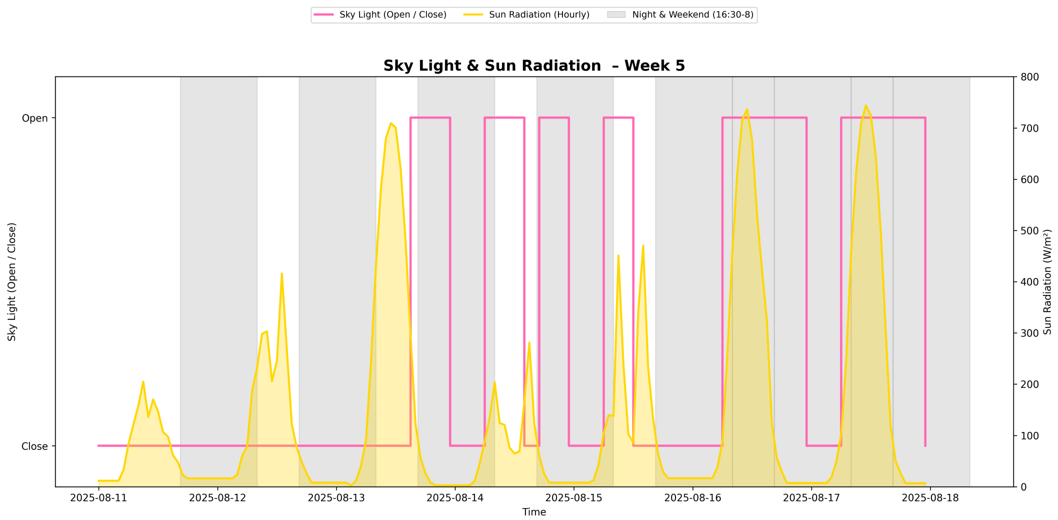


Figure 6.5: Hourly solar radiation and skylight opening state during the first monitoring week. The yellow curve represents measured solar radiation, while the binary skylight signal indicates open and closed states. Grey shaded areas night-time and weekend periods (16:30–08:00), during which night cooling is active.

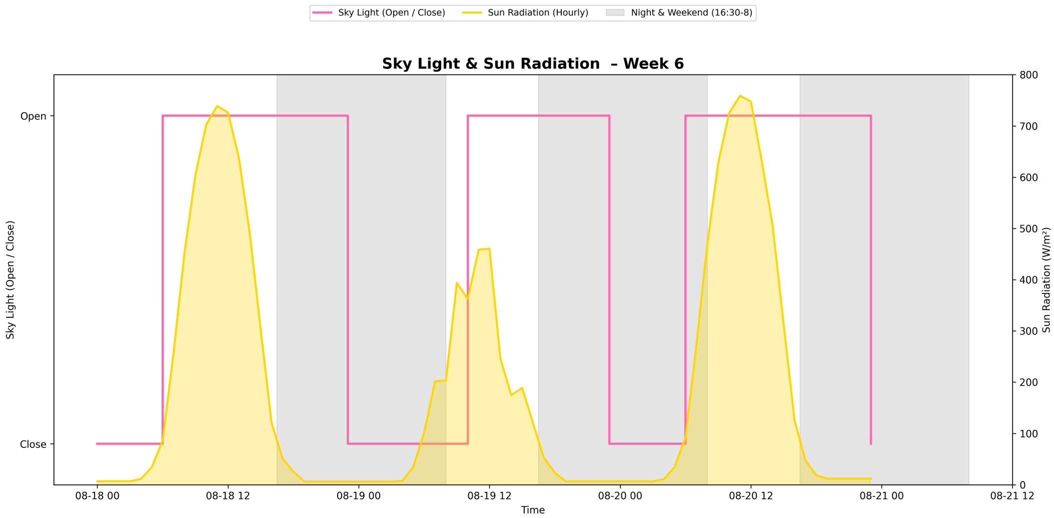


Figure 6.6: Hourly solar radiation and skylight opening state during the first monitoring week. The yellow curve represents measured solar radiation, while the binary skylight signal indicates open and closed states. Grey shaded areas night-time and weekend periods (16:30–08:00), during which night cooling is active.

Chapter 7

Appendix-B-Rooms analysis

7.1 Room 1315

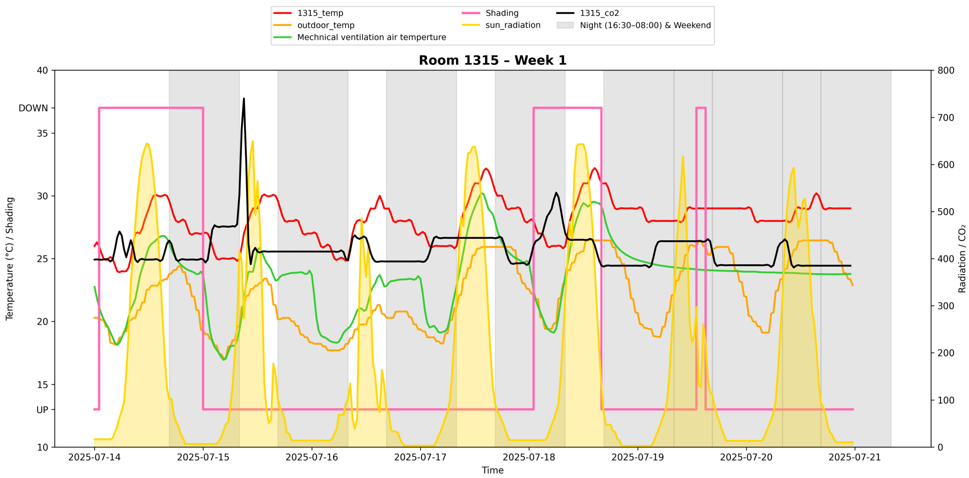


Figure 7.1: Indoor temperature profile for Room 1315 during Week 29

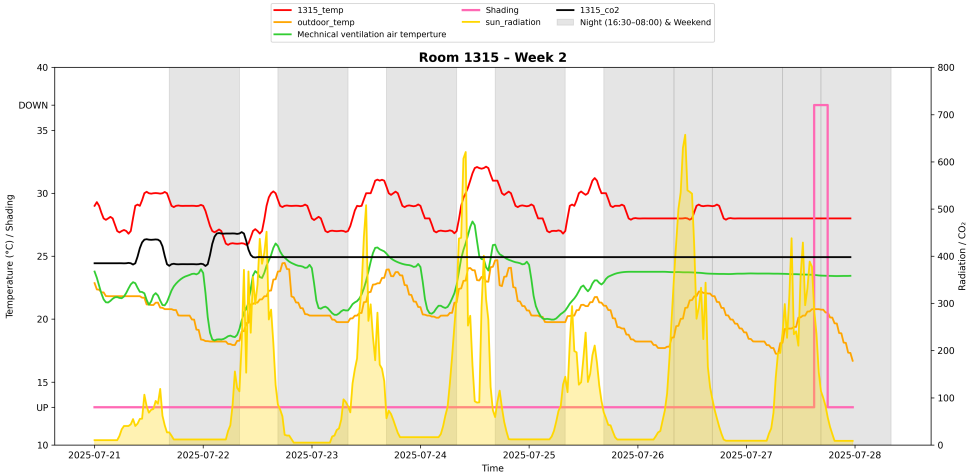


Figure 7.2: Indoor temperature profile for Room 1315 during Week 30

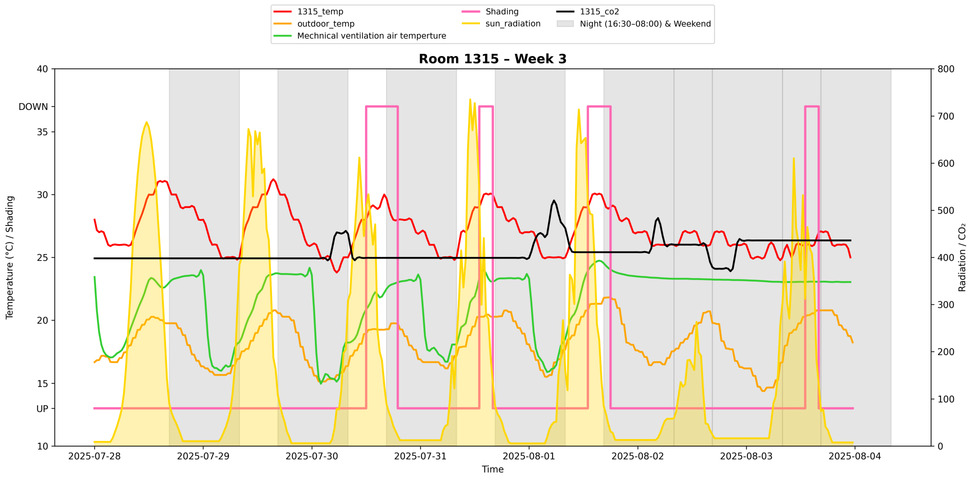


Figure 7.3: Indoor temperature profile for Room 1315 during Week 31

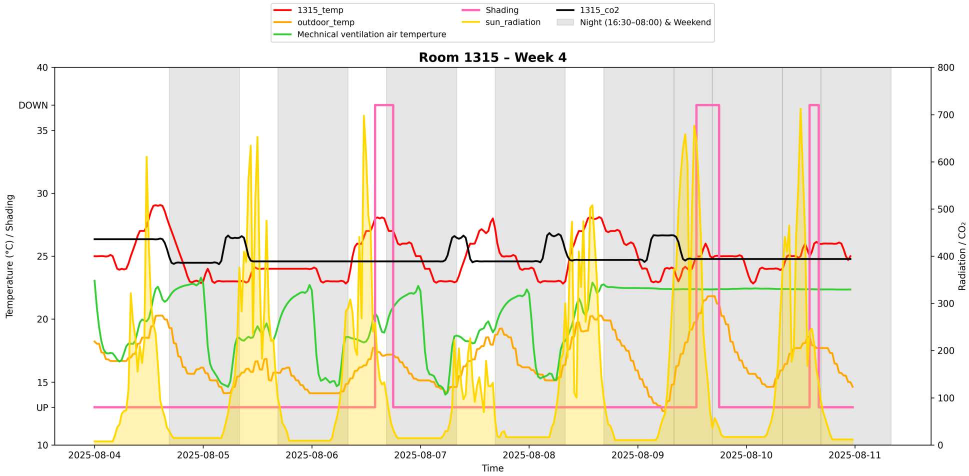


Figure 7.4: Indoor temperature profile for Room 1315 during Week 32

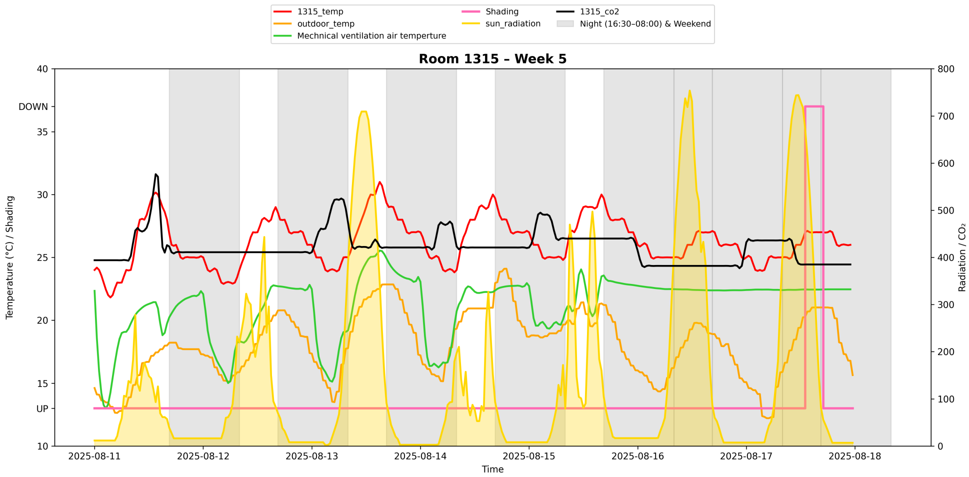


Figure 7.5: Indoor temperature profile for Room 1315 during Week 33

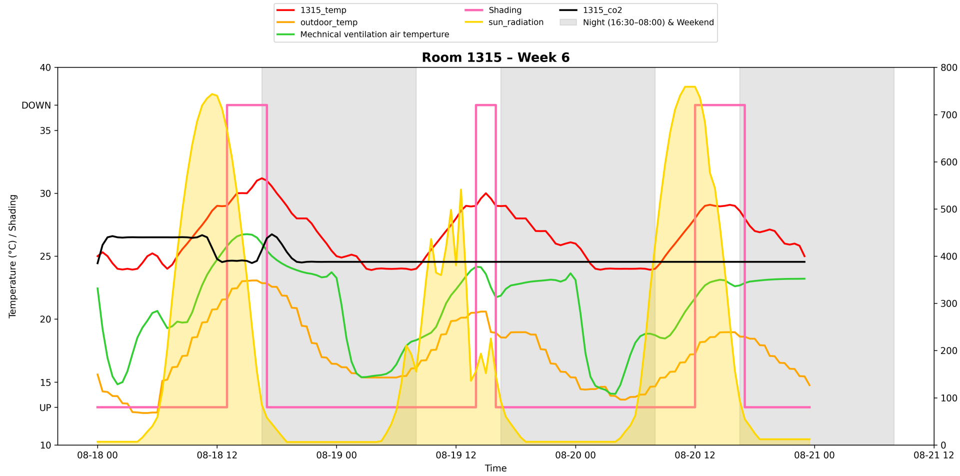


Figure 7.6: Indoor temperature profile for Room 1315 during Week 34

7.2 Room 1317

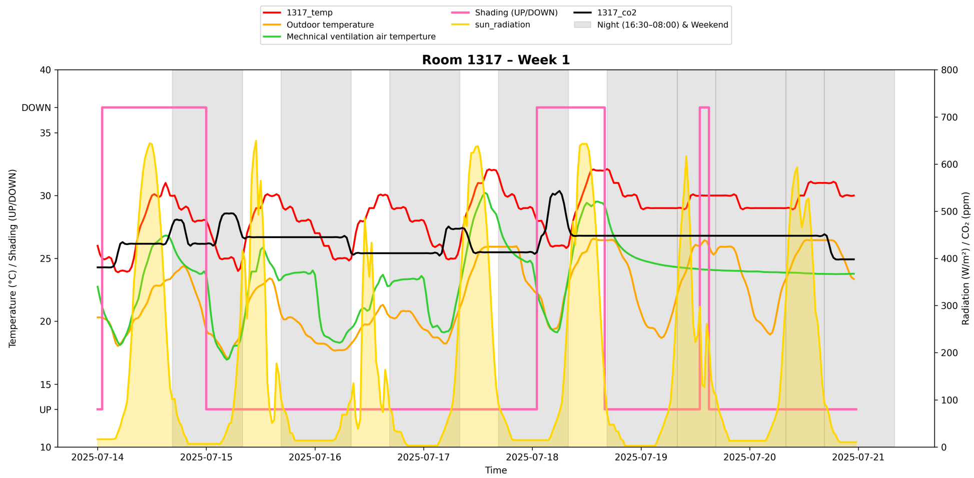


Figure 7.7: Indoor temperature profile for Room 1317 during Week 29

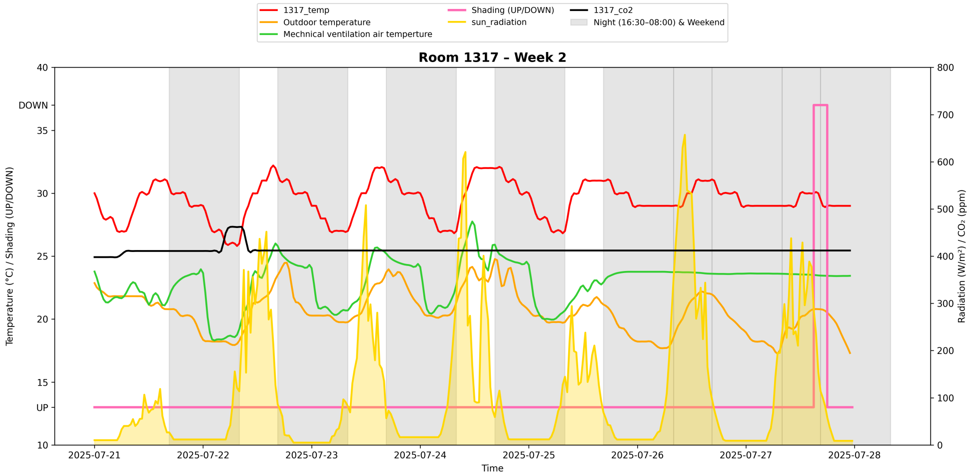


Figure 7.8: Indoor temperature profile for Room 1317 during Week 30

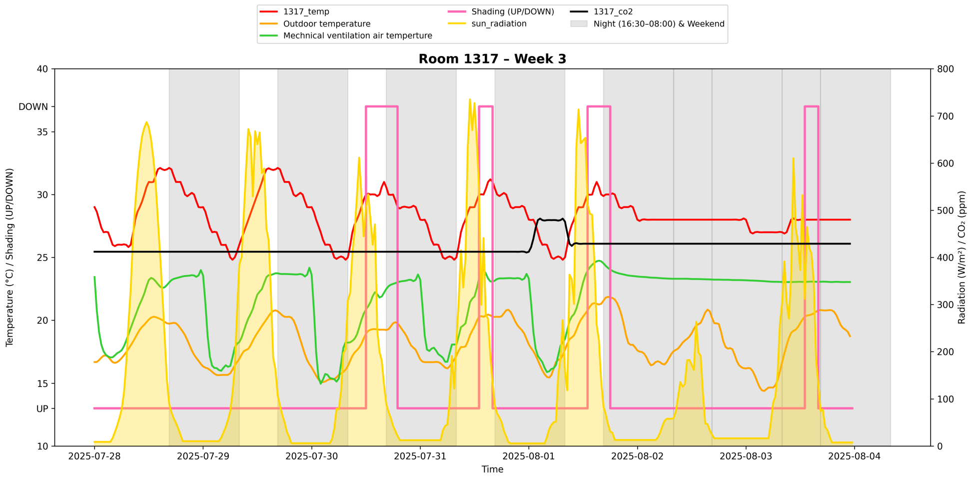


Figure 7.9: Indoor temperature profile for Room 1317 during Week 31

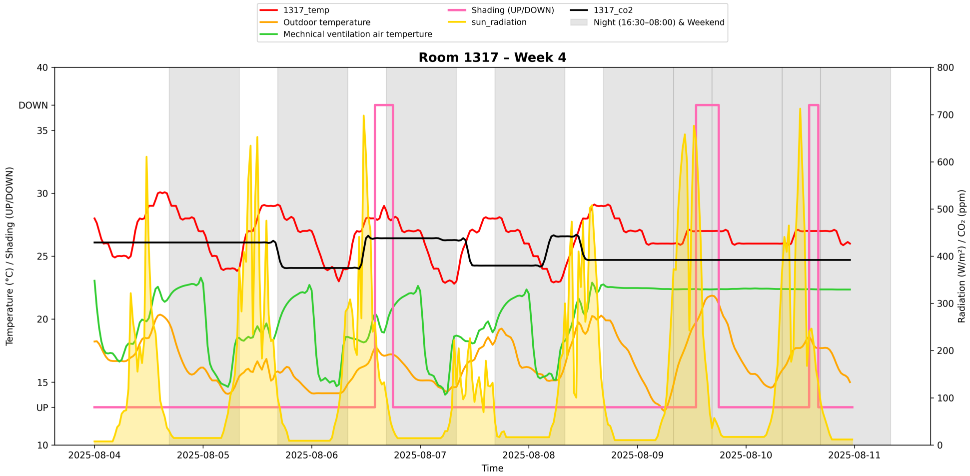


Figure 7.10: Indoor temperature profile for Room 1317 during Week 32

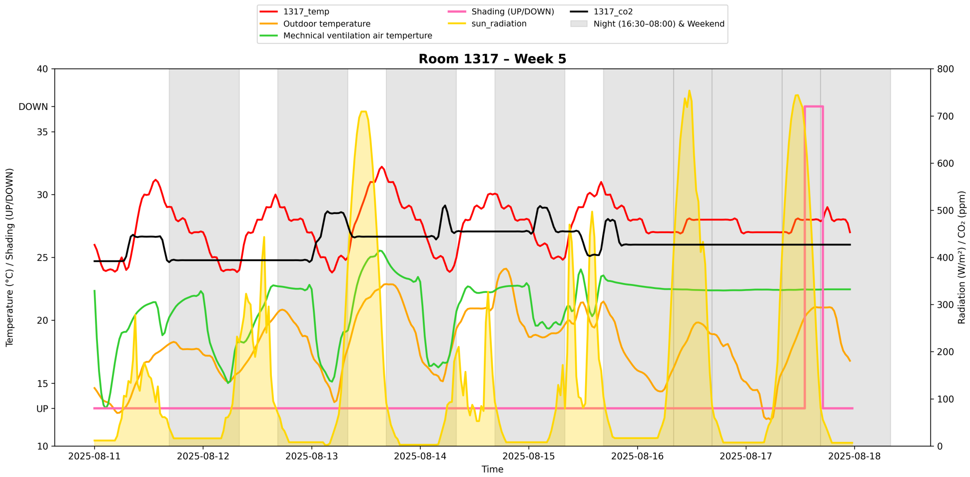


Figure 7.11: Indoor temperature profile for Room 1317 during Week 33

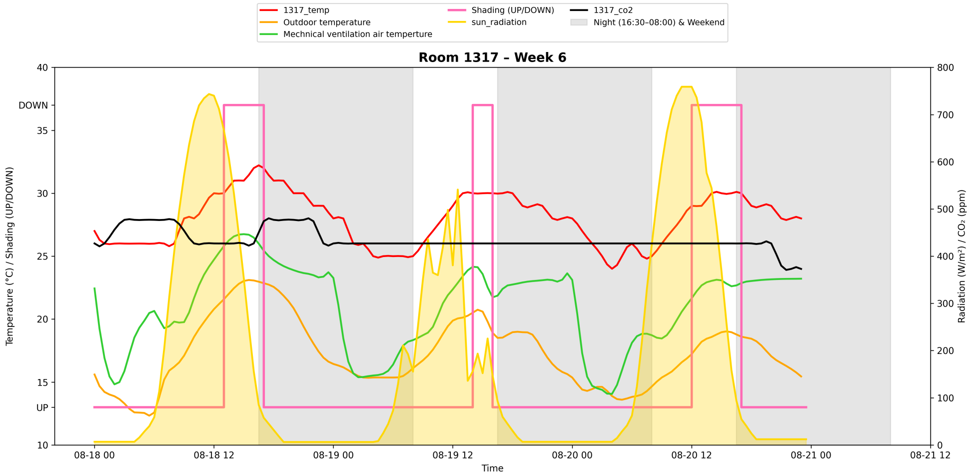


Figure 7.12: Indoor temperature profile for Room 1317 during Week 34

7.3 Room 1319

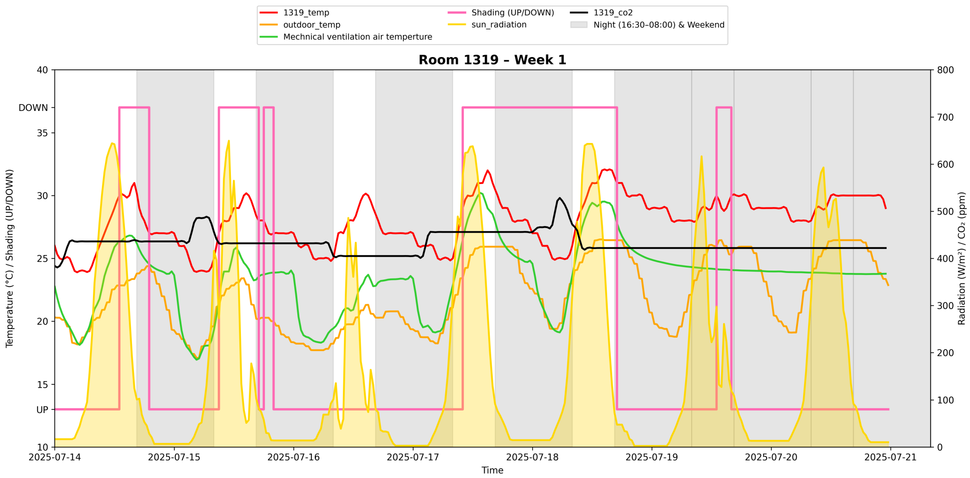


Figure 7.13: Indoor temperature profile for Room 1319 during Week 29

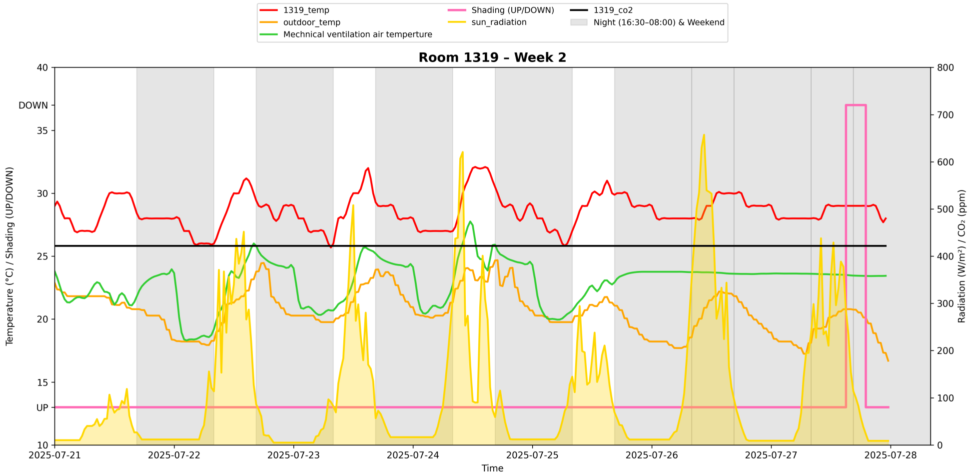


Figure 7.14: Indoor temperature profile for Room 1319 during Week 30

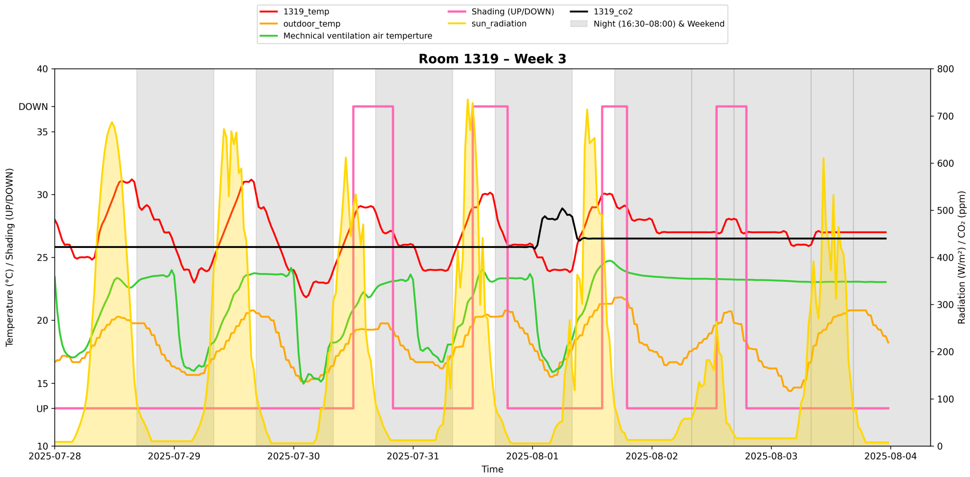


Figure 7.15: Indoor temperature profile for Room 1319 during Week 31

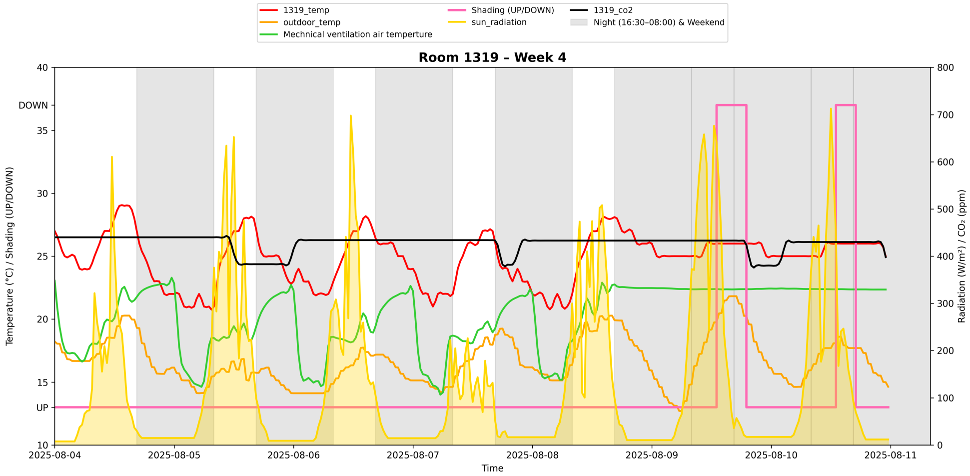


Figure 7.16: Indoor temperature profile for Room 1319 during Week 32

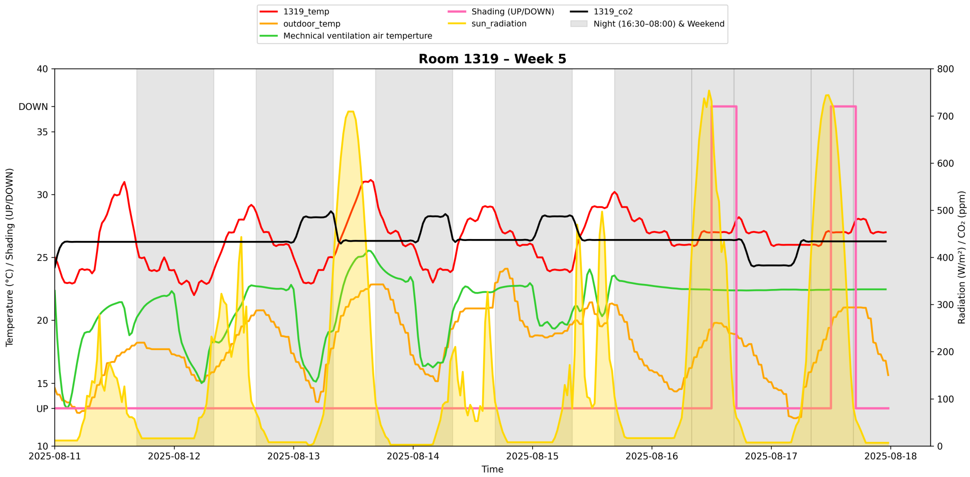


Figure 7.17: Indoor temperature profile for Room 1319 during Week 33

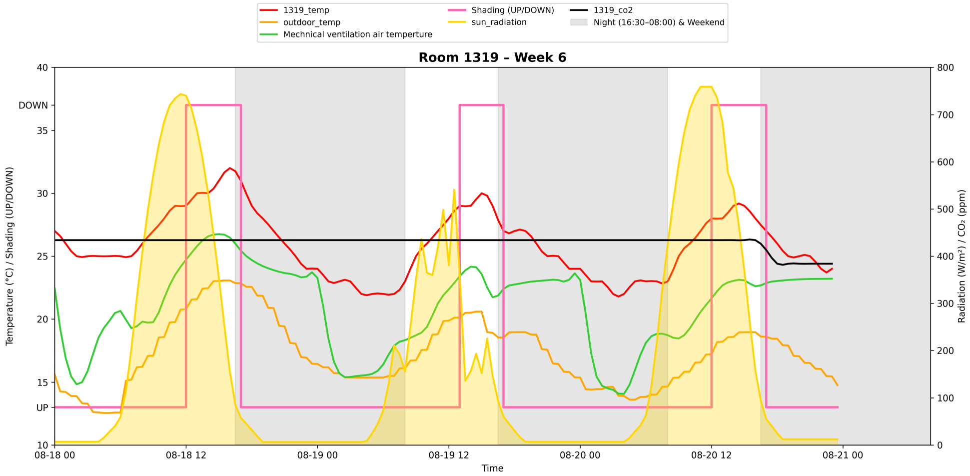


Figure 7.18: Indoor temperature profile for Room 1319 during Week 34

7.4 Room 1321

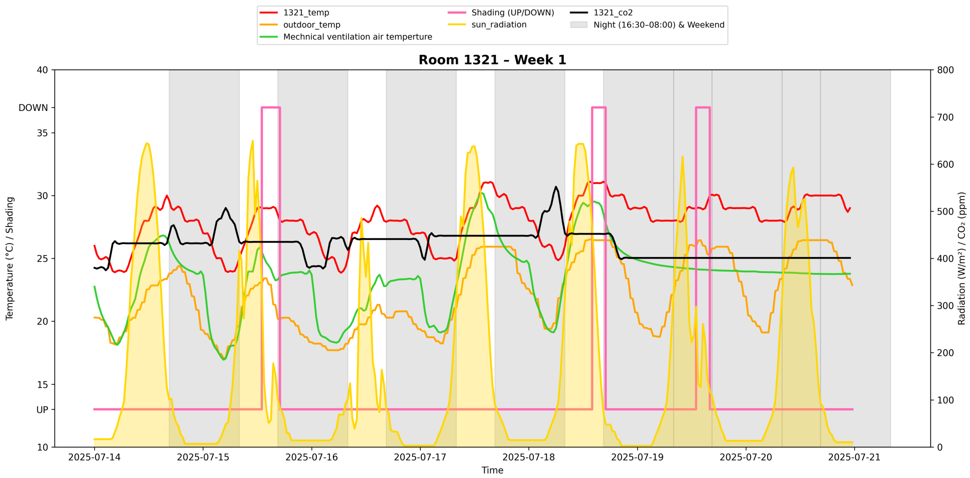


Figure 7.19: Indoor temperature profile for Room 1321 during Week 29

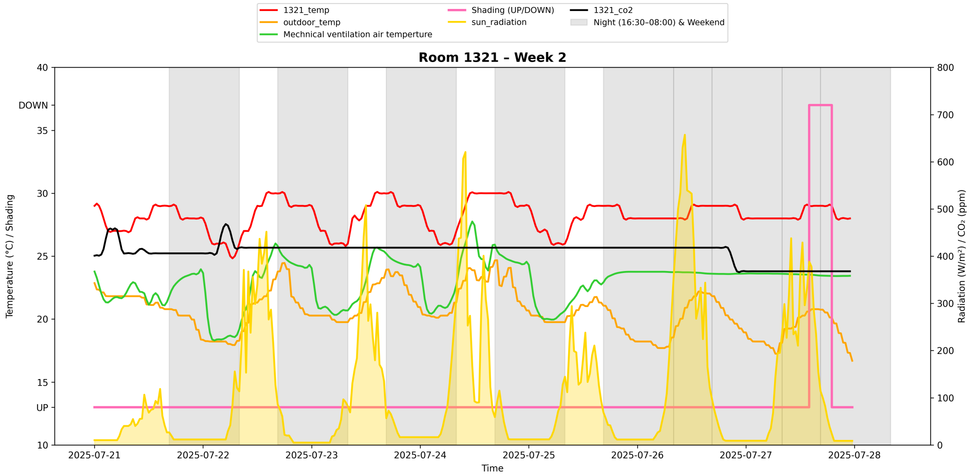


Figure 7.20: Indoor temperature profile for Room 1321 during Week 30

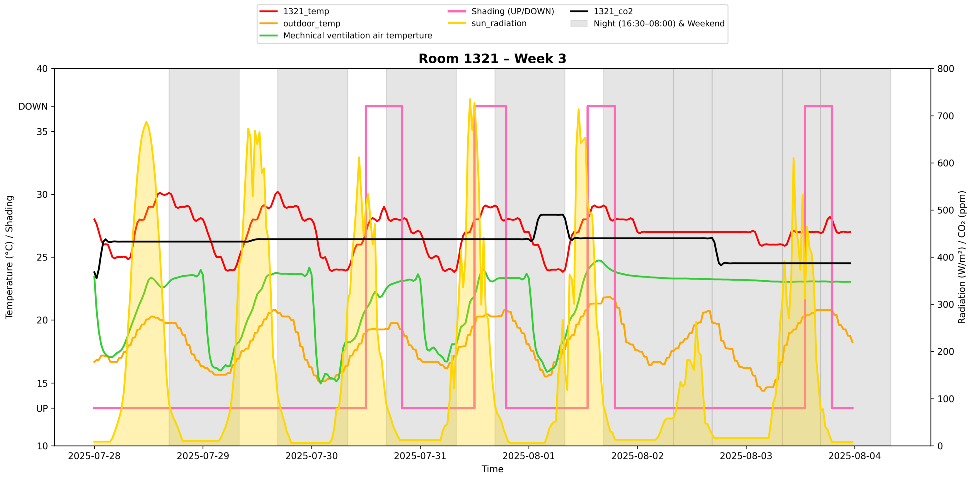


Figure 7.21: Indoor temperature profile for Room 1321 during Week 31

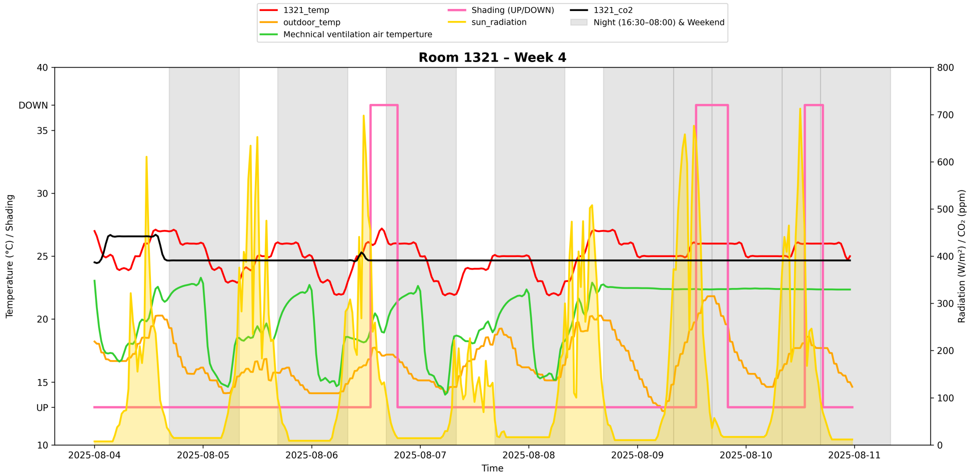


Figure 7.22: Indoor temperature profile for Room 1321 during Week 32

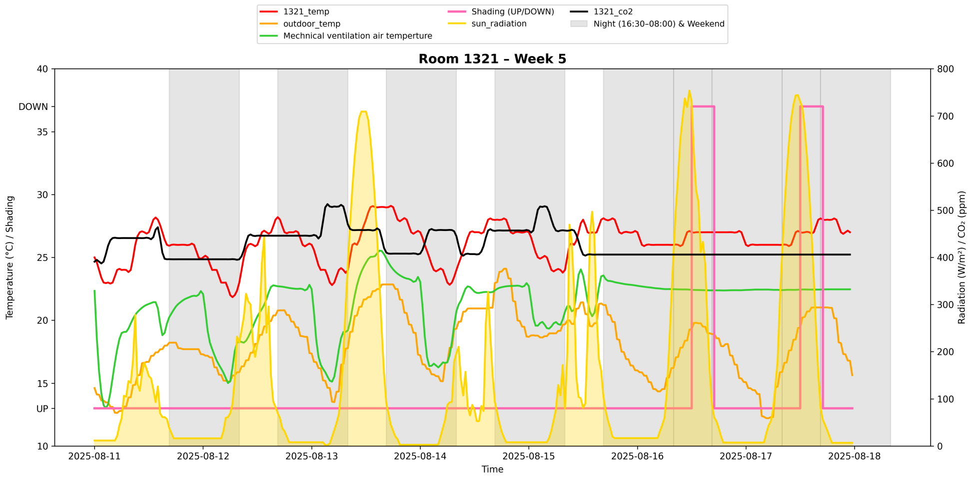


Figure 7.23: Indoor temperature profile for Room 1321 during Week 33

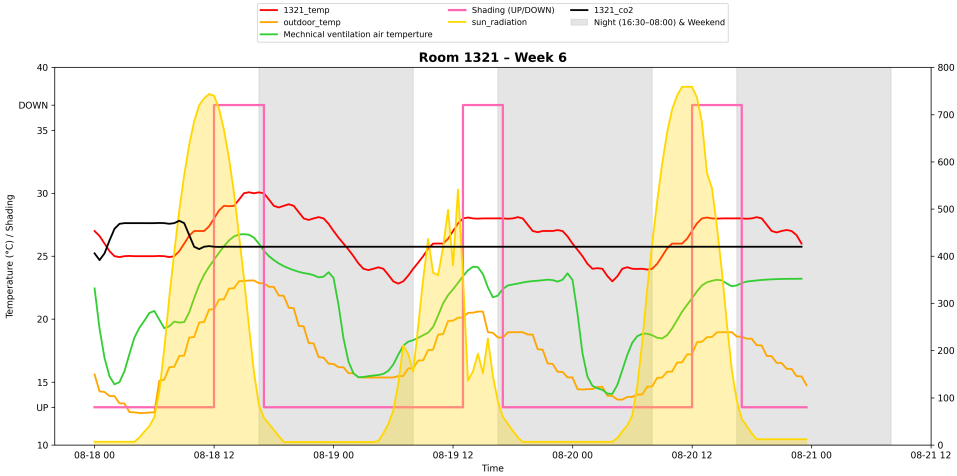


Figure 7.24: Indoor temperature profile for Room 1321 during Week 34

7.5 Room 1323

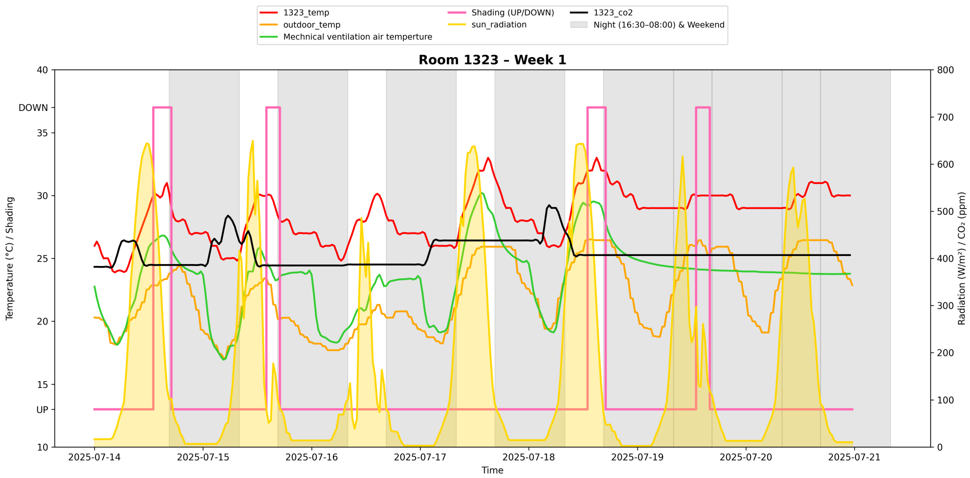


Figure 7.25: Indoor temperature profile for Room 1323 during Week 29

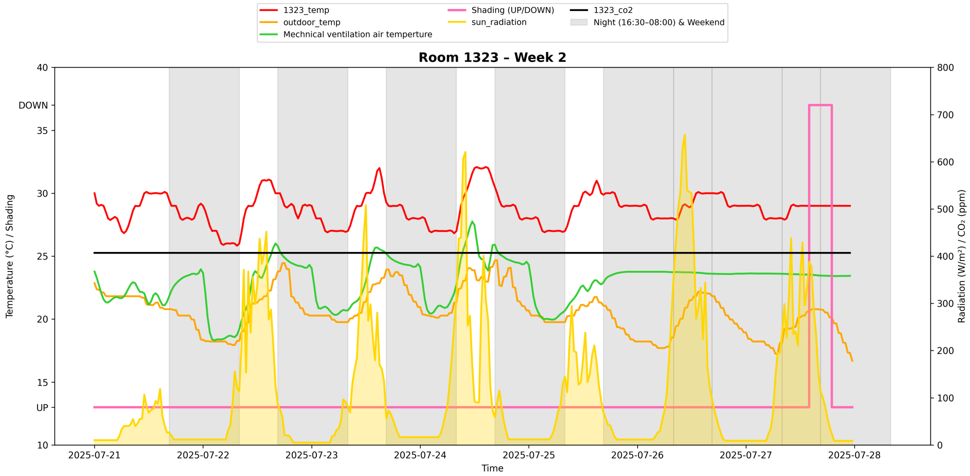


Figure 7.26: Indoor temperature profile for Room 1323 during Week 30

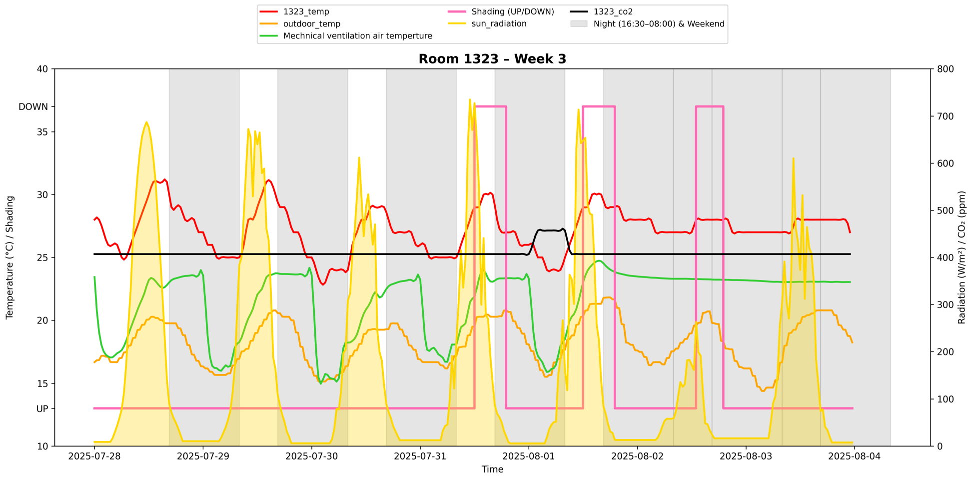


Figure 7.27: Indoor temperature profile for Room 1323 during Week 31

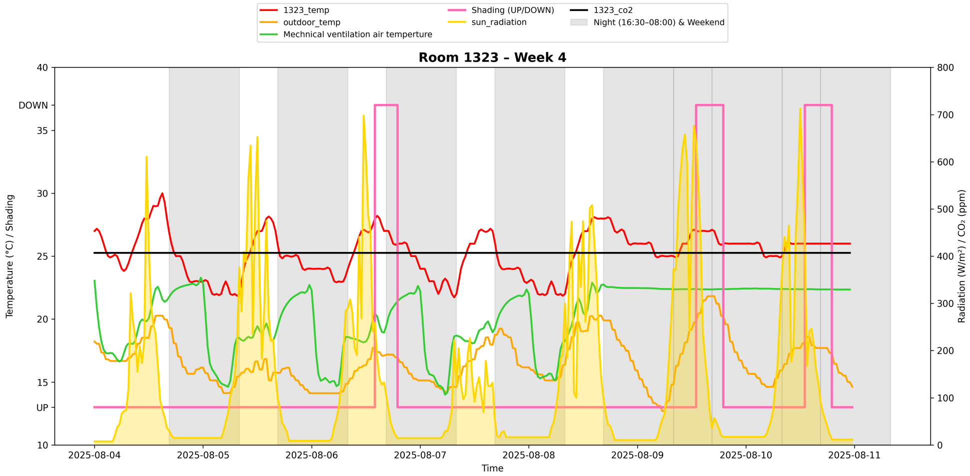


Figure 7.28: Indoor temperature profile for Room 1323 during Week 32

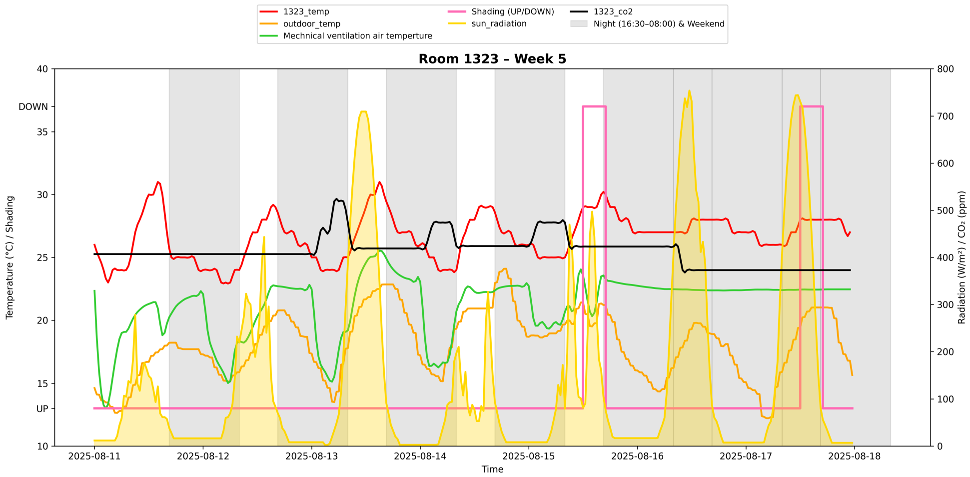


Figure 7.29: Indoor temperature profile for Room 1323 during Week 33

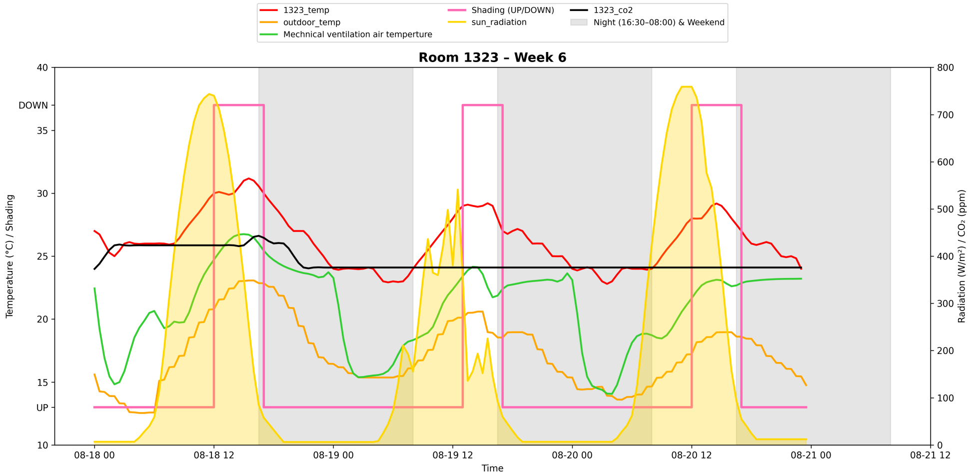


Figure 7.30: Indoor temperature profile for Room 1323 during Week 34

7.6 Room 1325

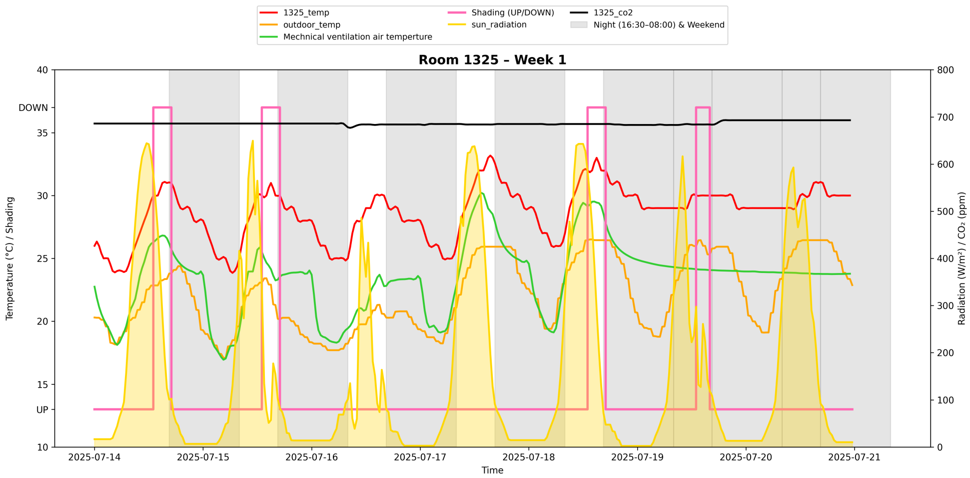


Figure 7.31: Indoor temperature profile for Room 1325 during Week 29

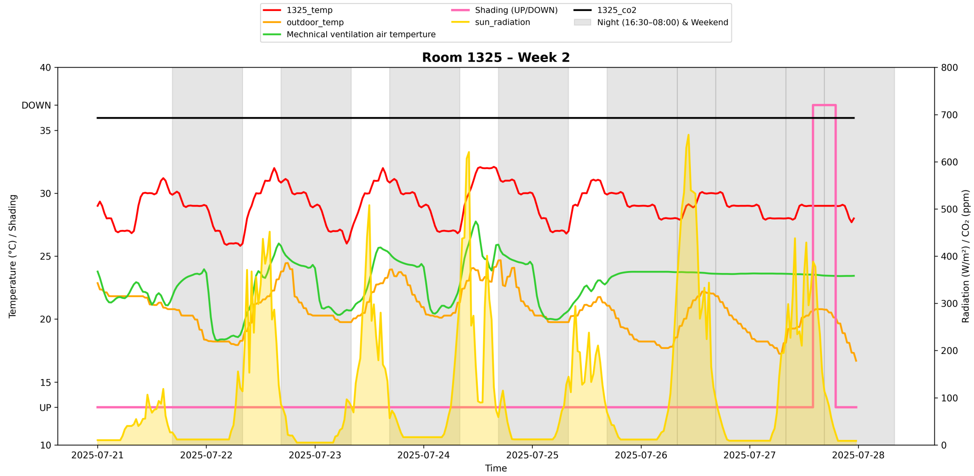


Figure 7.32: Indoor temperature profile for Room 1325 during Week 30

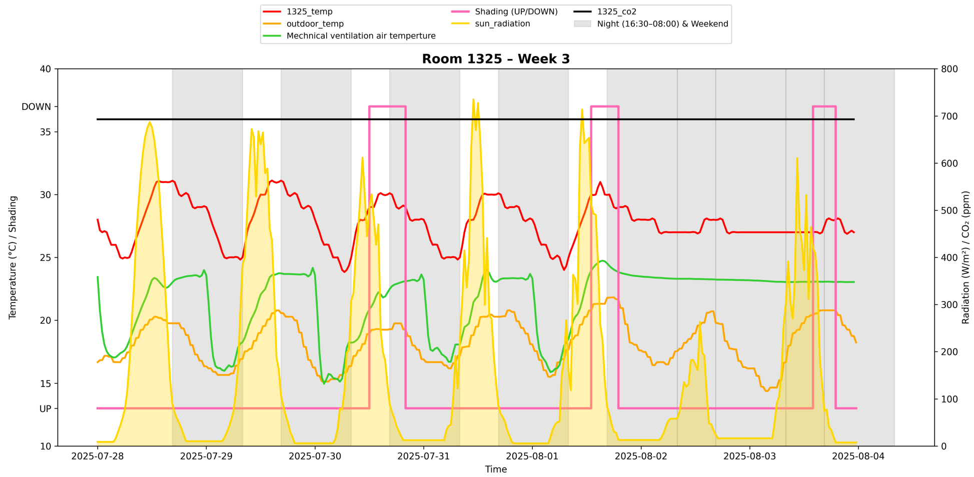


Figure 7.33: Indoor temperature profile for Room 1325 during Week 31

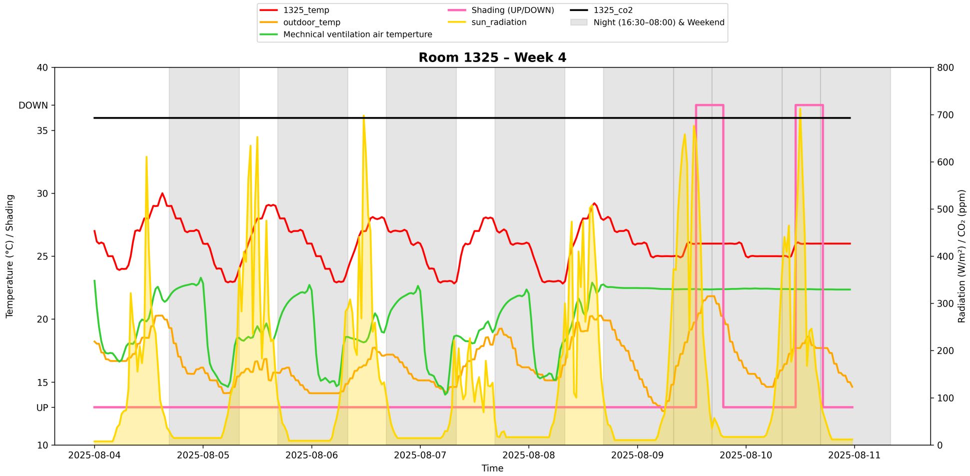


Figure 7.34: Indoor temperature profile for Room 1325 during Week 32

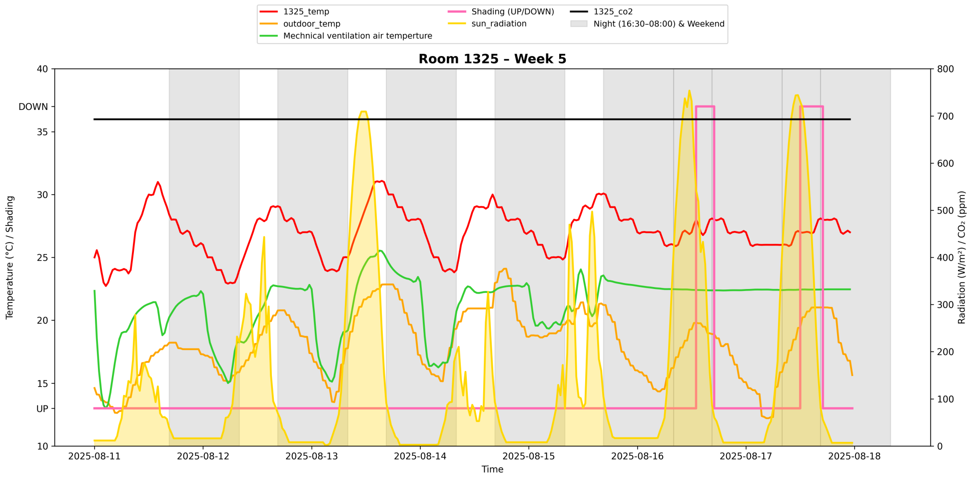


Figure 7.35: Indoor temperature profile for Room 1325 during Week 33

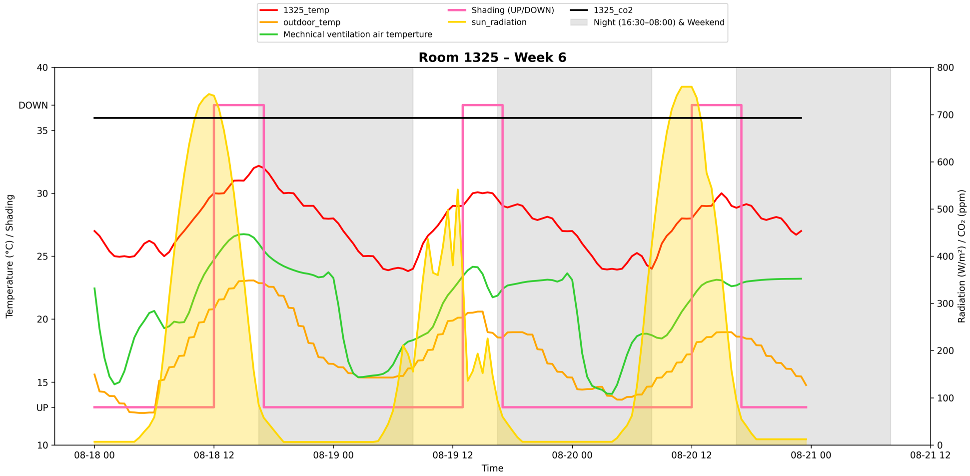


Figure 7.36: Indoor temperature profile for Room 1325 during Week 34

7.7 Room 1327

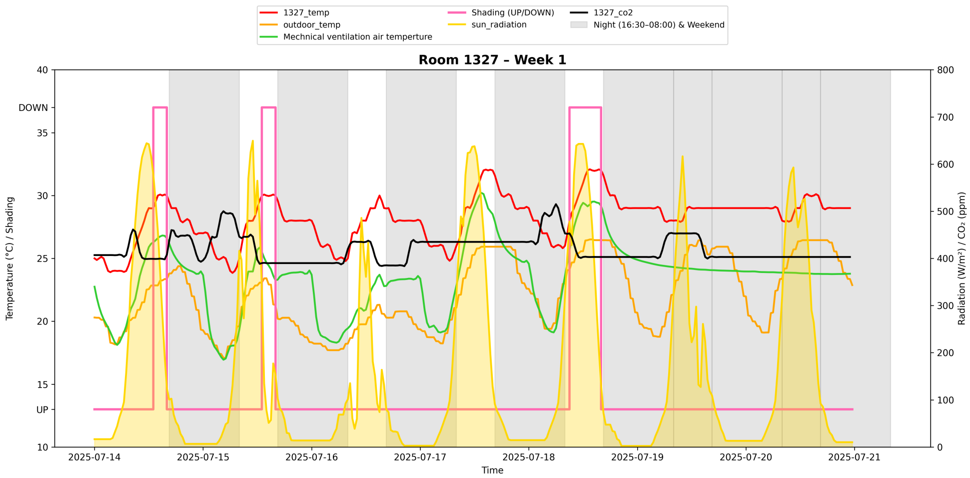


Figure 7.37: Indoor temperature profile for Room 1327 during Week 29

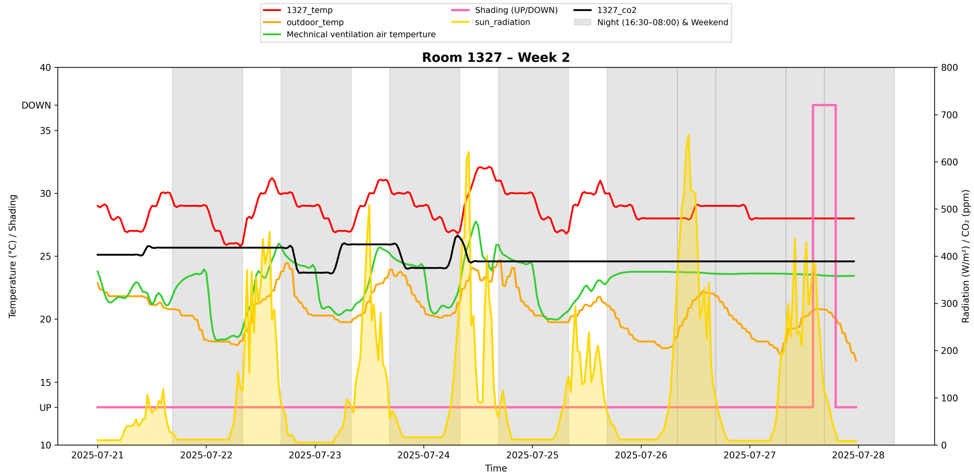


Figure 7.38: Indoor temperature profile for Room 1327 during Week 30

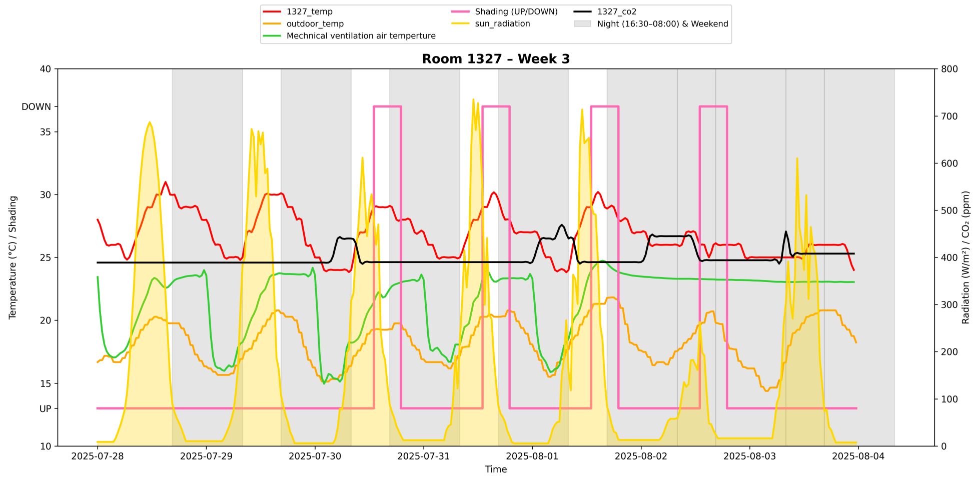


Figure 7.39: Indoor temperature profile for Room 1327 during Week 31

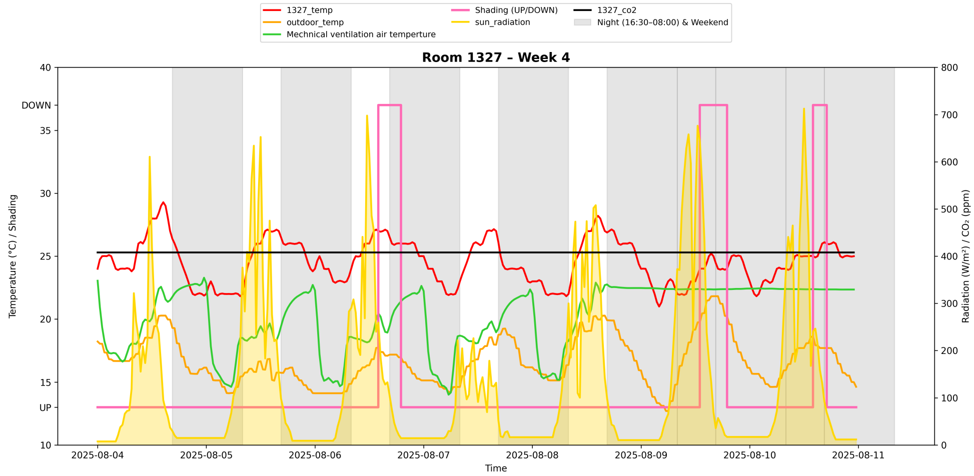


Figure 7.40: Indoor temperature profile for Room 1327 during Week 32

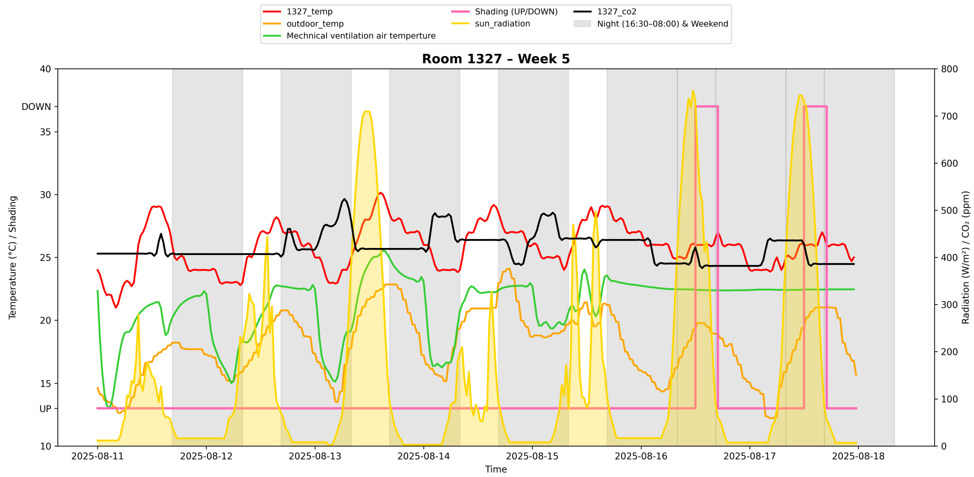


Figure 7.41: Indoor temperature profile for Room 1327 during Week 33

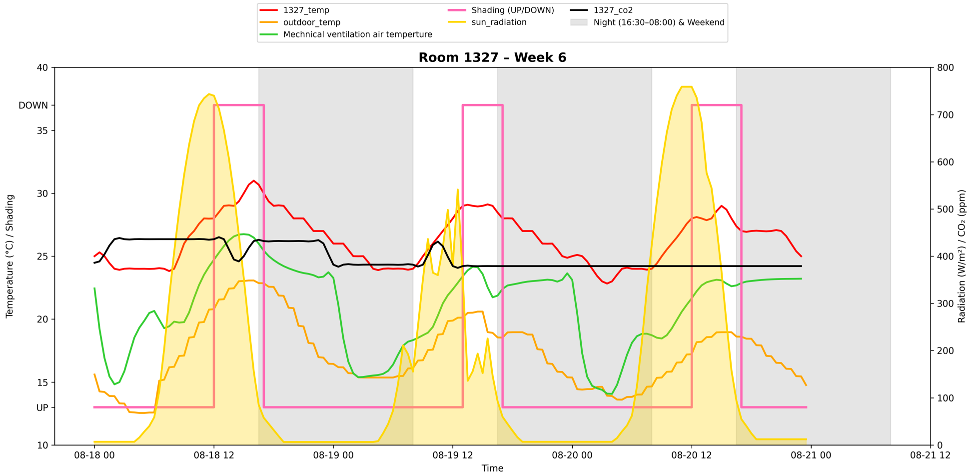


Figure 7.42: Indoor temperature profile for Room 1327 during Week 34

Chapter 8

Appendix-C- Air flow, out side temp and inside temp analysis

Figure 8.1: Airflow for all rooms

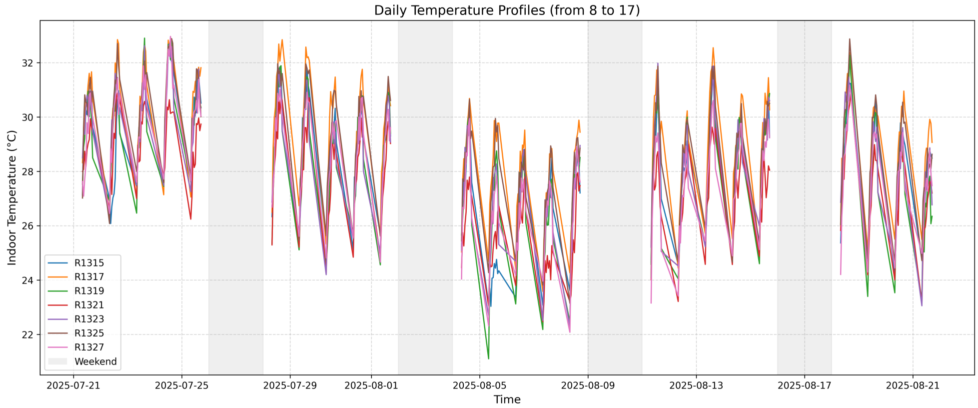


Figure 8.2: temp for all rooms in week 30

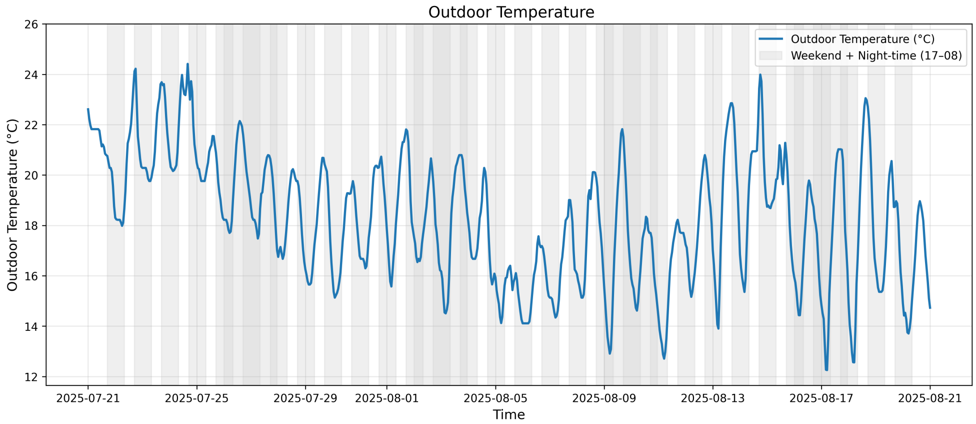
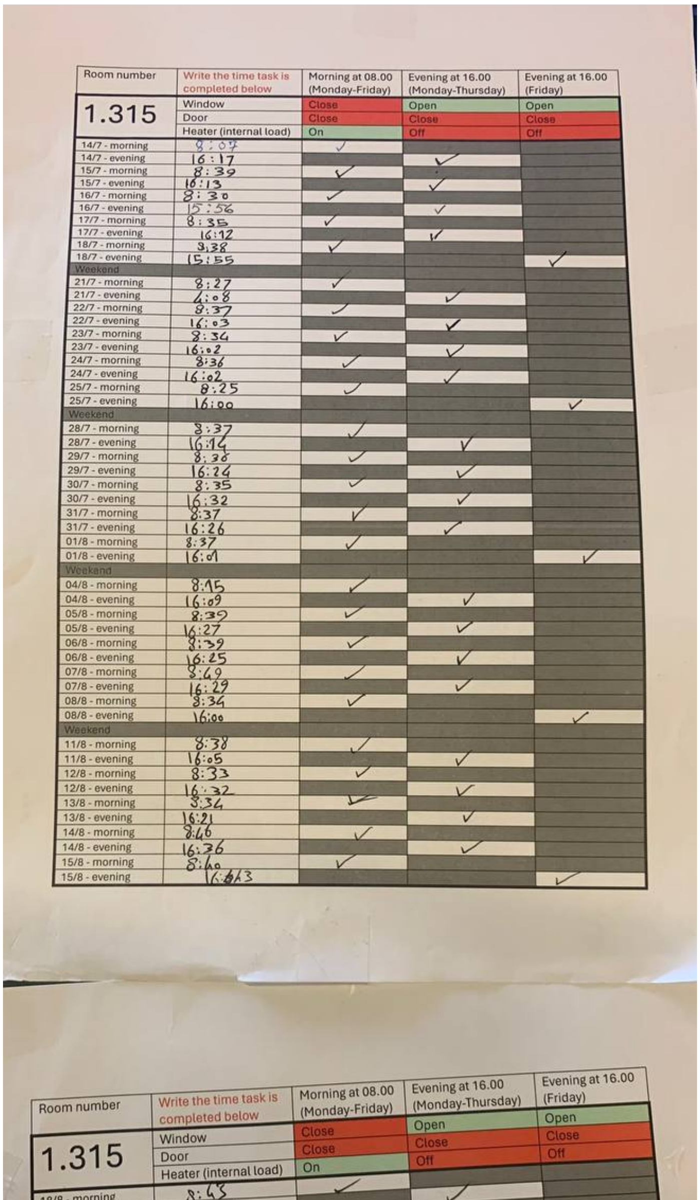


Figure 8.3: Out side temp for all rooms

Chapter 9

Appendix-D-Documentation of Manual Interventions During the Measurement Period

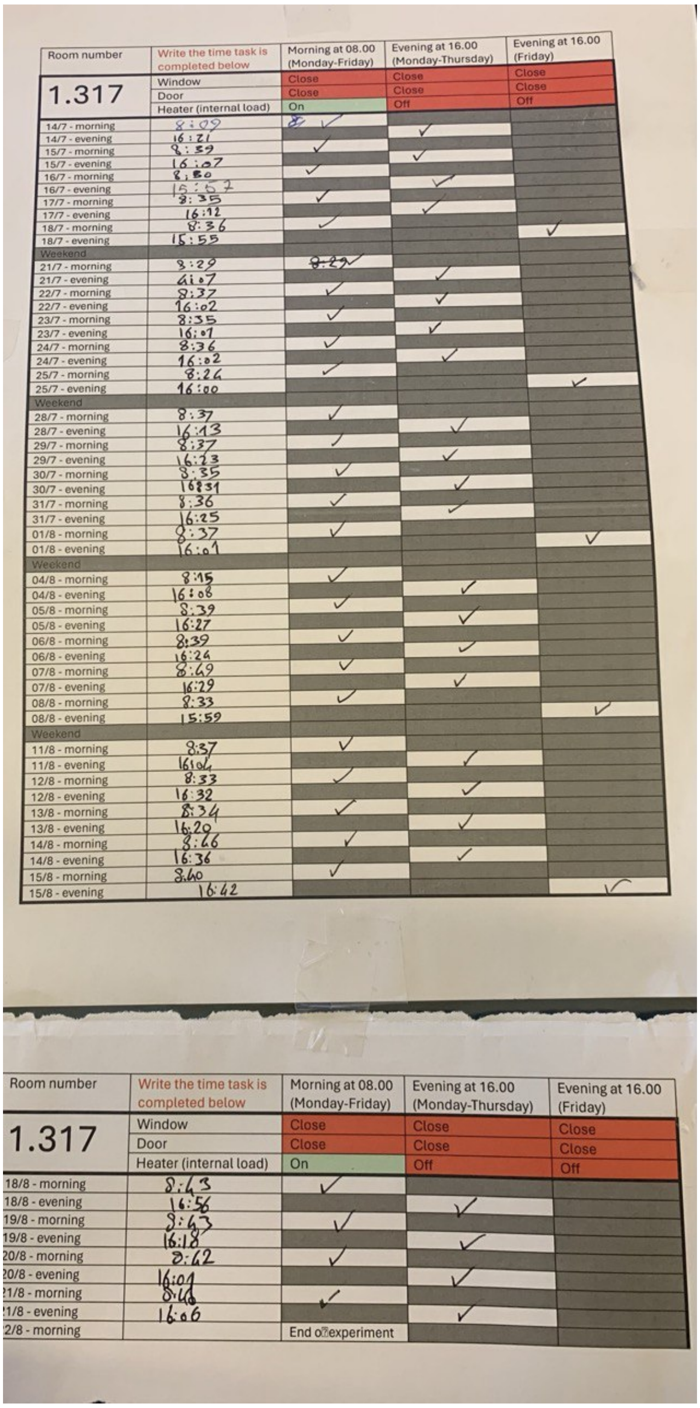
9.1 Experimental Operation Schedule for Room 1315



Room number	Write the time task is completed below	Morning at 08.00 (Monday-Friday)	Evening at 16.00 (Monday-Thursday)	Evening at 16.00 (Friday)
1.315	Window	Close	Open	Open
	Door	Close	Close	Close
	Heater (internal load)	On	Off	Off
14/7 - morning	8:07	✓		
14/7 - evening	16:17		✓	
15/7 - morning	8:39	✓		
15/7 - evening	16:13		✓	
16/7 - morning	8:30	✓		
16/7 - evening	15:56		✓	
17/7 - morning	8:35	✓		
17/7 - evening	16:12		✓	
18/7 - morning	8:38	✓		
18/7 - evening	15:55			✓
Weekend				
21/7 - morning	8:27	✓		
21/7 - evening	4:08		✓	
22/7 - morning	8:37	✓		
22/7 - evening	16:03		✓	
23/7 - morning	8:34	✓		
23/7 - evening	16:02		✓	
24/7 - morning	8:36	✓		
24/7 - evening	16:02		✓	
25/7 - morning	8:25	✓		
25/7 - evening	16:00			✓
Weekend				
28/7 - morning	8:37	✓		
28/7 - evening	16:14		✓	
29/7 - morning	8:36	✓		
29/7 - evening	16:24		✓	
30/7 - morning	8:35	✓		
30/7 - evening	16:32		✓	
31/7 - morning	8:37	✓		
31/7 - evening	16:26		✓	
01/8 - morning	8:37	✓		
01/8 - evening	16:01			✓
Weekend				
04/8 - morning	8:15	✓		
04/8 - evening	16:09		✓	
05/8 - morning	8:39	✓		
05/8 - evening	16:27		✓	
06/8 - morning	8:39	✓		
06/8 - evening	16:25		✓	
07/8 - morning	8:49	✓		
07/8 - evening	16:29		✓	
08/8 - morning	8:34	✓		
08/8 - evening	16:00			✓
Weekend				
11/8 - morning	8:38	✓		
11/8 - evening	16:05		✓	
12/8 - morning	8:33	✓		
12/8 - evening	16:32		✓	
13/8 - morning	8:34	✓		
13/8 - evening	16:21		✓	
14/8 - morning	8:46	✓		
14/8 - evening	16:36		✓	
15/8 - morning	8:40	✓		
15/8 - evening	16:43			✓

Room number	Write the time task is completed below	Morning at 08.00 (Monday-Friday)	Evening at 16.00 (Monday-Thursday)	Evening at 16.00 (Friday)
1.315	Window	Close	Open	Open
	Door	Close	Close	Close
	Heater (internal load)	On	Off	Off
18/8 - morning	8:43	✓		

9.2 Experimental Operation Schedule for Room 1317

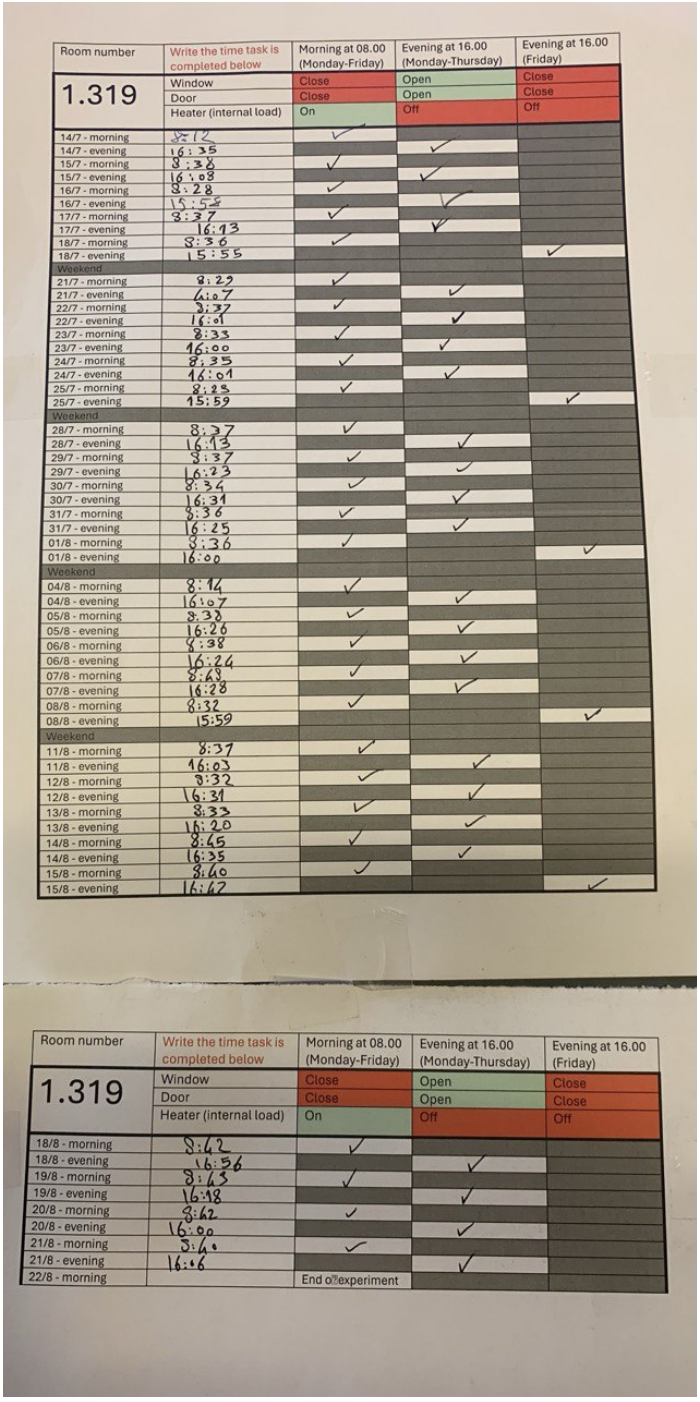


Room number	Write the time task is completed below	Morning at 08.00 (Monday-Friday)	Evening at 16.00 (Monday-Thursday)	Evening at 16.00 (Friday)
1.317	Window	Close	Close	Close
	Door	Close	Close	Close
	Heater (internal load)	On	Off	Off
14/7 - morning	8:09	8 ✓		
14/7 - evening	16:21		✓	
15/7 - morning	8:39	✓		
15/7 - evening	16:07		✓	
16/7 - morning	8:30	✓		
16/7 - evening	15:57		✓	
17/7 - morning	8:35	✓		
17/7 - evening	16:12		✓	
18/7 - morning	8:36	✓		
18/7 - evening	15:55			✓
Weekend				
21/7 - morning	8:29	~~8:29~~ ✓		
21/7 - evening	16:07		✓	
22/7 - morning	8:37	✓		
22/7 - evening	16:02		✓	
23/7 - morning	8:35	✓		
23/7 - evening	16:07		✓	
24/7 - morning	8:36	✓		
24/7 - evening	16:02		✓	
25/7 - morning	8:26	✓		
25/7 - evening	16:00			✓
Weekend				
28/7 - morning	8:37	✓		
28/7 - evening	16:13		✓	
29/7 - morning	8:37	✓		
29/7 - evening	16:23		✓	
30/7 - morning	8:35	✓		
30/7 - evening	16:31		✓	
31/7 - morning	8:36	✓		
31/7 - evening	16:25		✓	
01/8 - morning	8:37	✓		
01/8 - evening	16:01			✓
Weekend				
04/8 - morning	8:15	✓		
04/8 - evening	16:08		✓	
05/8 - morning	8:39	✓		
05/8 - evening	16:27		✓	
06/8 - morning	8:39	✓		
06/8 - evening	16:24		✓	
07/8 - morning	8:49	✓		
07/8 - evening	16:29		✓	
08/8 - morning	8:33	✓		
08/8 - evening	15:59			✓
Weekend				
11/8 - morning	8:37	✓		
11/8 - evening	16:04		✓	
12/8 - morning	8:33	✓		
12/8 - evening	16:32		✓	
13/8 - morning	8:34	✓		
13/8 - evening	16:20		✓	
14/8 - morning	8:46	✓		
14/8 - evening	16:36		✓	
15/8 - morning	8:40	✓		
15/8 - evening	16:42			✓

Room number	Write the time task is completed below	Morning at 08.00 (Monday-Friday)	Evening at 16.00 (Monday-Thursday)	Evening at 16.00 (Friday)
1.317	Window	Close	Close	Close
	Door	Close	Close	Close
	Heater (internal load)	On	Off	Off
18/8 - morning	8:43	✓		
18/8 - evening	16:56		✓	
19/8 - morning	8:43	✓		
19/8 - evening	16:18		✓	
20/8 - morning	8:42	✓		
20/8 - evening	16:01		✓	
21/8 - morning	8:48	✓		
21/8 - evening	16:06		✓	
22/8 - morning		End of experiment		

Figure 9.2: Manual operation log documenting window position, door status, and heater operation times for Room 1.317 during the measurement period. The log was used to ensure consistent operational conditions and to support the interpretation of measured temperature data.

9.3 Experimental Operation Schedule for Room 1319

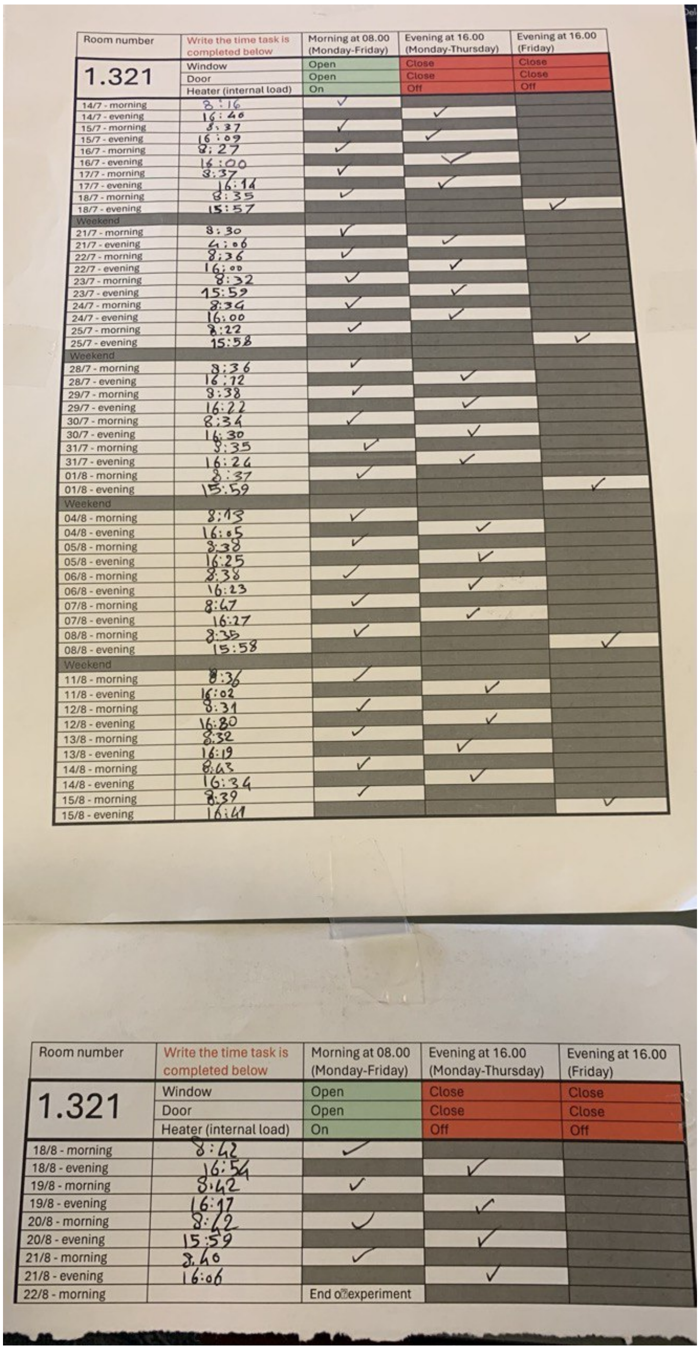


Room number	Write the time task is completed below	Morning at 08.00 (Monday-Friday)	Evening at 16.00 (Monday-Thursday)	Evening at 16.00 (Friday)
1.319	Window	Close	Open	Close
	Door	Close	Open	Close
	Heater (internal load)	On	Off	Off
14/7 - morning	8:12	✓		
14/7 - evening	16:35		✓	
15/7 - morning	8:38	✓		
15/7 - evening	16:08		✓	
16/7 - morning	8:28	✓		
16/7 - evening	15:58		✓	
17/7 - morning	8:37	✓		
17/7 - evening	16:13		✓	
18/7 - morning	8:36	✓		
18/7 - evening	15:55			✓
Weekend				
21/7 - morning	8:29	✓		
21/7 - evening	6:07		✓	
22/7 - morning	8:37	✓		
22/7 - evening	16:01		✓	
23/7 - morning	8:33	✓		
23/7 - evening	16:00		✓	
24/7 - morning	8:35	✓		
24/7 - evening	16:01		✓	
25/7 - morning	8:25	✓		
25/7 - evening	15:59			✓
Weekend				
28/7 - morning	8:37	✓		
28/7 - evening	16:13		✓	
29/7 - morning	8:37	✓		
29/7 - evening	16:23		✓	
30/7 - morning	8:34	✓		
30/7 - evening	16:31		✓	
31/7 - morning	8:36	✓		
31/7 - evening	16:25		✓	
01/8 - morning	8:36	✓		
01/8 - evening	16:00			✓
Weekend				
04/8 - morning	8:14	✓		
04/8 - evening	16:07		✓	
05/8 - morning	8:38	✓		
05/8 - evening	16:26		✓	
06/8 - morning	8:38	✓		
06/8 - evening	16:24		✓	
07/8 - morning	8:43	✓		
07/8 - evening	16:28		✓	
08/8 - morning	8:32	✓		
08/8 - evening	15:59			✓
Weekend				
11/8 - morning	8:37	✓		
11/8 - evening	16:03		✓	
12/8 - morning	8:32	✓		
12/8 - evening	16:31		✓	
13/8 - morning	8:33	✓		
13/8 - evening	16:20		✓	
14/8 - morning	8:45	✓		
14/8 - evening	16:35		✓	
15/8 - morning	8:40	✓		
15/8 - evening	16:42			✓

Room number	Write the time task is completed below	Morning at 08.00 (Monday-Friday)	Evening at 16.00 (Monday-Thursday)	Evening at 16.00 (Friday)
1.319	Window	Close	Open	Close
	Door	Close	Open	Close
	Heater (internal load)	On	Off	Off
18/8 - morning	8:42	✓		
18/8 - evening	16:56		✓	
19/8 - morning	8:43	✓		
19/8 - evening	16:18		✓	
20/8 - morning	8:42	✓		
20/8 - evening	16:00		✓	
21/8 - morning	8:40	✓		
21/8 - evening	16:06		✓	
22/8 - morning		End of experiment		

Figure 9.3: Manual operation log documenting window position, door status, and heater operation times for Room 1.319 during the measurement period. The log was used to ensure consistent operational conditions and to support the interpretation of measured temperature data.

9.4 Experimental Operation Schedule for Room 1321



Room number	Write the time task is completed below	Morning at 08.00 (Monday-Friday)	Evening at 16.00 (Monday-Thursday)	Evening at 16.00 (Friday)
1.321	Window	Open	Close	Close
	Door	Open	Close	Close
	Heater (internal load)	On	Off	Off
14/7 - morning	8:16	✓		
14/7 - evening	16:40		✓	
15/7 - morning	8:37	✓		
15/7 - evening	16:09		✓	
16/7 - morning	8:27	✓		
16/7 - evening	16:00		✓	
17/7 - morning	8:37	✓		
17/7 - evening	16:14		✓	
18/7 - morning	8:35	✓		
18/7 - evening	15:57			✓
Weekend				
21/7 - morning	8:30	✓		
21/7 - evening	4:06		✓	
22/7 - morning	8:36	✓		
22/7 - evening	16:00		✓	
23/7 - morning	8:32	✓		
23/7 - evening	15:59		✓	
24/7 - morning	8:34	✓		
24/7 - evening	16:00		✓	
25/7 - morning	8:22	✓		
25/7 - evening	15:58			✓
Weekend				
28/7 - morning	8:36	✓		
28/7 - evening	16:12		✓	
29/7 - morning	8:38	✓		
29/7 - evening	16:22		✓	
30/7 - morning	8:34	✓		
30/7 - evening	16:30		✓	
31/7 - morning	8:35	✓		
31/7 - evening	16:24		✓	
01/8 - morning	8:37	✓		
01/8 - evening	15:59			✓
Weekend				
04/8 - morning	8:13	✓		
04/8 - evening	16:05		✓	
05/8 - morning	8:38	✓		
05/8 - evening	16:25		✓	
06/8 - morning	8:38	✓		
06/8 - evening	16:23		✓	
07/8 - morning	8:47	✓		
07/8 - evening	16:27		✓	
08/8 - morning	8:35	✓		
08/8 - evening	15:58			✓
Weekend				
11/8 - morning	8:36	✓		
11/8 - evening	16:02		✓	
12/8 - morning	8:31	✓		
12/8 - evening	16:30		✓	
13/8 - morning	8:32	✓		
13/8 - evening	16:19		✓	
14/8 - morning	8:43	✓		
14/8 - evening	16:34		✓	
15/8 - morning	8:39	✓		
15/8 - evening	16:41			✓

Room number	Write the time task is completed below	Morning at 08.00 (Monday-Friday)	Evening at 16.00 (Monday-Thursday)	Evening at 16.00 (Friday)
1.321	Window	Open	Close	Close
	Door	Open	Close	Close
	Heater (internal load)	On	Off	Off
18/8 - morning	8:42	✓		
18/8 - evening	16:54		✓	
19/8 - morning	8:42	✓		
19/8 - evening	16:17		✓	
20/8 - morning	8:42	✓		
20/8 - evening	15:59		✓	
21/8 - morning	8:40	✓		
21/8 - evening	16:06		✓	
22/8 - morning		End of experiment		

Figure 9.4: Manual operation log documenting window position, door status, and heater operation times for Room 1.321 during the measurement period. The log was used to ensure consistent operational conditions and to support the interpretation of measured temperature data.

9.5 Experimental Operation Schedule for Room 1323

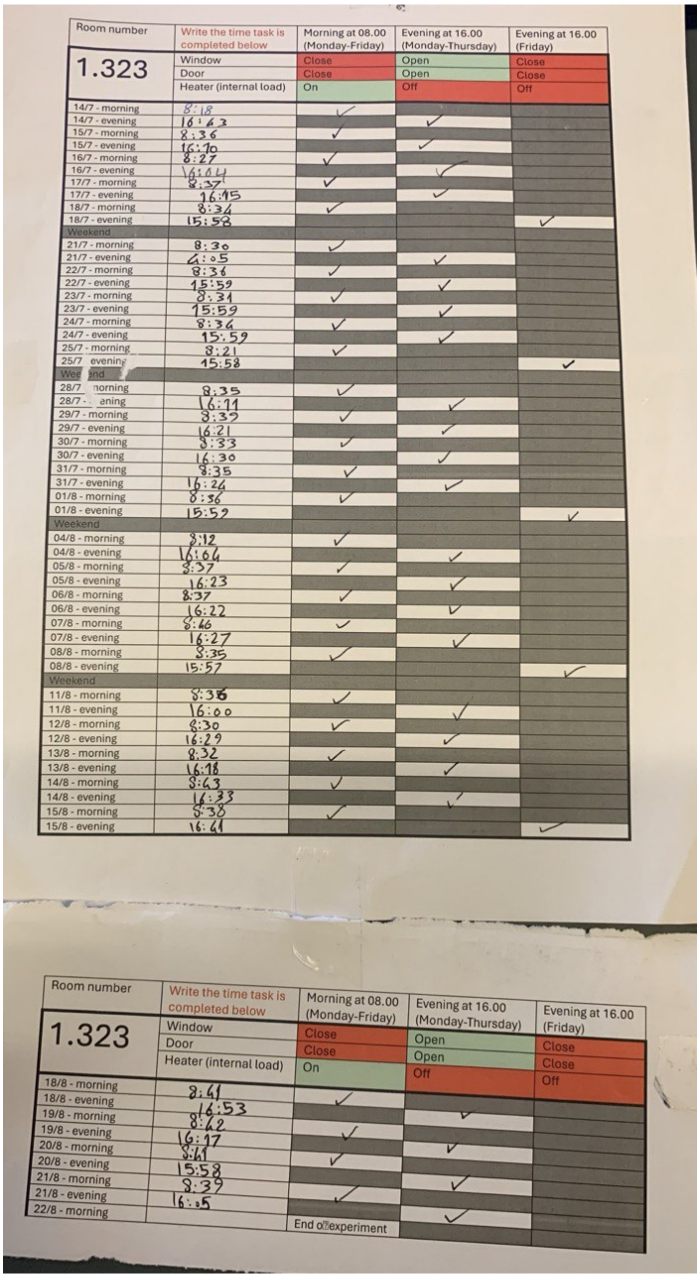
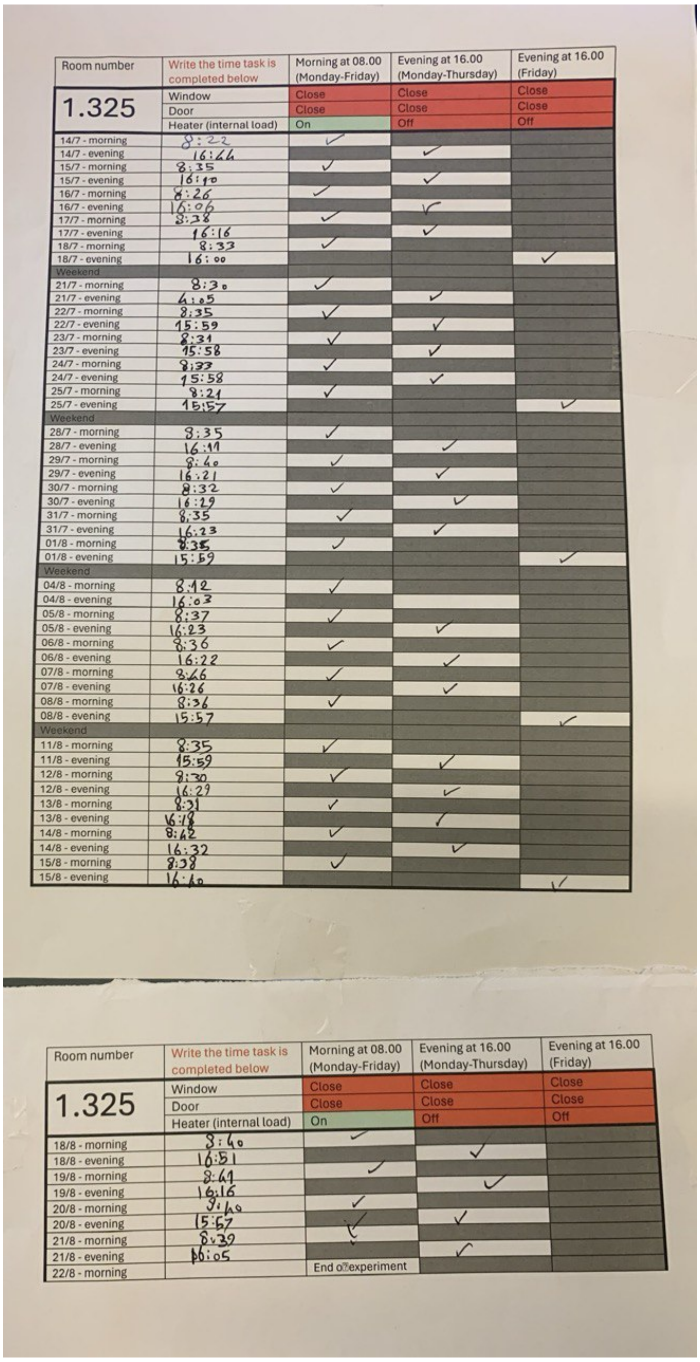


Figure 9.5: Manual operation log documenting window position, door status, and heater operation times for Room 1.323 during the measurement period. The log was used to ensure consistent operational conditions and to support the interpretation of measured temperature data.

9.6 Experimental Operation Schedule for Room 1325

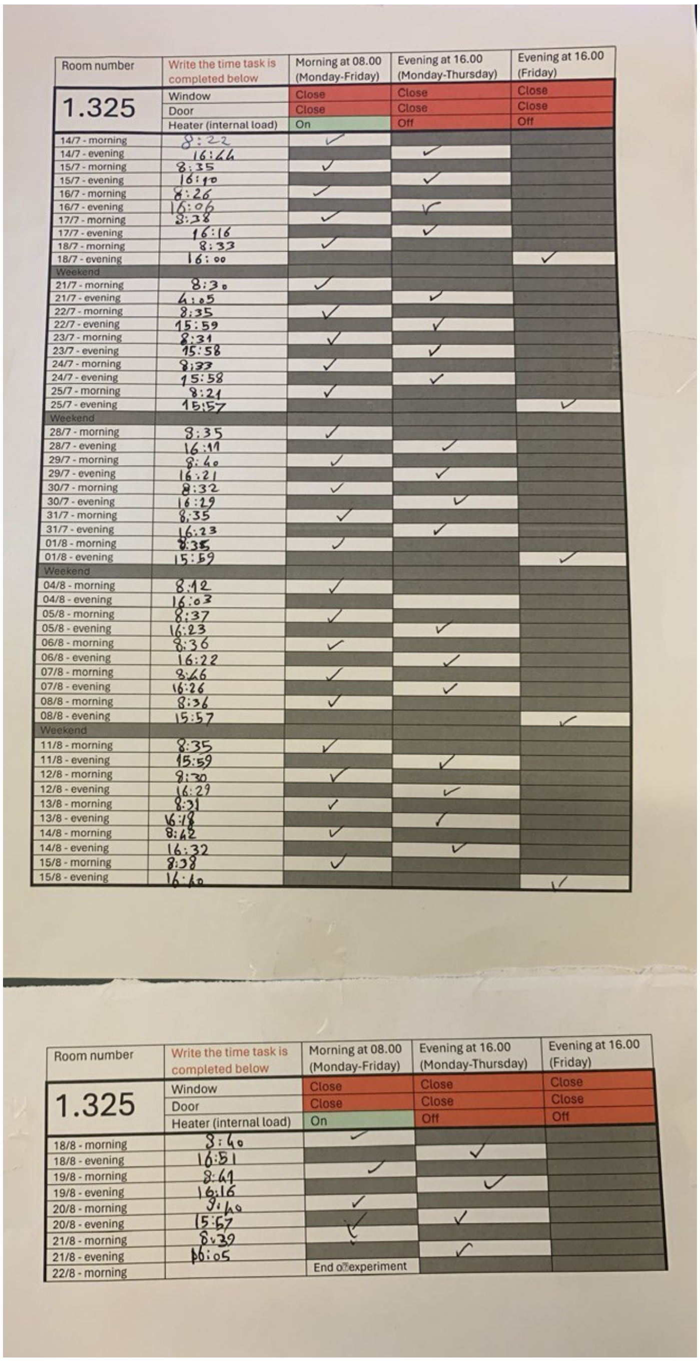


Room number	Write the time task is completed below	Morning at 08.00 (Monday-Friday)	Evening at 16.00 (Monday-Thursday)	Evening at 16.00 (Friday)
1.325	Window	Close	Close	Close
	Door	Close	Close	Close
	Heater (internal load)	On	Off	Off
14/7 - morning	8:22	✓		
14/7 - evening	16:44		✓	
15/7 - morning	8:35	✓		
15/7 - evening	16:10		✓	
16/7 - morning	8:26	✓		
16/7 - evening	16:06		✓	
17/7 - morning	8:38	✓		
17/7 - evening	16:16		✓	
18/7 - morning	8:33	✓		
18/7 - evening	16:00			✓
Weekend				
21/7 - morning	8:30	✓		
21/7 - evening	4:05		✓	
22/7 - morning	8:35	✓		
22/7 - evening	15:59		✓	
23/7 - morning	8:31	✓		
23/7 - evening	15:58		✓	
24/7 - morning	8:33	✓		
24/7 - evening	15:58		✓	
25/7 - morning	8:21	✓		
25/7 - evening	15:57			✓
Weekend				
28/7 - morning	8:35	✓		
28/7 - evening	16:11		✓	
29/7 - morning	8:40	✓		
29/7 - evening	16:21		✓	
30/7 - morning	8:32	✓		
30/7 - evening	16:29		✓	
31/7 - morning	8:35	✓		
31/7 - evening	16:23		✓	
01/8 - morning	8:35	✓		
01/8 - evening	15:59			✓
Weekend				
04/8 - morning	8:12	✓		
04/8 - evening	16:03			
05/8 - morning	8:37	✓		
05/8 - evening	16:23		✓	
06/8 - morning	8:36	✓		
06/8 - evening	16:22		✓	
07/8 - morning	8:46	✓		
07/8 - evening	16:26		✓	
08/8 - morning	8:36	✓		
08/8 - evening	15:57			✓
Weekend				
11/8 - morning	8:35	✓		
11/8 - evening	15:59		✓	
12/8 - morning	8:30	✓		
12/8 - evening	16:29		✓	
13/8 - morning	8:31	✓		
13/8 - evening	16:18		✓	
14/8 - morning	8:42	✓		
14/8 - evening	16:32		✓	
15/8 - morning	8:38	✓		
15/8 - evening	16:40			✓

Room number	Write the time task is completed below	Morning at 08.00 (Monday-Friday)	Evening at 16.00 (Monday-Thursday)	Evening at 16.00 (Friday)
1.325	Window	Close	Close	Close
	Door	Close	Close	Close
	Heater (internal load)	On	Off	Off
18/8 - morning	8:40	✓		
18/8 - evening	16:51		✓	
19/8 - morning	8:41	✓		
19/8 - evening	16:16		✓	
20/8 - morning	8:40	✓		
20/8 - evening	15:57		✓	
21/8 - morning	8:39	✓		
21/8 - evening	16:05		✓	
22/8 - morning		End o?experiment		

Figure 9.6: Manual operation log documenting window position, door status, and heater operation times for Room 1.325 during the measurement period. The log was used to ensure consistent operational conditions and to support the interpretation of measured temperature data.

9.7 Experimental Operation Schedule for Room 1327



Room number	Write the time task is completed below	Morning at 08.00 (Monday-Friday)	Evening at 16.00 (Monday-Thursday)	Evening at 16.00 (Friday)
1.325	Window	Close	Close	Close
	Door	Close	Close	Close
	Heater (internal load)	On	Off	Off
14/7 - morning	8:22	✓		
14/7 - evening	16:44		✓	
15/7 - morning	8:35	✓		
15/7 - evening	16:10		✓	
16/7 - morning	8:26	✓		
16/7 - evening	16:06		✓	
17/7 - morning	8:38	✓		
17/7 - evening	16:16		✓	
18/7 - morning	8:33	✓		
18/7 - evening	16:00			✓
Weekend				
21/7 - morning	8:30	✓		
21/7 - evening	4:05		✓	
22/7 - morning	8:35	✓		
22/7 - evening	15:59		✓	
23/7 - morning	8:31	✓		
23/7 - evening	15:58		✓	
24/7 - morning	8:33	✓		
24/7 - evening	15:58		✓	
25/7 - morning	8:21	✓		
25/7 - evening	15:57			✓
Weekend				
28/7 - morning	8:35	✓		
28/7 - evening	16:11		✓	
29/7 - morning	8:40	✓		
29/7 - evening	16:21		✓	
30/7 - morning	8:32	✓		
30/7 - evening	16:29		✓	
31/7 - morning	8:35	✓		
31/7 - evening	16:23		✓	
01/8 - morning	8:35	✓		
01/8 - evening	15:59			✓
Weekend				
04/8 - morning	8:12	✓		
04/8 - evening	16:03			
05/8 - morning	8:37	✓		
05/8 - evening	16:23		✓	
06/8 - morning	8:36	✓		
06/8 - evening	16:22		✓	
07/8 - morning	8:46	✓		
07/8 - evening	16:26		✓	
08/8 - morning	8:36	✓		
08/8 - evening	15:57			✓
Weekend				
11/8 - morning	8:35	✓		
11/8 - evening	15:59		✓	
12/8 - morning	8:30	✓		
12/8 - evening	16:29		✓	
13/8 - morning	8:31	✓		
13/8 - evening	16:18		✓	
14/8 - morning	8:42	✓		
14/8 - evening	16:32		✓	
15/8 - morning	8:38	✓		
15/8 - evening	16:40			✓

Room number	Write the time task is completed below	Morning at 08.00 (Monday-Friday)	Evening at 16.00 (Monday-Thursday)	Evening at 16.00 (Friday)
1.325	Window	Close	Close	Close
	Door	Close	Close	Close
	Heater (internal load)	On	Off	Off
18/8 - morning	8:40	✓		
18/8 - evening	16:51		✓	
19/8 - morning	8:41	✓		
19/8 - evening	16:16		✓	
20/8 - morning	8:40	✓		
20/8 - evening	15:57	✓	✓	
21/8 - morning	8:39	✓		
21/8 - evening	16:05		✓	
22/8 - morning		End o[illegible]experiment		

Figure 9.7: Manual operation log documenting window position, door status, and heater operation times for Room 1.327 during the measurement period. The log was used to ensure consistent operational conditions and to support the interpretation of measured temperature data.