HeriTACE

Comfort and IAQ in Heritage Townhouses

Deliverable D3.2

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Abbreviations and acronyms

Acronym	Description
WP	Work Package
T#.#.#	Task number #.#.#
D#.#.#	Deliverable #.#
CO_2	Carbon Dioxide
EPBD	Energy Performance of Building Directive
IEQ	Indoor environmental quality
MCT	Middle-class townhouse (Belgian building archetype)
IAQ	Indoor Air Quality
EPBD	Energy Performance of Buildings Directive
RH	Relative Humidity
SC	Space Conditioning
PB	Pre-renovation Baseline
RB	Renovation Baseline
HeriTACE	Future-proofing **Heri**tage Buildings by Optimising Comfort and Energy in **T**ime and Sp**ACE**

Executive Summary

Project context

'D3.2 Comfort and IAQ in Heritage Townhouses' is a report that documents the work of task 'T3.1- Analysis of comfort, IAQ and HVAC systems in heritage townhouses' in work package 3 (WP3) of the HeriTACE project.

The objective of WP3 is to develop energy-efficient HVAC systems optimizing comfort and IAQ in space and time:

- To develop smart HVAC concepts that safeguard the heritage value of townhouses and optimise comfort energy efficiency and IAQ based on sufficiency.
- To develop methods for sizing smart HVAC systems which integrate existing components with the aim to facilitate R^2ES-based energy supply.
- To develop ventilation and conditioning strategies to remove moisture and mould built-up in historical constructions
- To develop methods for assessing the potential of ventilative cooling in heritage townhouses
- To develop simulation-based design guidelines for optimal holistic renovation of heritage townhouses, balancing their heritage value with envelope and HVAC interventions, reducing the design cost in future projects
- To demonstrate the methodology by developing a set of optimized holistic renovation concepts for the heritage case studies with quantified performance.

As part of the interdisciplinary analysis of heritage townhouses, in this task the IEQ, and present-day space conditioning concepts in existing heritage townhouses is investigated.

The rich dataset gathered through measurements of IEQ parameters will serve multiple purposes in the project. First, as will be discussed in this report, the measurements provide insights into the current IEQ conditions and place the investigated heritage buildings in relation to what if considered 'typical' in buildings with a similar function.

The observations on space conditioning systems and insights in comfort levels aided in the definition of pre-renovation and renovation baseline scenarios for the space conditioning systems of the investigated archetypes and serve as direct input to 'D5.4 Baseline scenarios'.

Later in the same work package, the same dataset can be used to verify modelling assumptions in WP3-T3.2, T3.3, T3.4 and T3.5 and check the outcome of the simulations with the gathered measured data.

Outcomes

In 22 cases measurements were done with sensors placed in several rooms across 4 countries and 3 European climate zones. All measurements are done with a high temporal and spatial resolution, and most measurements cover both the summer and winter months allowing the comparison of winter and summer use, comfort, and IEQ throughout the year.

Belgium

Findings on indoor environmental quality (IEQ), energy use, and thermal comfort in Belgian residential townhouse buildings are done based on the dataset and on-site observations. The results highlight the balance between maintaining good indoor air quality (IAQ) and energy demand, the influence of occupant behaviour on heating and temperature settings, and the challenges posed by specific Belgian archetype townhouse building characteristics such as airtightness, thermal mass, and spatial differences (main volumes vs annexes and attics).

Key Findings:

- Belgian cases show "medium" perceived air quality or better. This is better than initially expected.
- No clear seasonal pattern in window opening or leakage-related ventilation; bedrooms are ventilated either year-round or rely on infiltration.
- Occupants consciously operate homes to save energy, often accepting lower indoor temperatures.
- Radiator valves are commonly closed in bedrooms and hallways to maintain lower temperatures.
- Bathrooms are either unheated or heated only during use.
- Main living areas are generally kept slightly above the lower comfort boundary but still within acceptable IEQ classes.
- Large thermal mass in main building volumes helps dampen external temperature fluctuations and prevents overheating in summer.
- Nighttime cooling is effective in Belgium due to low summer night temperatures (<20°C), which helps buffer daytime heat.
- Annexes have thinner, lighter walls resulting in lower thermal mass and thermal resistance, making them challenging for HVAC design.
- Attics, often used as bedrooms are critical spaces for overheating. Active cooling (air conditioning) is found to be installed with priority in the attic to mitigate overheating.

The observed space conditioning systems were radiator heating systems equipped with thermostatic radiator valves in the large majority of cases and independent of archetype. This will also be the case for the pre-renovation baseline and one of the renovation baseline scenarios of the different archetypes. In a second renovation baseline scenario, new radiators are installed. In the renovation baselines, supply temperatures are lowered assuming improvements to the building envelope are made. No active cooling is assumed.

Norway

Monitoring of five Norwegian heritage townhouses reveals that, despite their age and limited mechanical systems, these buildings maintain stable indoor conditions largely within European thermal comfort and air quality standards. Key contributing factors include occupant control of heating, simple ventilation habits, and low occupancy density. Winter indoor temperatures frequently exceeded regulatory assumptions due to consistent heating practices, while summer temperatures remained moderate.

Humidity levels were mostly within comfort ranges, though localized spikes (e.g., in bathrooms) underscore the need for effective ventilation. CO_2 levels were generally acceptable, except in one case with high tourist turnover, highlighting how variable use can challenge indoor air quality.

These findings suggest that modest, targeted interventions—like improved thermal zoning and bathroom ventilation—can enhance performance without compromising heritage value. The results support renovation approaches that emphasize user control, adaptive comfort, and low-impact upgrades

Key-findings:

- Indoor temperatures exceed regulatory assumptions: Measured winter temperatures in all cases were significantly above the EPBD default of 18 °C—averaging 21–23 °C—demonstrating that occupants consistently maintain warmer indoor environments than assumed in energy performance calculations.
- Narrow seasonal temperature variation: Despite Norway's cold climate, the difference between average summer and winter indoor temperatures was generally less than 3 °C, due to continued heating use during cool and windy summers.
- High levels of thermal comfort achieved: More than 70% of occupied hours fell within adaptive thermal comfort category I (EN 16798) in most dwellings.
- CO_2 levels generally within acceptable limits: Indoor CO_2 concentrations remained below 1000 ppm in most cases, with higher levels (>2000 ppm) observed only in short-term summer rentals with low window-opening frequency. This suggests natural ventilation was generally sufficient in owner-occupied homes.
- Bathrooms exhibit localized humidity risks: Bathrooms in two homes (OccA and OccB) consistently experienced relative humidity above 70%, a level associated with increased mold risk. This highlights the need for improved ventilation in wet rooms.
- Moisture loads correlate with outdoor temperature: Indoor moisture excess peaked (6–8 g/m^3) during cold spells, particularly in the more airtight homes. Otherwise, typical moisture loads stayed within expected ranges, affirming that ventilation and envelope characteristics drive indoor humidity dynamics.
- Daily and weekly patterns reflect occupant behaviour: Temperature and CO_2 profiles revealed clear differences between weekdays and weekends, and between seasons—especially in homes with programmable thermostats or wood stoves. This illustrates the strong influence of user routines on indoor climate.
- Limited mechanical ventilation: Natural Airing Prevails: All buildings relied primarily on window airing and minimal exhaust fans. Yet, air quality and comfort remained mostly acceptable, indicating that simple, well-used systems can suffice in well-managed, low-occupancy and low airtightness heritage dwellings.
- Renovation practices favour low-Impact upgrades: Renovated buildings retained traditional heating and ventilation methods—such as electric radiators and wood stoves—with minimal zoning. Comfort improvements stemmed more from localized upgrades and insulation than from full system replacements.
- Heritage townhouses can support healthy indoor environments: Despite their age and limited technology, these wooden heritage buildings achieved acceptable thermal and air quality performance when combined with user awareness and modest modernization. This supports preservation-first renovation strategies.

The observed space conditioning systems were direct electric radiator heating in all cases except one which had underfloor hydronic heating as it underwent a relatively large renovation. Wood stoves are present but of secondary nature. Direct electric heating or high-temperature hydronic radiators with thermostatic radiator valves are the suggested pre-renovation baseline and renovation baseline scenarios. In the latter, the radiators are refurbished and supply temperatures lowered. No active cooling.

Estonia

Estonian cases demonstrated the challenges posed by airtight envelopes and long heating seasons. Moisture management was a particularly salient issue, with evidence of high internal humidity classes in several monitored rooms. At the same time, the widespread use of natural ventilation combined with well-managed heating practices helped maintain thermal comfort within EN Class II for most occupied periods. These cases emphasized the sensitivity of IAQ and comfort to both envelope interventions and user routines.

Key-findings:

- High temperature variability: Indoor temperatures in Estonian heritage townhouses varied significantly, particularly during summer months, with peak values often nearing or exceeding adaptive comfort thresholds.
- Consistently low relative humidity in winter: Relative humidity levels during winter were frequently below the recommended comfort range, indicating potential discomfort due to dry indoor air.
- Material-dependent indoor climate behaviour: wooden and brick buildings demonstrated distinct thermal and moisture characteristics, underscoring the need for HVAC solutions tailored to construction material.
- Thermal mass as a stabilizing factor: Brick-structured buildings leveraged their thermal mass to reduce indoor temperature swings, contributing to thermal comfort.
- Overheating risks in lightweight constructions: Wooden buildings, particularly those with attic rooms or minimal insulation, were more prone to overheating during summer.
- Moisture management required in specific zones: Elevated internal humidity classes in some rooms (e.g., bedrooms, living rooms, bathrooms) indicated localized risks of mold and condensation, pointing to the need for ventilation strategies.
- Effectiveness of night ventilation: Passive cooling strategies, such as night ventilation via window opening, proved effective in moderating indoor temperatures in the absence of active cooling.
- Need for spatial zoning in HVAC design: Significant variation in indoor conditions across rooms revealed the importance of spatial zoning in future HVAC system designs to optimize comfort and efficiency.

The observed space conditioning systems were radiator heating equipped with thermostatic radiator valves in the large majority of cases and independent of archetype. The proposed pre-renovation baselines are either radiator heating or relying on a wood stove for heating. In the proposed renovation baseline scenario, it is either radiator heating combined with a wood stove or an air-to-air heat pump combined with a wood stove. In a third scenario, space heating is only provided by radiators. In case of the air-to-air heat pump, also active cooling is possible.

Italy

The Italian cases revealed the critical role of HVAC systems in maintaining thermal comfort and air quality. Unconditioned buildings (Occ_A and Occ_B) experience frequent overheating in summer (above 26°C) with poor temperature control and likely CO_2 buildup, given the lack of mechanical ventilation. In contrast, the air-conditioned home (Occ_C) maintains better temperature and CO_2 levels, though wintertime dryness is a concern due to low relative humidity.

Ground-floor rooms perform quite good in summer due to proximity to the ground and passive shading from surrounding buildings without active cooling, but discomfort is very likely in upper floors or poorly shaded areas. To prepare for hotter summers under climate change, unconditioned homes would benefit from active cooling and improved ventilation. In conditioned spaces, occupancy-based system management are recommended to optimize comfort and energy efficiency year-round.

Key Findings:

- Unconditioned homes experience high summer temperatures: In unconditioned cases (Occ_A and Occ_B), summer indoor temperatures were elevated but generally stayed within adaptive comfort limits defined by EN 16798.
- Conditioned case shows effective temperature control: Case Occ_C, equipped with active heating and cooling systems, maintained stable temperatures throughout the year, showing the impact of conditioning.
- High CO_2 levels in conditioned home: Case Occ_C regularly exceeded the CO_2 concentration thresholds for IEQ Class II, suggesting that mechanical conditioning was not matched by effective ventilation.
- Internal humidity class III identified: The dining room of Occ_C reached Internal Humidity Class III, indicating high indoor moisture load with potential risk for condensation and mold.
- Room-to-room IEQ differences noted: Different spaces within the same dwelling exhibited significant variation in temperature, humidity, and CO_2, reinforcing the need for zoned HVAC strategies.
- Ventilation challenges in heavily used spaces: Occupied areas such as kitchens and bedrooms showed CO_2 spikes, indicating insufficient ventilation or air exchange during high-use periods.
- Active space conditioning systems were present but not fully utilized: Despite the availability of air conditioning and heating in Occ_C, actual use was limited or inconsistent, affecting both thermal and air quality outcomes.
- Natural ventilation still plays a role: Even in conditioned buildings, window airing remains a critical method of managing summer heat and indoor air quality.
- Dry air and inadequate humidification pose comfort risks: Substantial portions of monitored time, particularly in winter, showed RH levels below recommended thresholds, highlighting the need for humidification strategies or envelope adjustments.

The observed space conditioning systems were high-temperature radiator heating equipped with thermostatic radiator valves in the large majority of cases and independent of archetype. This will also be the case for the pre-renovation baseline and one of the renovation baseline scenarios of the different archetypes. In a second and third renovation baseline scenario, new radiators are installed.

For ventilation a difference between the first and second, and the third renovation baseline lies in the choice of ventilation system. In the first two scenarios, no dedicated ventilation system is present relying solely on operable windows for IAQ management. The third scenario additionally relies on a dedicated ventilation chimney connected to the central staircase to induce higher passive airflow rates. This ventilation chimney is an original feature found in the Italian archetype townhouses.

Finally, for all renovation baseline scenarios, multi-split air-to-air air conditioning is present for active cooling.

Conclusions

Deliverable D3.2 offers robust empirical support for a nuanced approach to heritage townhouse renovation. Rather than pursuing maximum technical intervention, it argues for systems and strategies that align with building characteristics, occupant behaviours, and climatic context. The insights and baselines derived from this work now serve as a critical foundation for the simulations and renovations that follow in WP3 and beyond. As climate targets tighten and energy expectations rise, such grounded, context-sensitive understanding will be essential for making Europe's architectural heritage both resilient and future-ready.

Key cross-region take-aways are:

Occupant Behaviour and Sufficiency:

The data clearly indicate that users apply sufficiency-based strategies—e.g., partial heating, night-time window opening, or unheated rooms—without significant detriment to comfort or health. This validates the HeriTACE project's hypothesis that non-uniform, time-and-space-dependent HVAC strategies are not only feasible but already in practice.

Construction type and overheating risk:

Across all regions, the non-wooden heritage townhouses benefited from their thermal mass to buffer against high temperature extremes. The wooden townhouse types have a higher overheating risk but are only found in the colder climatic region.

HVAC System Characteristics:

Most buildings featured traditional hydronic heating systems, often controlled by a central thermostat with additional thermostatic valves, or direct electric heaters. Only in the colder regions, woodstoves are still in use. Few included mechanical ventilation, and even fewer had mechanical cooling.

Risk of Moisture Damage:

While relative humidity was generally within acceptable comfort ranges, localised conditions (e.g., bathrooms, below-grade living spaces) posed mould and condensation risks. Moreover, building upgrades—especially those that enhance airtightness—could exacerbate these issues if not paired with effective ventilation strategies.

The following recommendations can inform building designers, policy makers, and heritage conservationists:

- Leverage existing occupant behaviour: New HVAC systems should be designed to support and optimize prevalent sufficiency-based behaviours rather than override them.

- Account for spatial variability: Renovation strategies should consider intra-building variation—particularly the thermal challenges posed by annexes, attics, and cellars.
- Targeted mechanical upgrades: Rather than overhauling entire HVAC systems, targeted lower-impact enhancements can potentially yield significant gains more fitting in a heritage context.
- Monitor airtightness effects: Any intervention aimed at improving airtightness should be complemented with humidity-sensitive ventilation design to mitigate internal moisture accumulation.
- Use advanced comfort models: Regulations and renovation targets should integrate advanced (adaptive) comfort frameworks, which better reflect occupant experience in heritage buildings than static setpoint-based metrics.

1 Introduction

This document reports on the work of task 'T3.1- Analysis of comfort, IAQ and HVAC systems in heritage townhouses' in work package 3 (WP3) of the HeriTACE project.

The objective of WP3 is to develop energy-efficient HVAC systems optimizing comfort and IAQ in space and time:

- To develop smart HVAC concepts that safeguard the heritage value of townhouses and optimise comfort energy efficiency and IAQ based on sufficiency.
- To develop methods for sizing smart HVAC systems which integrate existing components with the aim to facilitate R²ES-based energy supply.
- To develop ventilation and conditioning strategies to remove moisture and mould built-up in historical constructions
- To develop methods for assessing the potential of ventilative cooling in heritage townhouses
- To develop simulation-based design guidelines for optimal holistic renovation of heritage townhouses, balancing their heritage value with envelope and HVAC interventions, reducing the design cost in future projects
- To demonstrate the methodology by developing a set of optimized holistic renovation concepts for the heritage archetypes with quantified performance.

As a first step for all these tasks, an interdisciplinary analysis of heritage townhouses is carried out. In this task, the IEQ and present-day space condition systems in heritage townhouses is investigated, based on a thorough technical inventory and a measurement campaign in several case study buildings per region.

This report follows a four-part structure for each region. First, the setup of the monitoring campaign is outlined, detailing the number of case studies monitored and the measurement set-up used, as these vary by country.

Second, the rich dataset obtained through measurements of IEQ parameters is analysed. These measurements offer valuable insights into the current IEQ conditions and allow for comparison of the investigated heritage buildings with what is considered 'typical' for buildings with a similar function.

Third, the inventory of space conditioning systems is described focussing on the space conditioning systems and distribution of heating and cooling, as well as ventilation.

Finally, the observations regarding space conditioning systems and the insights into comfort levels have supported the definition of pre-renovation and renovation baseline scenarios for the space conditioning systems of the investigated archetypes. These are discussed in detail in this report and serve as direct input for Deliverable 'D5.4 Baseline scenarios'.

1.1 Measurement campaigns

HeriTACE –which refers to "...optimising in **T**ime And sp**ACE**"- investigates intentionally applying non-uniform and non-continuous heating/cooling/ventilation strategies to the building as a solution for achieving energy efficient, fit-for-55 heritage townhouse buildings.

However, the hypothesis is that occupants actually already apply these strategies to some extent. E.g. only heat their bathroom for 2 hours in the morning, maybe never heat the toilet, open a window while cooking, ... In addition, this would mean that people tend to accept spaces that are technically "too cold" or "too warm" and especially if they only reside in them for short periods of time. This behaviour and resiliency/adaptability has its impact on the building energy use. However, current typical building HVAC solutions do not always leverage the inherent resiliency of occupants and do not provide the means to control space condition systems to match actual minimum comfort expectations of occupants differing in time and space.

For this reason, a long-term monitoring campaign was launched in 4 cities across three climate zones. Data was collected in 22 buildings. The long-term monitoring campaign strived to:

- Inform us about how the spaces are actually used and how they are heated, cooled, and ventilated.
- Inform us about the levels of comfort that people find acceptable in a heritage townhouse.
- Aid in the development of '(pre-)renovation baseline scenario's' in each country that will be modelled later.
- Generate verification data for the modelling assumptions in T3.2 to T3.5

General guidelines for the design of measurement campaign were:

- Monitor with a room-to-room spatial resolution. So generally speaking, it is preferred to have less cases with a higher resolution then vice versa.
- Measure in each room that currently has a heat/cool emission system installed with at least a temperature sensor.
- Measuring the combination of a Temperature-RH-CO_2 is considered a normal standard in the critical spaces (living spaces, kitchen, bathrooms, main bedrooms).
- Other IAQ/IEQ sensors (E.g. Particle sensors), if available, are all applauded and will aid the overall purpose of the project.
- Sensors should be installed in a neutral location within the room. This means:
    - Not too close to doors/windows, ventilation inlets, above radiators, …
    - Preferably at the typical head-height of people in that room (in a bedroom +- at the level of the pillow, in a living +- a sitting height...)
    - If the room contains a stove or another localized high-temperature heating device, consider using multiple sensors to assess temperature non-uniformity throughout the space.

Practical constraints of inhabited spaces and available equipment didn't always allow to follow the general guidelines in the execution. The different measurement campaigns vary in duration and time of the year dictated by access to the (private) building. All measurements happened between March 2024 and May 2025.

1.2 Description of the data set

The measurement campaigns gathered a total of 16 542 109 data points for Temperature, Relative Humidity and CO_2. Time intervals range from 5-60 minutes to capture dynamic changes of the parameters over time. The dataset is structured with at least following columns: datetime, values, alias, parameter, room, country. Table 1-1 gives an overview of the datapoints per country and main IEQ parameter.

Table 1-1 Overview of datapoints for temperature, relative humidity, and CO_2

	Temperature	Relative Humidity	Carbon Dioxide - CO_2
Belgium	2 142 794	2 121 737	877 074
Norway	520 211	520 213	349 559
Estonia	3 266 195	3 266 195	3 266 195
Italy	86 751	91 315	33 870

The full dataset is not openly available since the data is considered sensitive data. Published graphs and analysis should be high-level to not breach personal data protection but the full dataset is available in support of the other tasks of the HeriTACE project: the same dataset can be used to verify modelling assumptions in WP3-T3.2, T3.3, T3.4 and T3.5 and check the outcome of the simulations with the gathered measured data.

Due to the potentially sensitive nature of the data, all analyses will refer to occupants rather than the individual case studies. In the Observations and Data Analysis section, acronyms such as Occ_A, Occ_B, etc., will be used. In the case of Estonia, an additional indication of the archetype will be provided – e.g. Wood_A1, Brick_B2 – as this distinction plays a significant role in the analysis. With regard to the inventory of systems, which contains no sensitive personal data, the original case names will be used, such as MEERS, KOMEEDI, or LEONARDO.

1.3 Data analyses

Data analysis is done around three larger themes of special interest to the project: IEQ, variability in time and space and potential moisture problems. The analysis is done and reported on for each country separately in sections 2 to 5. The different townhouse archetypes and climatic conditions legitimize this approach. Where possible, reference is made to EU standards to put the findings of the measurements in relation to guideline values of standards.

Eight aspects are discussed providing an answer to the following questions:

- **EPBD building temperature**: how do the measurements relate to the assumed EPC/EPBD whole building temperature assumption?
- **Temperature variability**: how do temperature levels change throughout the day? How different are temperature levels in winter versus summer?
- **Duration of the heating season**: how long is the heating and/or cooling season?
- **Adaptive thermal comfort**: how are comfort levels compared to standard adaptive thermal comfort levels (EN 16789-1)?
- **CO_2 variability**: how do CO_2 levels change throughout the day? How different are CO_2 levels in winter versus summer?
- **IEQ categories**: how are the expected perceived comfort levels (CO_2) compared to the standard IEQ-classes of EN 16789-1
- **Relative Humidity variability**: how do relative humidity levels change throughout the day? How different are relative humidity levels in winter versus summer?
- **Internal humidity classes**: what are the internal humidity classes of different spaces in current conditions?

1.4 Space conditioning systems and baselines

Apart from the measured dataset, information was gathered on the space conditioning systems for heating, cooling, and ventilation in each case and optionally in additional, unmonitored, cases. All space conditioning devices and their technical information were gathered as well as the controls applied to control the operation of the systems. A template was developed so that data gathering was uniform across countries.

The overview aided in the definition of the pre-renovation and renovation space condition baseline scenarios (D5.4) and will serve as input to T3.3-3.5.

This report includes a detailed description of the pre-renovation and renovation space conditioning baseline scenarios for each archetype. The scenarios are summarized in consistent tables using the following example (Figure 1-1).

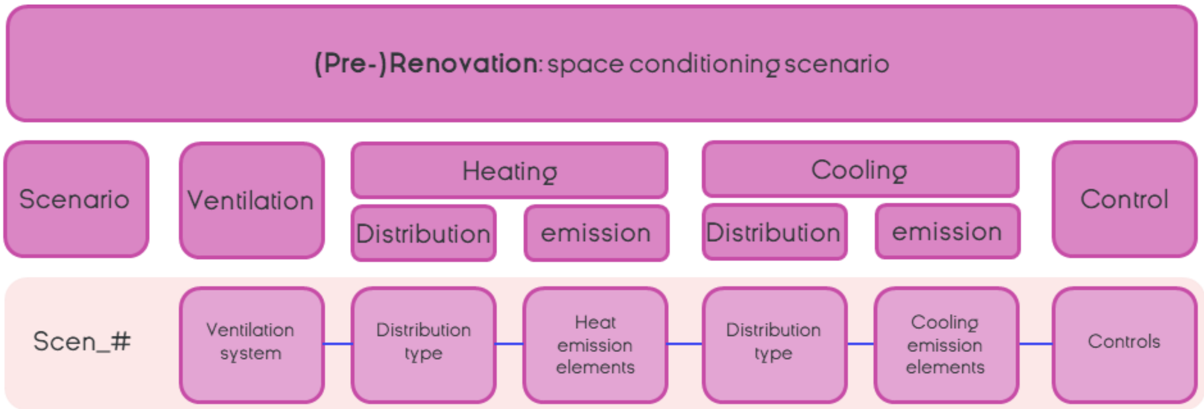


Figure 1-1 (pre-)Renovation baseline description template.

2 Belgium

2.1 Equipment and set-up

In five case-study buildings, measurements were done for temperature, relative humidity, and CO_2 in different rooms of each case study. This results in higher than typical temporal and spatial resolution for the measured case-studies. In total 5 141 605 datapoints were gathered over the period from March 2024 to April 2025. The dataset allows to observe how temperatures, CO_2 and humidity varies with time and provides valuable insights in how the building is used and operated differently in for e.g. summer versus winter. In addition, weather data was sourced from local open-weather data to be able to link the indoor and outdoor climatic conditions. Temperature and relative humidity measurements from Vlinderstation 71, located in the city centre of Ghent, is used (Ghent University, 2025). The rich dataset allows to gain better understanding of, for example, thermal comfort, perceived IAQ and interior moisture load.

The measurements were done using a combination of three types of dataloggers: 'HOBO MX1102A', The 'HOBO U12 T/RH' and 'Netatmo Indoor Modules'. Table 2-1 provides an overview of the sensor specification.

Table 2-1 Sensor specification of used devices for Belgium.

Datalogger Model	Parameter measured	Interval of measurement	Accuracy
HOBO® U12 Temp/RH Data Logger	Temperature	-20°C - +70°C	+/-0.35°C (0°C … +50 °C)
	Relative humidity	5% - 95%	+/- 2.5 % (10% … 90 %)
Netatmo Indoor module	Temperature	0-50 °C	+/-0.3 °C
	Relative humidity	0-100 %	+/- 3.0 %
	CO_2	0-5000 ppm	not available
HOBO® MX1102A Carbon Dioxide/Temp/RH Data Logger	Temperature	0-50 °C	+/-0.21 °C (0 … +50 °C)
	Relative humidity	1-90 %	+/- 2 % (20 … 80 %)
	CO_2	0-5000 ppm	+/- 50 ppm +/- 5 % of reading at 25°C

The five cases: MEERS, HERT, EYCK, MARTENS1, HOOG are subject of the measurement campaign. As mentioned in 7.2, for reasons of personal data protection reporting on the measurements will be done with pseudonymised names: Occ_A to Occ_E randomly assigned to the cases. MEERS, HERT and EYCK are of the middle-class townhouse archetype, MARTENS1 is of the modest house archetype and HOOG is if the private mansion archetype. "HeriTACE Case-study selection at building and neighbourhood levels" (Maton et al., 2024), deliverable D5.1 of the heritace project provides a full description of the different archetypes.

Apart from the long-term measurements, the space conditioning devices and ventilation provisions were noted for nine other cases. Sizing and technical information was gathered for e.g. the heat and cold-emission elements in all rooms if available. When not available, an estimation based on the physical characteristics of the device (e.g. type and size of a radiator) was made using the 'Powerheat' tool from the Belgian centre of innovation for the construction sector (Buildwise, 2023).

2.2 Observations and data analysis

2.2.1 EPBD building temperature

The indoor temperature has a substantial impact on the building heat losses and thus the energy use. In the Belgian national EPC/EPBD calculation frameworks, the whole building volume is assumed to be isothermal with a temperature of 18°C in winter and 23°C in summer. Figure 2-1 shows the distribution of the measured volume weighted average indoor temperature during winter (Dec-Jan-Feb) and summer (Jun-Jul-Aug) for the available data. The volume weighted temperature is calculated using the following equation:

$$\theta_{vw}(t)=\frac{\sum_i V_i \cdot \theta_i(t)+\sum_i V_j \cdot \theta_j(t)}{V_{tot}} \quad (1)$$

With

$\theta_{vw}(t)$ [°C] The volume weighted air temperature

V_i [m³] The interior volume of the space where a measurement took place.

V_j [m³] The interior volume of the spaces, where no measurement took place.

V_{tot} [m³] The total interior volume of all spaces

θ_i(t) [°C] The measured indoor air temperatures

$\theta_j(t)$ [°C] Assumed indoor air temperature of the other spaces.

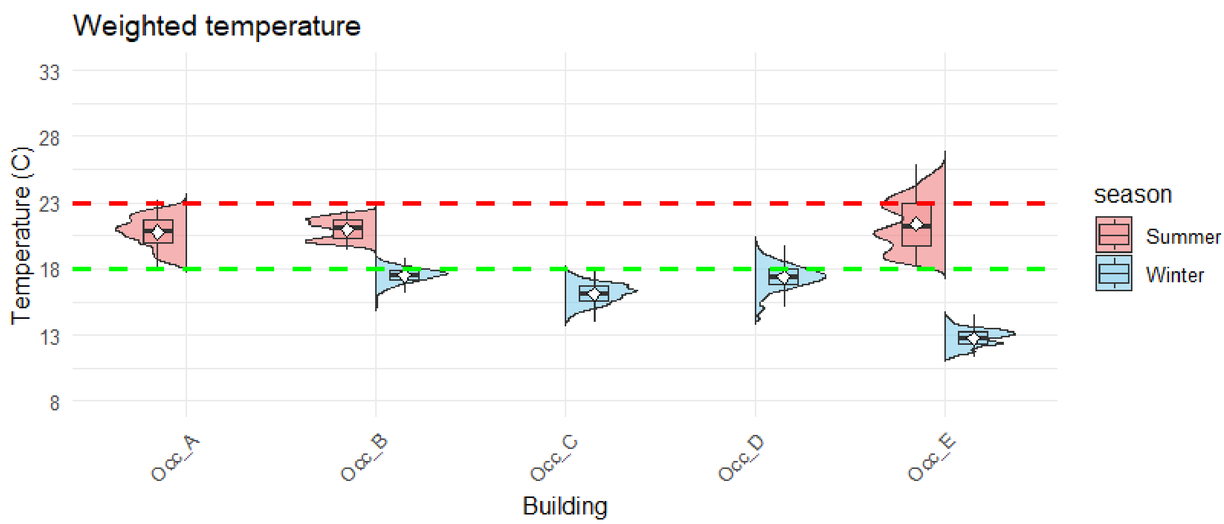


Figure 2-1 Distribution and boxplots of the building average temperature for summer (Jun-Jul-Aug) and winter (Dec-Jan-Feb) for the Belgian cases. Volume weighted temperature of all available temperature measurements of the case studies. The green dotted reference line (18°C) is the assumed winter temperature in the Belgian EPBD-EPC calculations. The red dotted reference line (23°C) is the assumed summer indoor setpoint temperature for cooling energy use.

The data shows that in all cases where winter data was available, the mean winter temperature is lower than the assumed 18°C. Furthermore, case Occ_E has a notably lower mean temperature of only 12.7 °C. In this case, substantial portions of the house had limited use that are kept unheated or minimally heated even during winter.

For the summer months, data was available for case Occ_A, Occ_B and Occ_E. In cases Occ_B and Occ_E the distribution does not have the typical bell-shape associated with normally distributed data. In Occ_E, the distribution of temperature is wider with more than 5% of the time above the EPBD reference line of 23°C. We observed that the spaces with limited use, which are coldest in winter are also hottest in summer as no action is being taken (e.g. window airing) to cool down the spaces.

2.2.2 Temperature variability

In addition to the average indoor temperature analysis before, investigating the variability of indoor temperatures in summer versus winter offers valuable insights into how occupants operate and interact with the building. Figure 2-2 shows the density plots of the indoor temperatures for the summer and winter in four main rooms of the cases. The variability within the approximately 5^{th}-95^{th} percentile is limited for the summer data in the sense that no clear dependency is observed between the temperature and the time of day - and thus the position of the sun. This behaviour can be attributed to a combination of the large available thermal mass of the buildings and passive measures taken by the occupants that keep temperatures quite moderate.

A notably different graph results from the bedroom data of case Occ_E. Here two density regions are clearly distinguishable at around 22°C and 25°C respectively, although no active cooling devices were present. At this point, no clear evidence can justify this behaviour and should be further analysed.

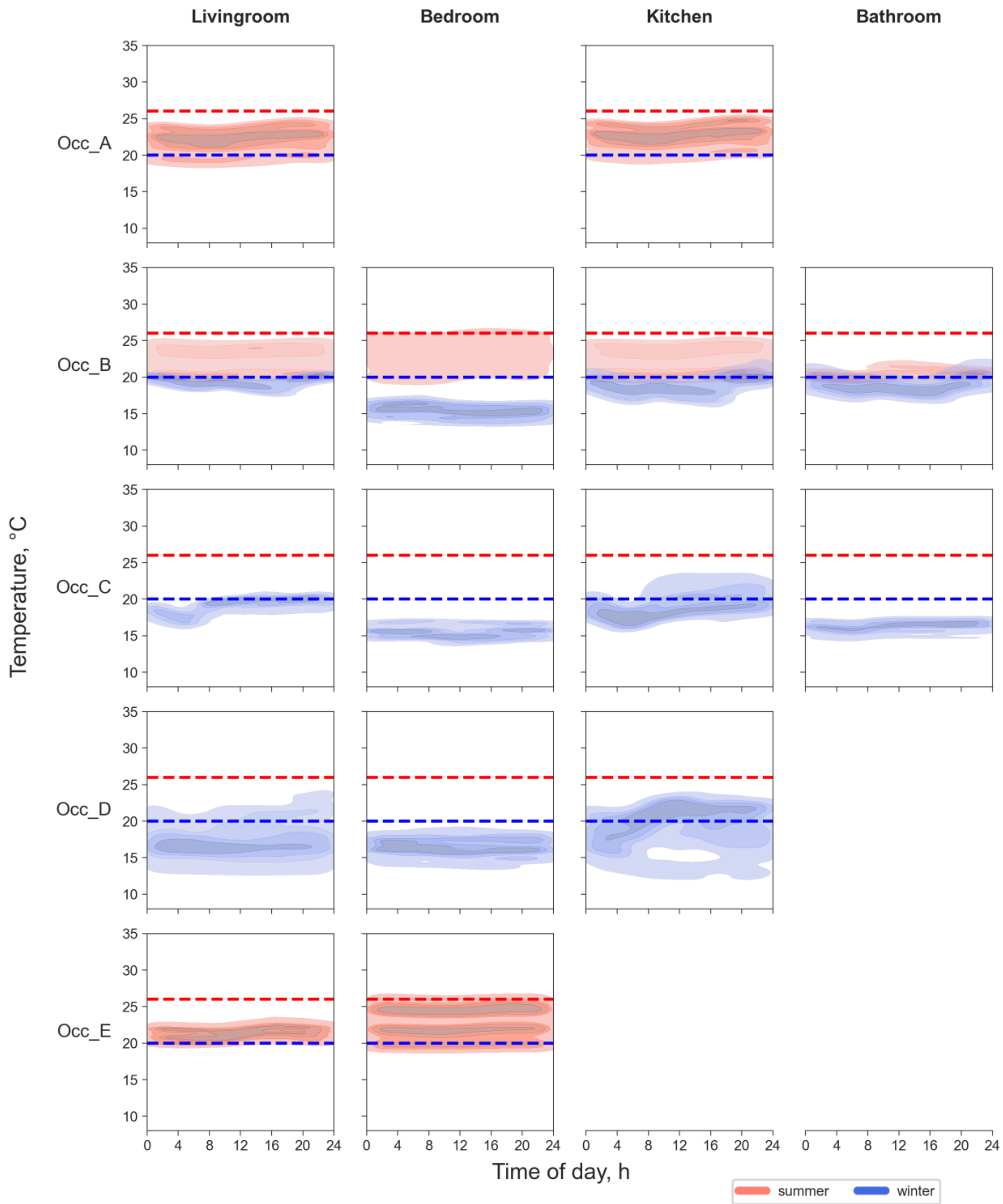


Figure 2-2 Indoor temperature distribution (density plot for approximately the 2.5th-97.5th percentile) as a function of the time of day for the Belgian cases. Display of summer (Jun-Jul-Aug) and winter (Dec-Jan-Feb) in four spaces: living, main bedroom, kitchen and bathroom. Empty slots mean no relevant data was available. The blue and red dotted reference lines are the minimum operative temperature for heating (20°C) and the maximum operative temperature for cooling (26°C), respectively for IEQ class II according to EN 16798.

When looking more in depth into the data of one case, for example Occ_B, the difference in variability can also be observed between week and weekend days. Figure 2-3 shows average, 2.5th and 97.5th percentile of temperatures occurring at a certain time of day for week and weekend days separately.

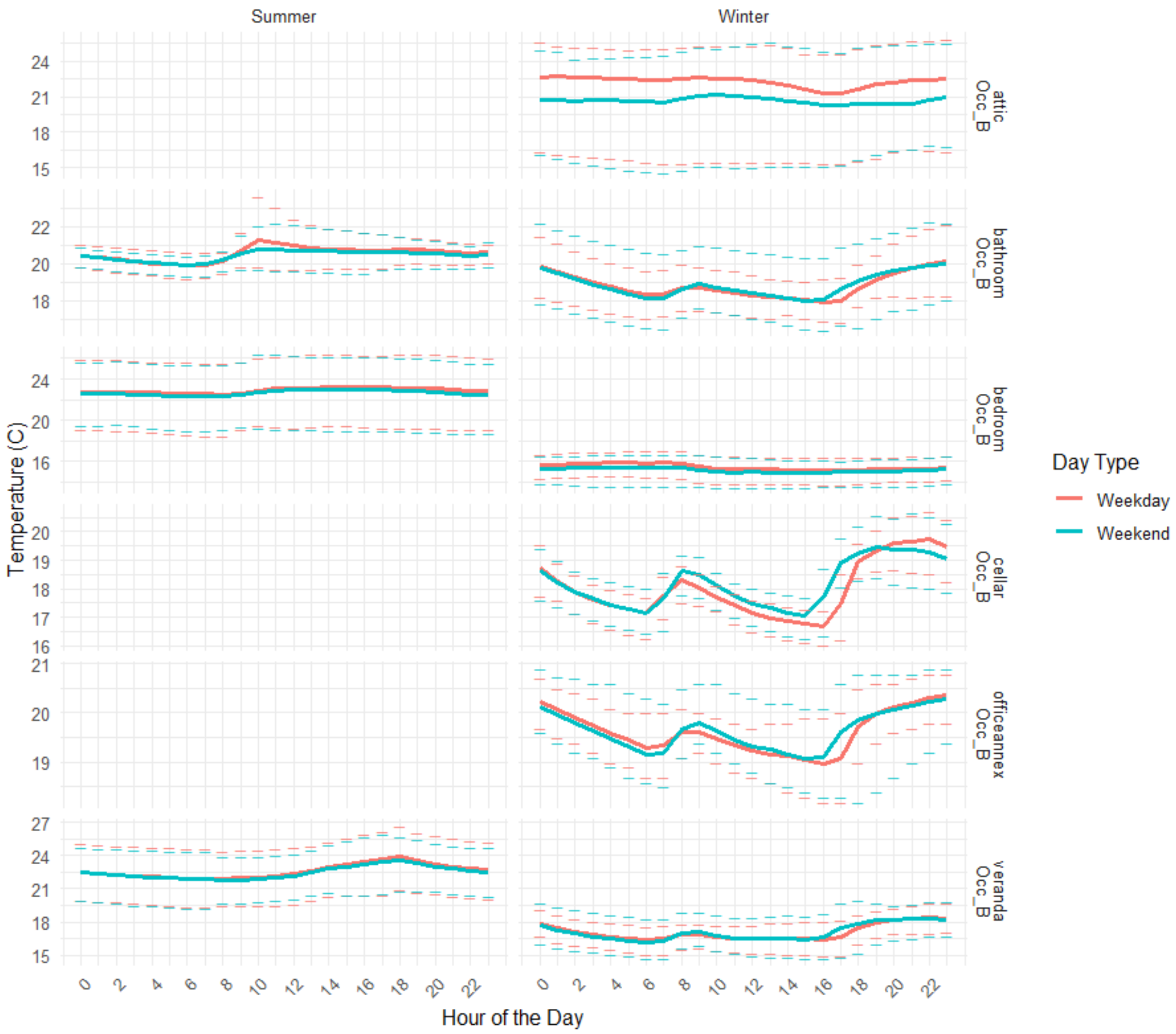


Figure 2-3 Temperature distribution in the specified rooms, comparing weekdays and weekends during summer and winter for the Belgian case Occ_B. Solid lines represent the mean indoor temperature as a function of time of day, separately for summer and winter, and for weekdays and weekends. Dotted lines indicate the 5th and 95th percentiles of the corresponding data.

From this, the dynamics of a typical temperature profile of a space can be observed. In the case of Occ_B, as well as all other cases, the difference in dynamics is limited as the occupation for week and weekend is quite constant. The temperature profiles quite clearly show that the main heating system operates for 2h in the morning and for 6h in the evening (7h in weekends). The bathroom, dining, living, kitchen, and office_annex have their radiator valve open or benefit clearly from higher temperatures in neighbouring rooms. Notably, the temperature in the office_annex rises and drops more quickly than in the other living spaces. A lower thermal mass (due to the thin walls of the annex) and more heat loss area causes this more pronounced temperature profile. The cellar also shows the same temperature profile, but this is attributed to the gas boiler being located in the cellar. The veranda is clearly a lot cooler in winter than the other living spaces, while in summer the temperatures are quite similar. Finally, the attic has quite constant and high mean and 95th percentile temperatures during winter. The attic is renovated into a separate appertement, with an occupant that has a high comfort requirement and is used to warm indoor climates.

2.2.3 Duration of heating season

In the data it is sometimes possible to pin-point when the occupants started to heat the building. This is valuable input to relate the building yearly energy needs (WP4), occupant behaviour (WP5) and comfort levels. Based on the temperature measurements of the living rooms the approximate start and end of the heating season was determined if available, as shown in Table 2-2. The derived dates and durations are still an approximation and should be treated with deliberation.

Table 2-2 Summary of the observed start and end of the heating season for the Belgian cases.

	Start	**End**	**Duration**
Occ_A	1 October	-	7 hours/day
Occ_B	1 October	-	8 hours/day
Occ_C	-	1 May	16 hours/day
Occ_D	10 September	1 May*	18 hours/day
Occ_E**	1 October	15 June	24 hours/day

- Measurements stopped before the end of the heating season of started during the heating season
* Derived from the smart meter data of 2024
** Heating system is enabled the whole year, thermostat determines when heating is on. Consequently, the demarcation of the heating season is less clear

It is clear that most of the cases have the same heating season that starts in October and ends at the end of April. Occ_D and Occ_E have slightly longer heating seasons, which could be attributed to the fact that floor heating is present. A variety in the duration of the activation of the heating system is observed, ranging from only seven hours per day, to the entire day.

2.2.4 EN 16798 Adaptive Thermal Comfort

The adaptive comfort theory and method described by the EN 16798 standard provides a valuable reference to benchmark the measurements in terms of thermal comfort (CEN, 2019). A visual representation of such analysis is shown in Figure 2-4. It shows the indoor temperatures as a function of the exponentially weighted running average outdoor temperature for the living room of Occ_B and Occ_C. The other cases have similar or more positive results.

For all cases, more than 97.5% of the measured data points fall within at least acceptability class III. Results are at the lower end of the acceptability range and have the expected horizontal trend when outdoor temperatures are low (winter) and a sloped trend when temperatures are higher (summer).

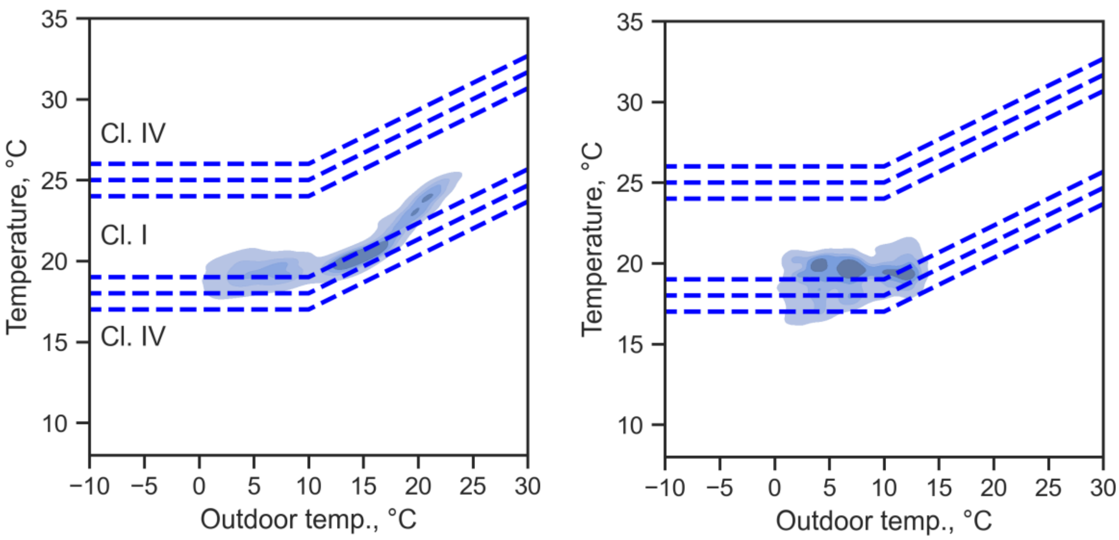


Figure 2-4 Temperature distribution of the measured indoor temperature as a function of the exponentially weighted outdoor temperature (density plot for approximately the 2.5th-97.5th percentile data) for the living room of Belgian cases Occ_B (left) and Occ_C (right). The dotted reference lines are based on the adaptive thermal comfort acceptability limits (Airspeed <0.6ms) as described in the EN-16798 standard.

The adaptability analysis is summarized in Table 2-3 by calculating the percentage of measured data assigned to a certain class (including outside, above, or below). Note that not all cases have data on all seasons. Occ_B has the most complete dataset. As expected, based on the visual analysis, no overheating issues are expected in the living rooms. A maximum of 3.3% of datapoints fall below the acceptability ranges.

Table 2-3 Percentage of datapoints in or outside adaptive temperature class for the living room, All data of Belgian cases.

% of datapoints in	Occ_A	Occ_B	Occ_C	Occ_D*	Occ_E
Hours of data considered	3600 h	7000 h	3400 h	2700 h	4200 h
Start-end of data	Jun - Oct	May - Feb	Dec - Apr	Dec - Apr	Jun - Nov
Overheating	0%	0%	0%	0%	0%
Class I	36.5%	54.8%	54.9%	73.0%	33.7%
Class II	33.2%	41.4%	27.8%	22.7%	46.0%
Class III	27.9%	3.6%	13.8%	4.0%	17.0%
Below	2.3%	0.3%	3.5%	0.2%	3.3%
***The office is considered instead of the living room, as the occupant is more present in the office.**					

Since Table 2-3 includes all measured datapoints, it also includes a large amount of datapoints without presence. Since thermal comfort relates to the occupants, it makes sense to only look at data with a higher likelihood of occupancy. We can use the CO_2 data which is available in all living rooms to only include the indoor temperature data when simultaneously the CO_2 concentration in that room is above 600ppm (or a ΔCO2 of 200ppm above outdoors assumed at 400ppm) at that time.

This will not perfectly distinguish between occupation or absence as it takes some time for a space to go above 600pmm once someone enters just like it can take some time for CO_2

values to go down when someone leaves the room. Additionally, times when substantial amounts of infiltration and airing occurs while someone is present to the level that the 600ppm is not reached will also not be in the data. So acknowledging that the 600ppm filter will not be all the data of occupation nor absence, the likelihood of someone being present at that time is much higher than just considering all the data. The results for the adaptive thermal comfort analysis filtered for CO_2 > 600 ppm are summarized in Table 2-4.

Comparing to the original table, results are generally better in terms of expected thermal comfort level in the living room. Lower percentages outside the acceptability range and higher percentages in the better acceptability ranges indicate the higher comfort level. Interventions by occupants and time-dependent controls of the heating system will lie at the basis of this improvement.

Table 2-4 Percentage of datapoints in or outside adaptive temperature class for the living room, data of Belgian cases when CO2 level is above 600ppm

% of datapoints in	Occ_A	Occ_B	Occ_C	Occ_D*	Occ_E
Hours of data considered	1000 h	2600 h	380 h	450 h	300 h
Start-end of data	Jun - Oct	May - Feb	Dec - Apr	Dec - Apr	Jun - Nov
Overheating	0%	0%	0%	0%	0%
Class I	33.9%	62.6%	82.0%	99.3%	50.6%
Class II	40.7%	36.4%	17.7%	2.1%	40.4%
Class III	26.3%	1.5%	1.9%	0.2%	9.6%
Below	0.2%	0%	0%	0%	1%
*The office is considered instead of the living room, as the occupant is more present in the office.					

2.2.5 CO_2 variability

It is interesting to look at the CO_2 concentration variability in summer versus winter to observe how the building is used and its impact on perceived IAQ is. Figure 2 shows the density plots of the CO_2 concentration for the summer and winter in four relevant rooms of the cases. For all summer cases, the variability within the 5^{th}-95^{th} percentile is limited. This is to be expected since window opening is likely.

For the winter data, the variability is higher but overall the distribution is narrow and does not change a lot as a function of time. The exception is the bedroom of Occ_C which has a high density above 1500 ppm during night hours. Secondly, in the bedroom of Occ_B an increase during night hours is visible but values are moderate. Thirdly, the office of Occ_B also shows a clear peak in the data during evening hours. Finally, the kitchen of Occ_C shows more data points with higher CO_2 concentrations around 19h related to the family dining together in the kitchen. All other data is relatively flat, indicating no distinct CO_2 concentration patterns.

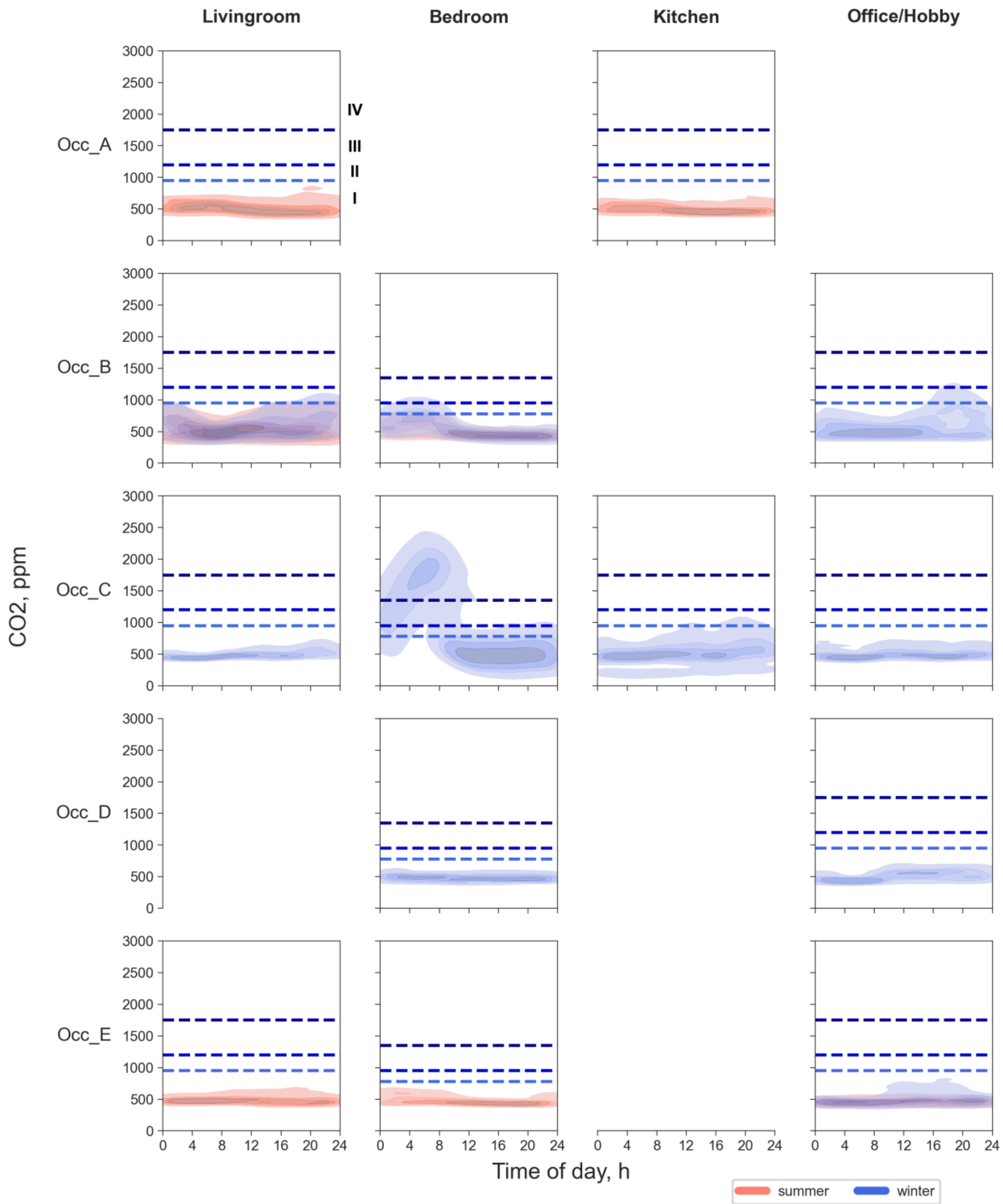


Figure 2-5 CO2 distribution (density plot for approximately the 2.5th-97.5th percentile) as a function of the time of day for the Belgian cases. Display of summer (Jun-Jul-Aug) and winter (Dec-Jan-Feb) in four spaces: living, main bedroom, kitchen and office/hobby room. Empty slots mean no relevant data was available. The blue dotted reference lines are the threshold values of the CO_2 IEQ classes according to EN-16798.

When looking more in depth into the data of one case, for example Occ_B, the difference in variability can also be observed between week and weekend days. Figure 2-6 shows average, 5th and 95th percentile of CO_2 occurring at a certain time of day for week and weekend days separately. From this, the dynamics of a typical CO_2 profile of a space can be observed. In the bedroom, the build-up of CO_2 for case Occ_B, which occurs during the night and was less distinguishable from the previous graph, is better visualised. In summer, the same pattern is visible but with lower mean and lower 95th percentile concentrations.

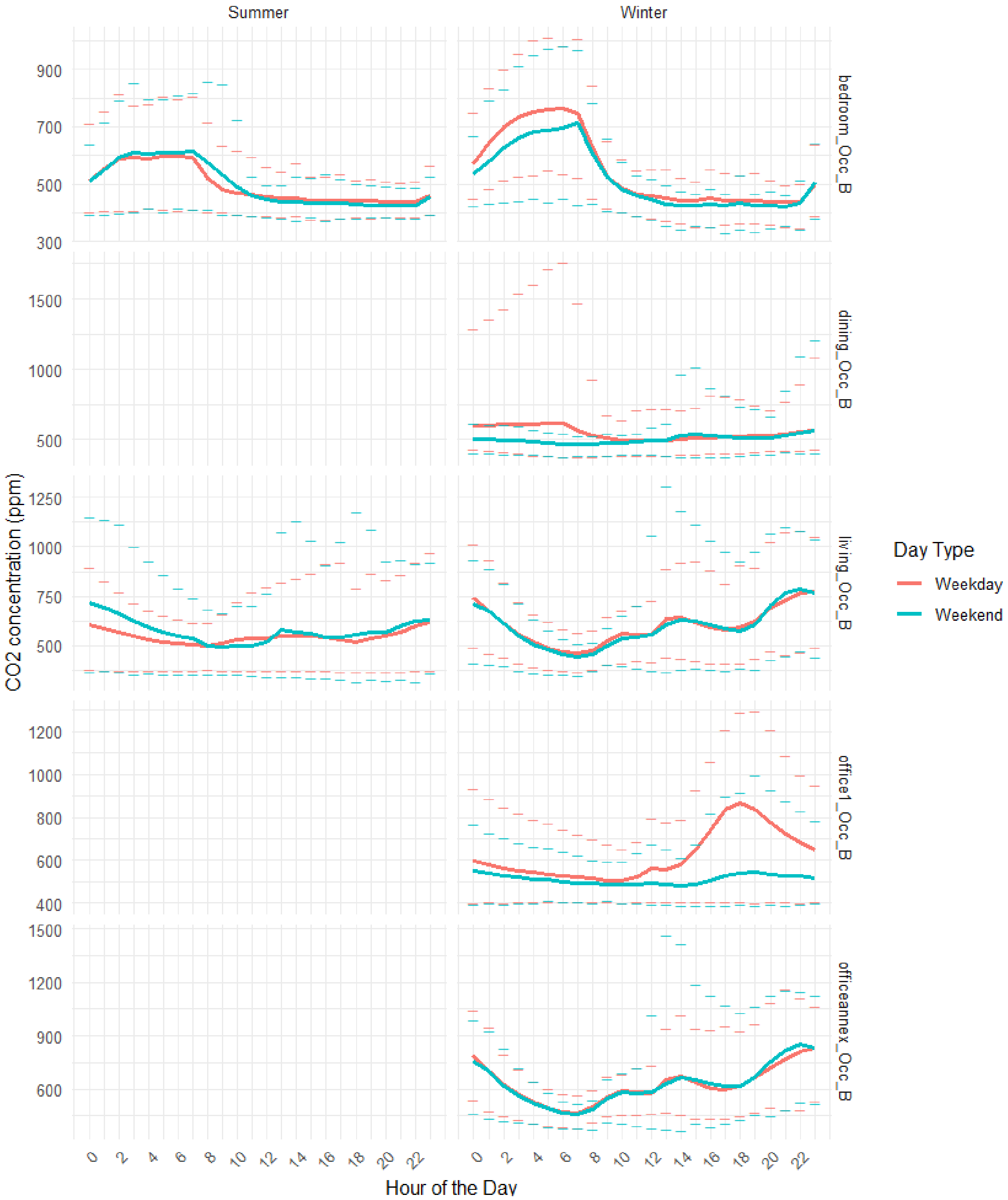


Figure 2-6 CO_2 concentration distribution in the specified rooms, comparing weekdays and weekends during summer and winter for the Belgian case Occ_B. Solid lines represent the mean CO_2 concentration as a function of time of day, separately for summer and winter, and for weekdays and weekends. Dotted lines indicate the 5th and 95th percentiles of the corresponding data.

In the office, there is a distinct pattern in the mean concentration with a peak during the evening hours on weekdays. In weekends, the mean concentration doesn't show this pattern but the 95th percentile shows the same pattern. This indicates that also during weekends, the office is used but less intensive as during the week. For the dining room, the 95th percentile indicates that on a regular basis (>5% of weekdays), also here a build-up of CO_2 occurs. This kind of analysis can be done for all CO_2 data and will give valuable input to later tasks of the HeriTACE project.

2.2.6 EN 16798 IEQ categories

The EN16798-1:2019 standard describes a classification system for IEQ. One aspect is based on perceived air quality and expressed as limit values for CO_2 above the outdoor air concentration. We used the suggested design ΔCO_2 concentration in Table B.12 of the EN16798-1:2019 to define the limits of the IEQ-classes in our analysis. Since the CO_2 dataloggers self-calibrate to 400ppm as outdoor air concentration, the limit values can be expressed as absolute measured values, an overview in Table 2-5.

Table 2-5 Limit values for the perceived air quality IEQ classes classification expressed as absolute values (assuming 400ppm)

	Level of expectation	Living rooms [ppm]	Bedrooms [ppm]
Category I	High	950	780
Category II	Medium	1200	950
Category III	Moderate	1750	1350
Category IV	Low	>1750	>1350

Figure 2-7 shows the distribution of CO_2 as a function of outdoor temperature for the living room of case Occ_A and case Occ_B The top half of the contour of the plot is most interesting to look at in this case as this will represent a situation that will occur at least 5% of the time and the spaces will be occupied at this time. Good IAQ management will be able to keep this value below the design criteria.

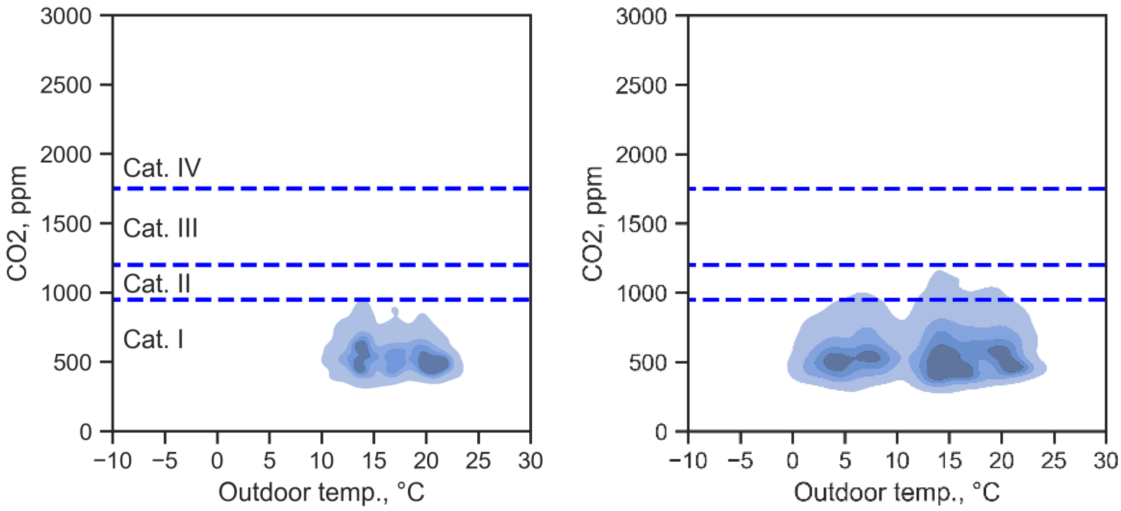


Figure 2-7 Distribution of the measured CO2 as a function of the exponentially weighted outdoor temperature (density plot for approximately the 2.5th-97.5th percentile data) for the living room of Belgian cases Occ_A (left) and Occ_B (right). The dotted reference lines are the limits of the IEQ categories.

The two plots are the two worst examples of all results and still, the 95th percentiles do not go above the category II limit, which would be the typical target level for residential units.

Interestingly, no clear relationship between CO_2 concentration and outdoor temperature seems to be present while we might expect a reverse correlation with outdoor temperature.

The IEQ-classes analysis was done for the living rooms of all cases. Each day in the dataset was assigned a category based on its 97.5th percentile CO_2 concentration value. The percentage of days of the living room in a certain category is shown in Table 2-6.

Table 2-6 CO_2 based IEQ categorisation for the living rooms of all Belgian cases

% of days in Cat. #	Occ_A	Occ_B	Occ_C	Occ_D*	Occ_E
Days in dataset	154 days	294 days	149 days	113 days	177 days
Start-end of data	Jun - Oct	May - Feb	Dec - Apr	Dec - Apr	Jun - Nov
Category I	90%	77%	100%	97%	100%
Category II	8%	17%	0%	3%	0%
Category III	1%	4%	0%	0%	0%
Category IV	0%	2%	0%	0%	0%
***The office is considered instead of the living room, as the occupant is more present in the office.**					

The same analysis can be done for the bedrooms. Figure 2-8 shows the two worst results of all cases. Nevertheless, do the results for case Occ_B show that almost all datapoints lie within IEQ category I. The results of Occ_C deviate from all others with substantial amounts of datapoints in category IV. This is in line with the results of the CO_2 variability that showed high CO_2 levels during night hours.

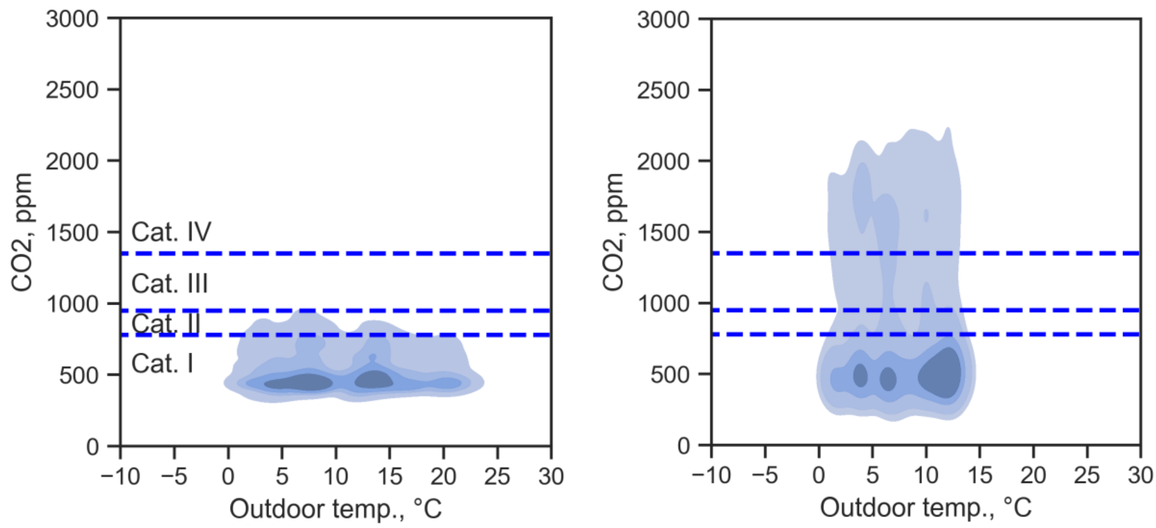


Figure 2-8 Distribution of the measured CO2 as a function of the exponentially weighted outdoor temperature (density plot for approximately the 2.5th-97.5th percentile data) for the bedrooms of Belgian cases Occ_B (left) and Occ_C (right). The dotted reference lines are the limits of the IEQ categories.

Table 2-7 presents the overview of days in a certain IEQ category for all main bedrooms. Overall the results are good, with low percentages in category III and IV. As expected, Occ_C shows that in 80% of registered nights, the bedroom CO_2 concentration exceeds the 1350 ppm threshold.

Table 2-7 CO2 based IEQ categorisation for the main bedrooms of all Belgian cases.

% of days in Cat. #	Occ_A	Occ_B	Occ_C	Occ_D	Occ_E
Days in dataset	89 days	294 days	103 days	112 days	177 days
Start-end of data	Mar - May	Apr - Feb	Dec - Apr	Dec - Apr	Jun - Nov
Category I	75%	73%	17%	99%	99%
Category II	19%	24%	3%	0%	0%
Category III	6%	5%	0%	1%	1%
Category IV	0%	0%	80%	0%	0%

2.2.7 Relative humidity variability

The relative humidity of a space has an influence on perceived comfort of the occupant: both low and high RH values are considered discomfortable. The ideal RH is around 50% with margins of 10-20% considered good.

Figure 2-9 shows an overview of the relative humidity data in 4 relevant spaces. The difference between summer and winter relative humidity levels, related to outdoor conditions, is truly clear and as expected. Although variability is high, overall, no serious discomfort issues are expected.

The first exceptions are the living room of Occ_A and Occ_E, with a larger part of the data above the 70% RH limit, for these spaces the moisture load should be investigated further. One possible explanation is that both living rooms are located beneath the street level with colder average indoor temperatures in summer, low expected infiltration airflow rates and possibly vapor ingress from the soil.

The second exception is the kitchen of Occ_C with larger parts beneath the 30% RH range. Looking at the temperature variability, this can be explained by the occurrence of relatively high temperatures in winter. In general, only living rooms seem to be critical in summer. This can be explained by a combination of two effects: (1) Outdoor air has high absolute humidity levels in summer, when this enters the cooler building (which is the case in summer in the Belgian townhouses), this results in high background relative humidity levels. (2) When its warmer outside than inside, windows will stay closed although people are emitting moisture in the space, leading to the higher RH levels.

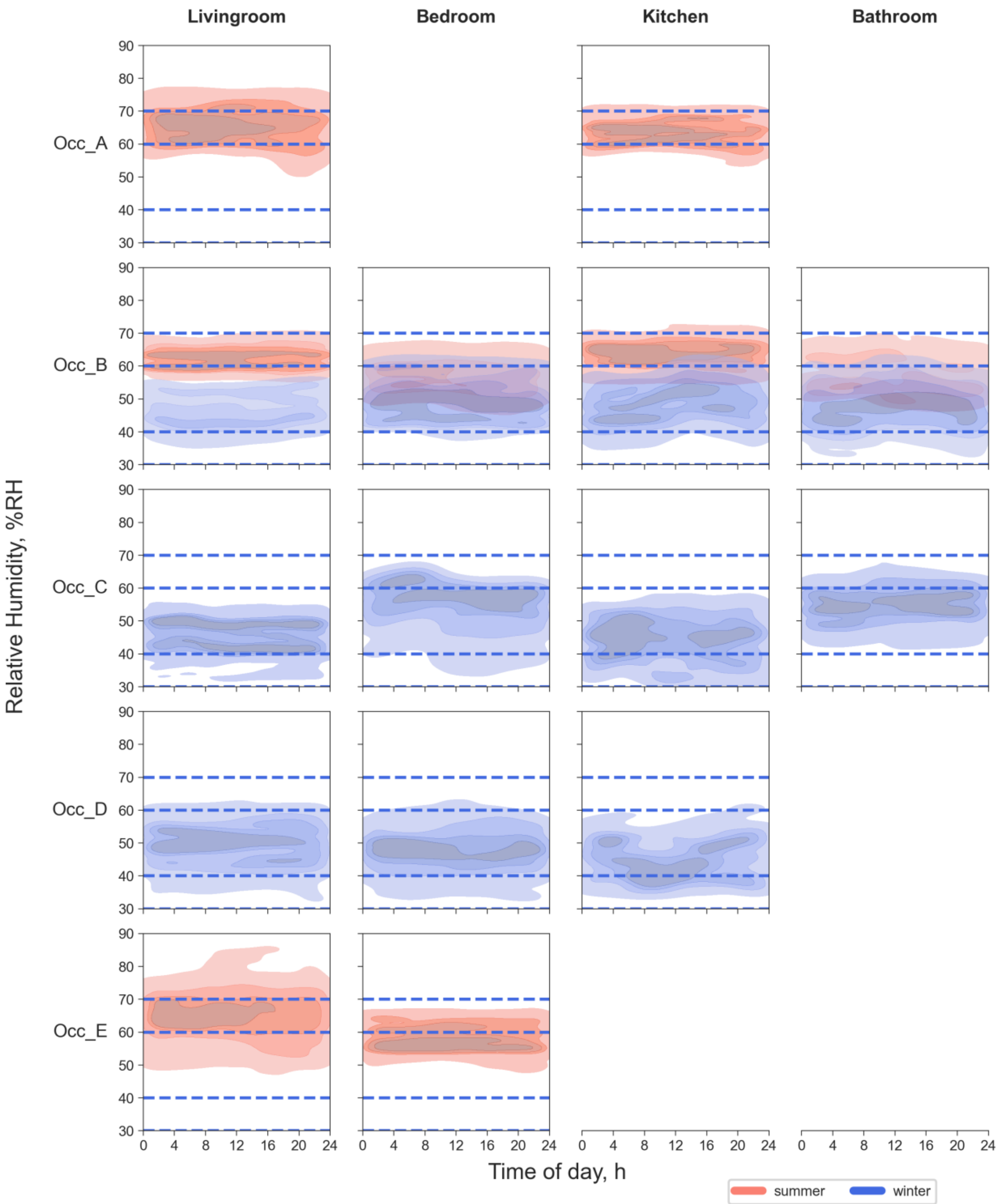


Figure 2-9 Relative humidity distribution (density plot for approximately the 2.5th-97.5th percentile) as a function of the time of day for the Belgian cases. Display of summer (Jun-Jul-Aug) and winter (Dec-Jan-Feb) in four spaces: living, main bedroom, kitchen and bathroom. Empty slots mean no relevant data was available. The blue dotted reference lines at 30-40% and 60-70% indicate typically used intervals considered to be perceived as comfortable by people.

2.2.8 Internal humidity classes

The Internal humidity classes methods described in EN ISO 13788:2012 (CEN, 2012) can be used to classify the internal humidity load of a space from class 1 (low internal humidity load) to class 5 (high internal humidity load). This is an important boundary condition for moisture related problems like mold growth on a thermal bridge or internal condensation on a wall. According to the standard, dwellings usually lie within class II.

Figure 2-10 to Figure 2-12 show the moisture excess at any given time as a function of the exponentially weighted outdoor temperature. The blue dotted lines indicate the different internal humidity classes.

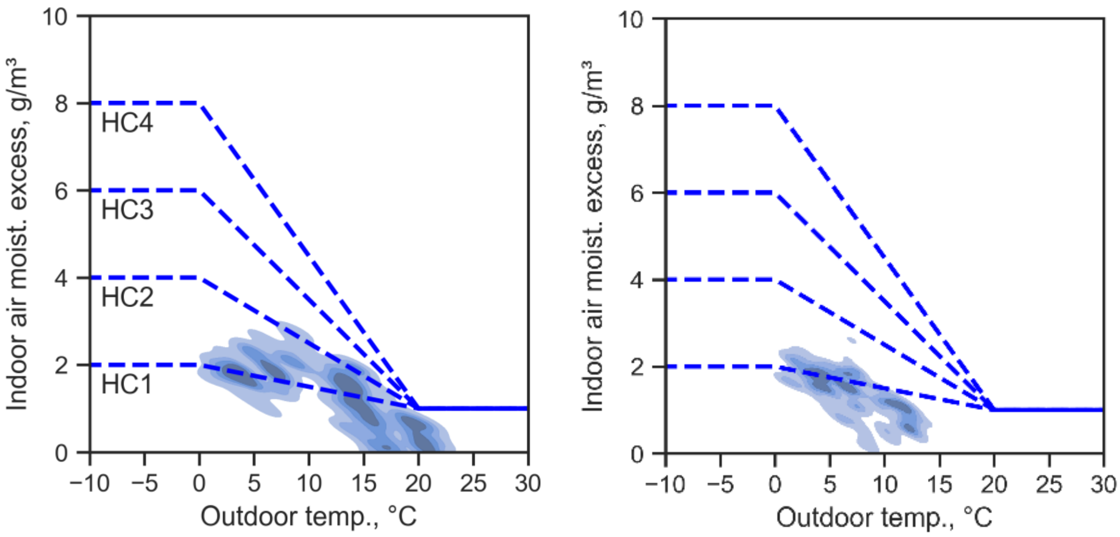


Figure 2-10 Weekly average indoor air moisture excess distribution as a function of the exponentially weighted outdoor temperature (density plot for approximately the 2.5th-97.5th percentile data) for the living room of Belgian cases Occ_B (left) and Occ_C (right). The dotted reference lines represent the threshold values defined by the internal humidity classes as described in the EN ISO 13788:2012 standard.

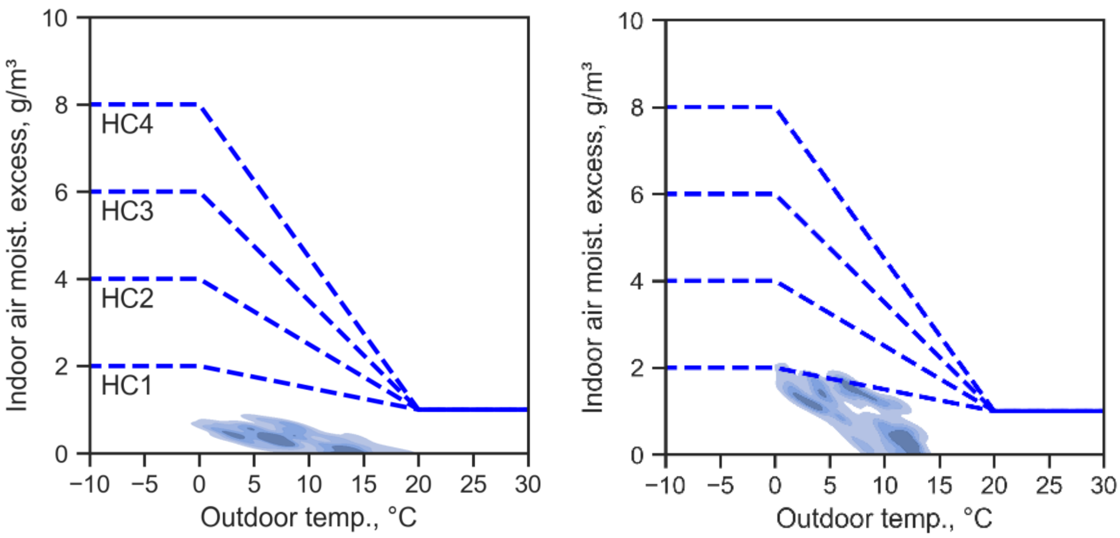


Figure 2-11 Weekly average indoor air moisture excess distribution for the bedrooms of Belgian cases Occ_B (left) and Occ_C (right).

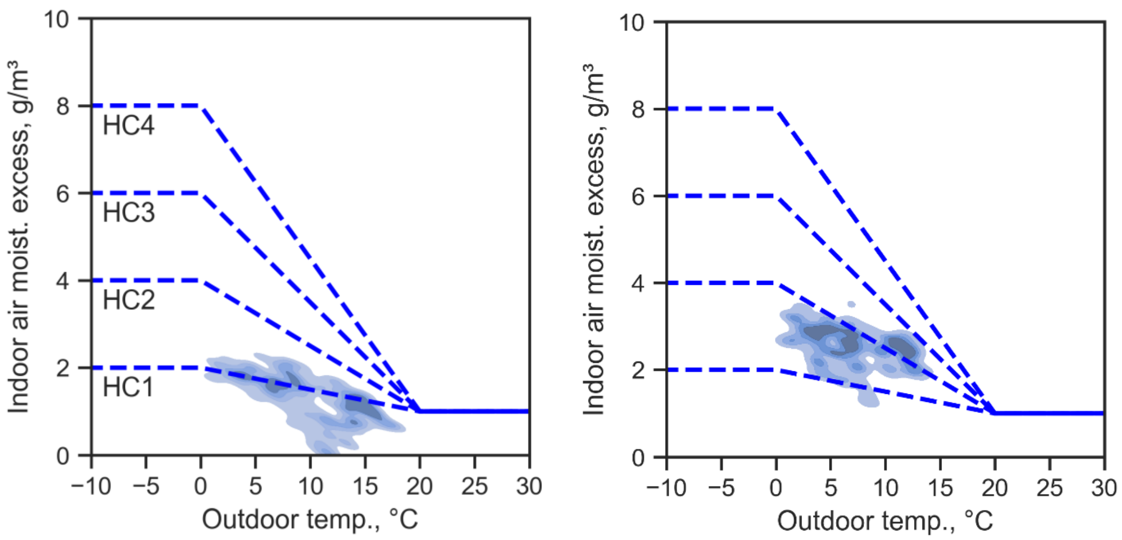


Figure 2-12 Weekly average indoor air moisture excess distribution for the bathrooms of Belgian cases Occ_B (left) and Occ_C (right).

Based on the figures, a certain internal humidity class was assigned to the space. Table 2-8 summarizes the data for all Belgian cases for the three most relevant rooms. Given the current state of the building and habits of the occupants in terms of heating and airing, bedrooms fall within class I while the Living rooms mostly fall within class II. Also, the bathroom of Occ_B falls within class II with a similar moisture excess distribution as the living room in the same case. The bathroom of Occ_C has the highest recorded humidity class, class III.

Table 2-8 Internal humidity classification of the worst bathroom, main bedroom and living rooms for the Belgian cases.

	Bathroom*	**Main bedroom**	**Living**
Occ_A	Class 1	Class 1	Class 2
Occ_B	Class 2	Class 1	Class 2
Occ_C	Class 3	Class 1	Class 2
Occ_D		Class 1	Class 2
Occ_E		Class 1	Class 1
***Worst condition bathroom if more present in the building**			

2.2.9 Insights

Considering the whole dataset, observations on-site and the in-depth analysis done in the previous parts, this section aims to conclude and summarize overall findings. Critical to the conservation of these heritage townhouse buildings, is to not burden the structural integrity of the building, as such repairs and replacements can be avoided. This goes hand in hand with providing a healthy and comfortable indoor environment as habitation aids in conservation.

2.2.9.1 Indoor Air Quality and window opening

For the Belgian cases we found the IEQ levels for perceived air quality quite good ('medium') and better than hypothesized initially. However, the good IEQ will come hand in hand with a high energy demand.

For example, to keep CO_2 levels to the low levels we found in the bedrooms without a ventilation system, either window opening occurs or the windows are very leaky with large natural uncontrolled infiltration airflow rates as a consequence. In D2.1 of the HeriTACE project, the low airtightness of the buildings is measured and indeed found to be poor.

In the bedroom of Occ_C, which has different CO_2 variability and higher IEQ classifications, the windows were already replaces with new harmonizing windows. Together with other interventions, replacing the windows will have resulted in better airtightness then the other cases. The impact of energy saving measures - like airtightness improvement - without considering the indoor environment can easily shift the IEQ class from 'good' or 'medium' to 'low'. This would be an argument to attribute the low CO_2 levels only to a low airtightness. However, some occupants have reported to always sleep with their window open. It is not possible to derive the difference between air leakages and intentional window opening from the data. What can be noted, is that there is never an inverse correlation between outdoor temperatures and CO_2 levels, which indicates that the way the bedrooms are aired (be it window opening or through leakages) is not season-dependent.

2.2.9.2 Sufficiency, thermal mass, and spatial temperature distribution.

It's well-known that the occupant has a significant impact on the building energy use. In the cases that are monitored, it is clear that all occupants operate their houses with energy savings in mind. In bedrooms for example, temperatures of around 15°C all-day in winter are common in all the cases. This is lower than the current design temperature of 18°C. On further investigation, it is not that the heating power of the installation that is insufficient, but it really is the occupants closing the radiator valves as they feel higher temperatures are not necessary in a bedroom. Idem for the hallways, where the heating system is only used to reach a minimum temperature when needed, although there is a possibility to heat them appropriate.

Bathrooms exhibit two types of use. Either they are also not heated (winter temperatures of around 15°C) or only heated during certain periods of use. In case Occ_B the bathroom seems to be coupled to the central thermostat which activates the heating only 2h in the morning and 6-7h in the evening.

Nevertheless, temperature set-points in the main residence spaces are mostly kept just above the lower class I boundary. Only Occ_C reported to, intentionally, allow lower set-point temperatures to also be sufficient in energy use. This explains the percentages in lower thermal IEQ classes, however, a sizeable portion of the data is still in IEQ class I.

There is also a difference to be seen between the main building volume and the annexes. The annexes are typically built with lighter and thinner brick walls, so less thermal mass, and less thermal resistance. These annexes will be critical spaces in terms of HVAC design.

Looking closer at the summer data, it seems that interventions like opening windows and natural shading (by other buildings or trees) make it possible to have little to no overheating. This is also due to the large thermal mass of the buildings which dampens external disturbance (e.g. sun entering the building, couple of hours extremely hot outside) so much that interior temperatures do not rise to high levels. In Belgium, even in summer, the temperatures at night are below 20°C, allowing to cool down the building to be able to buffer higher temperatures the day after.

The only problematic spaces in the buildings with regards to overheating are the attics. The attic, often in use as bedrooms, do not benefit from large thermal mass or shading and have a large part of its envelope connected to outside. Additionally, thermal buoyancy within the building will drive hot air towards the attic. This all leads to higher temperatures in the attics throughout the year and overheating risks in summer. In one of the cases, active cooling (air conditioning) was installed in the attic to cope with these higher temperatures.

2.2.9.3 Moisture

Alongside the temperature levels and perceived (CO_2) air quality discussed earlier, the relative humidity levels and moisture excess levels are investigated, as they are evenly important for the environmental quality and the prevention of damage to the building.

In general, Figure 2-9 illustrates that relative humidity levels will be perceived as comfortable in most spaces, all of the time. Some higher or lower humidity levels can be observed, as a consequence of the typical (sufficient) user behaviour. Summer is found to be more critical than winter. Again, the actions of occupants are critical here: higher RH levels are accepted if the alternative is higher indoor temperatures related to the window opening at that time.

When investigating possible damages to the building itself as a result of undesirable hygro-thermal conditions, it is not the relative humidity levels as such that is important. The more critical parameter is the absolute outdoor-indoor moisture level difference. The measured levels, in current condition, are quite good given the lack of a ventilation system. Nevertheless, a bathroom at class III was recorded which puts it in a higher internal humidity class then the standard would assume for residential use.

Also notable is the fact that within one building, a variety of humidity classes can be found. This indicates that different building lay-outs can have a significant impact on the expected damages. E.g. a bathroom at the rear of the building, not connected to the valuable façade will be more desirable then vice-versa. When working on the building envelope, making it more airtight will increase the internal humidity load. A well-design ventilation system should be able to counter this effect.

2.3 Space conditioning and IAQ management

For the five cases where long time measurements were carried out, a detailed inventory of the space conditioning systems present in those dwellings was carried out. In Table 2-9, the focus is on the distribution and emission systems (with the corresponding control system), alongside with the ventilation systems. The overview of the energy systems can be found in ‘D4.1 R²ES-Based Energy Supply Concepts for Heritage Buildings in Historical Neighbourhoods’.

The five considered cases feature a conventional central heating system with a hydronic distribution network, using radiators, sometimes supplemented by underfloor heating. Control is generally uniform: a standard living room thermostat regulates the entire system, shutting it off once the living room reaches the setpoint temperature. Thermostatic radiator valves, present in four of the five cases, enable local temperature control. A night setback is applied in four cases, with an additional daytime setback in three. Only one dwelling includes a cooling system (a local air conditioning unit); the others lack cooling entirely. Central mechanical ventilation is absent in all cases, though local exhaust systems in bathrooms and toilets are more common.

Apart from the 5 case-study buildings where the detailed measurements took place, 9 other townhouse buildings that correspond to the archetype were visited to catalogue the space conditioning system. Table 2-10 and Table 2-11 provide an overview of the gathered information in the additional cases.

These additional case studies reinforce the findings from the initial five monitored cases: this type of townhouse is typically equipped with a hydronic central heating system, where radiators—occasionally supplemented by fan coil units—provide space heating. A central thermostat and thermostatic radiator valves are commonly used to regulate room temperatures. However, across these nine additional cases, some smart thermostatic valves were observed, enabling zonal temperature control. In cases where control settings were examined, night setback was consistently applied, and daytime setback was also common. Cooling remains an exception, with only one further case featuring air conditioning units. Similarly, central ventilation systems are rare. Only one extensively renovated case included mechanical extract ventilation, primarily serving the refurbished section. In the remaining cases, local extraction in bathrooms and toilets was more prevalent, though not always working as expected. Kitchen range hoods were present in nearly all cases.

From these observations, several insights can be drawn regarding baseline configurations for this type of townhouse, which are discussed in the following chapter. Notably, there appears to be little distinction between extensively renovated dwellings and those largely in their original state. Another striking finding is the limited adoption of central ventilation systems in Belgian townhouses. While mandatory in new builds and deep energy renovations, less stringent requirements apply to standard renovations. Regarding ventilation, additional air supply vents are only required when windows are replaced. Heritage regulations introduce further exemptions: listed monuments and buildings in protected cityscape are entirely exempt from ventilation requirements, and buildings on the inventory of ascertained built heritage are not obliged to include air supply openings when replacing windows visible from public roads.

Nevertheless, local extraction is frequently provided, despite not being a legal obligation.

Table 2-9 Overview of space conditioning installations for MEERS, HERT, EYCK, MARTENS1 and HOOG

Building code			MEERS	HERT	EYCK	MARTENS1	HOOG
Heated area, m²			239.67	327.79	331.12	202.70	523.27
Archetype			MCT	MCT	MCT	Modest house	Private mansion
Distribution	Heating	central/local	Central				
		Transport medium	Hydronic				
		Type of distribution system	Two-pipe				
	Cooling	central/local	n/a	n/a	Local	n/a	n/a
		Transport medium	n/a	n/a	Refrigerant	n/a	n/a
		Type of distribution system	n/a	n/a	Two-pipe	n/a	n/a
Emission	Heating	Main type	Radiators	Radiator	Radiators	Radiators floor heating	Radiators floor heating
		total installed power, W	31932	31672	43823	36691	58597
	Cooling	Main type	n/a	n/a	Aircond.	n/a	n/a
		total installed power, W	n/a	n/a	21500	n/a	n/a
	Ventilation	Central ventilation system	n/a				
		Bathroom extraction, m³/h	22	250	n/a	Yes (not detectable)	n/a
		Toilet extraction, m³/h	n/a	n/a	n/a	n/a	Carbon filter
		Range hood, m³/h	n/a	200	180	Carbon filter	2000
	Temperature control	Control type	Central thermostat	Central thermostat Thermostatic valves	Central thermostat, Thermostatic valves	Central thermostat, Thermostatic valves	Zonal control with multiple thermostats, Thermostatic valves
		Night setback, °C	3	5	5	4	0
		Day setback, °C	3	4	No setback	No setback	No setback

Table 2-10 Overview of space conditioning installations for KONING, CITADEL, KEIZER, MARTENS and MUINK

Building code			**KONING**	**CITADEL**	**KEIZER**	**MARTEN.**	**MUINK**
Heated area, m²			225.98	226.94	254.66	341.604	385.15
Archetype			MCT	MCT	MCT	MCT	Private mansion
Distribution	Heating	central/local	Central				
		Transport medium	Hydronic				
		Type of distribution system	Two-pipe				
	Cooling		n/a				
Emission	Heating	Main type	Radiators	Radiator	Radiators	Radiators	Radiators Fan coil units
		total installed power, W	29 226	19 096	24 957	42 579	61 753
	Cooling		n/a				
	Ventilation	Central ventilation system	n/a	n/a	n/a	Demand controlled MEV	n/a
		Bathroom extraction, m³/h	n/a	n/a	53	89	Yes (not detectabl e)
		Toilet extraction, m³/h	15	n/a	n/a	7	Yes (not detectabl e)
		Range hood, m³/h	Yes	Yes (not used)	Yes	249	1500
	Temperature control	Control type	Central thermosta t Thermost atic valves	Central thermosta t Thermost atic valves	Central thermosta t, Thermosta atic valves	Zonal control via smart thermosta tic valves	Clock, thermosta tic valves
		Night setback, °C	-	4.5	-	5	-
		Day setback, °C	-	No setback	-	5	-

Table 2-11 Overview of space conditioning installations for KUIPER, BREDERODE, KDENDER and MUINK2

Building code			KUIPER	BREDERO.	DENDER	MUINK2
Heated area, m²			n/a			
Archetype			MCT	Modest house	Private mansion	MCT
Distribution	Heating	central/local	Central			
		Transport medium	Hydronic			
		Type of distribution system	Two-pipe			
	Cooling	central/local	n/a			Local
		Transport medium	n/a			Refrigerant
		Type of distribution system	n/a			Two-pipe
Emission	Heating	Main type	Radiators Fan coil units	Radiator	Radiators Fan coil units	Radiators
		total installed power, W	24 238	-	-	23 148
	Cooling	Main type	n/a			Aircond.
		total installed power, W	n/a			-
Ventilation		Central ventilation system	n/a			
		Bathroom extraction, m³/h	140	Yes	Yes	Yes
		Toilet extraction, m³/h		Yes	n/a	-
		Range hood, m³/h	-	Yes	Yes	-
Temperature control		Control type	Central thermostat	Central thermostat Thermostatic valves	Central thermostat, Smart thermostatic valves	Central thermostat Thermostatic valves
		Night setback, °C	-	4.5	5	3
		Day setback, °C	-	4.5	5	3

2.4 Defining space conditioning pre-renovation baselines and renovation baselines

Finally, based on the observations made in the case-study buildings and taking into account expertise and experience of Ghent University, the city of Ghent and SWECO on renovation of heritage buildings, for each Belgian townhouse archetype as described in 'D5.1 Case-study selection at building and neighbourhood levels' (Maton et al., 2024), a pre-renovation and renovation baseline for space conditioning is derived. The pre-renovation baseline is the condition in which these types of buildings were before the introduction of EPBD regulations (situation in '90-'00). The renovation baseline is the condition of these type of buildings as if they would be renovated today. In this report, only the baseline scenarios regarding the space conditioning systems (emission, distribution, and ventilation part of the HVAC systems) are described. The complete baseline scenarios (including heritage value, building envelope, energy systems and use scenarios) will be described in 'D5.4 Baseline scenarios'.

2.4.1 Pre-renovation baseline

In all Belgian archetypes, a similar hydronic radiator heating system is the obvious choice for the space conditioning pre-renovation baseline. There is no need to make a distinction between the different archetypes.

For this baseline, these townhouses are all equipped with a central hydronic heating system. Each heated space (cellar and attic are not heated) is equipped with high-temperature radiators. They are designed to deliver the full heating power at a certain steady state outdoor temperature with a nominal temperature supply of 90°C and a delta of around 20°C, or in other words: a regime of 90/70/20. In Ghent, -8°C would be the design steady state outdoor air temperature. A wood-based fireplace is present in the living room.

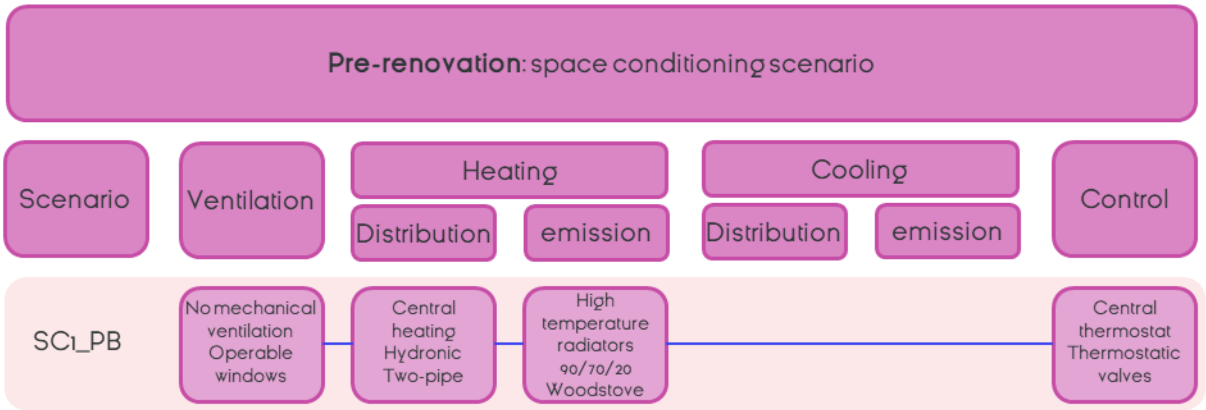


Figure 2-13 Schematic overview of the Pre-renovation Baseline (PB) Space Conditioning (SC) scenario for the Belgian archetypes.

In the living room, a central thermostat decides to either activate or deactivate the whole heating system using a typical on-off controller with a bandwidth of 1°C around the set-point temperature. As a secondary controlling element, each radiator is equipped with an analogue thermostatic radiator valve. These valves limit the flow through the radiator to adjust the actual emission power when the room temperature is close to the set-point.

A cooling system or whole building (mechanical) ventilation system is not present. To air the spaces openable windows are present in all rooms. In the kitchen, a rangehood that vents to the outside is proposed but is only used while cooking a hot meal, around once a day.

In Figure 2-13, an overview of the pre-renovation space conditioning baseline for all the archetypes is given.

Additionally, a comfort baseline is proposed, consisting of a schedule of the temperature settings for space heating and cooling. This baseline is not entirely based on the observations of the measurements, as the habitants of the case study buildings clearly choose to live with lower setpoint temperatures and lower comfort expectations (as discussed in 2.2.9). This will be further investigated in T3.4. Instead, a typical and realistic heating schedule is proposed for the baseline, presuming a high comfort level and all the rooms that are used being heated. These values are based on the design operative temperatures for category II in EN 16798-1:2019, the work of Verbruggen (Verbruggen et al., 2021b, 2021a) and the observations from the measurements.

The living room is heated to a setpoint of 20°C during the day. During the night, a setback of 5°C is applied, decreasing the setpoint to 15°C. The thermostat in the living room determines the working of the central heating system, so when there is a setback in the living room, there is de facto also a setback in the other rooms. By using the thermostatic radiator valves, the setpoint temperatures in the other rooms can be determined as well. The bedrooms will be heated to a setpoint of 18°C during the day, the hallways to a setpoint of 16°C. The veranda is also assumed to be heated to 16°C during the day, as this room is not really part of the living spaces during the winter, but rather a buffer between inside and outside. The bathroom is heated to a setpoint of 24°C, but only when it is in use. During a few hours in the morning and in the evening, the temperature is set to 24°C, the other hours, the valve is closed, so a setpoint temperature of 18°C is reached.

The temperature setpoints, as shown in Figure 2-14, are the same for each day of the week, including the weekend.

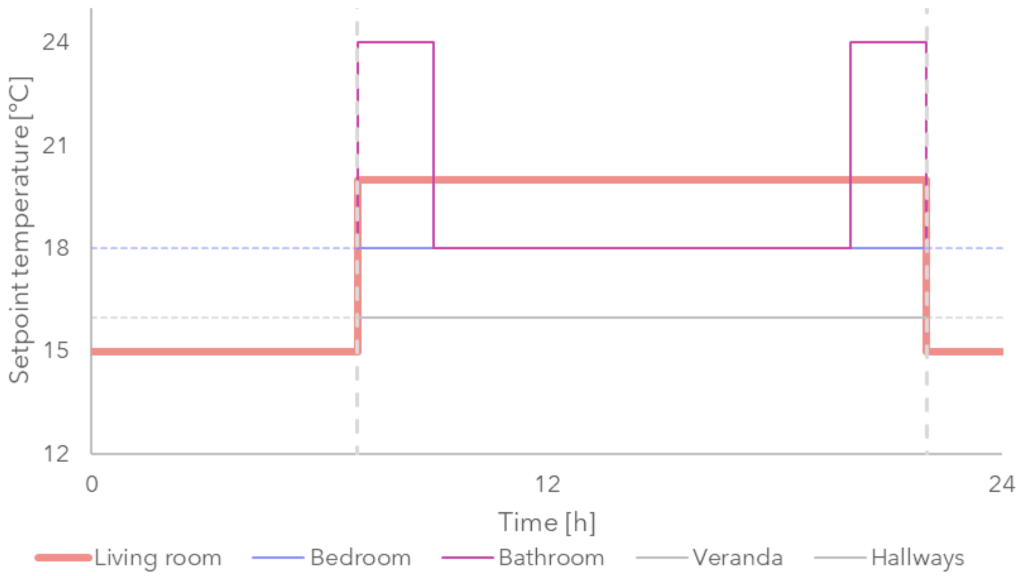


Figure 2-14 Pre-renovation baseline setpoint temperature overview for the Belgian archetypes.

2.4.2 Renovation baseline

As the pre-renovation space conditioning baseline in all archetypes are similar, also how these are renovated is similar. More variation in the renovation strategy can be expected, especially given the new functions these buildings can get after renovation. The proposed renovation baseline scenario is the following (see Figure 2-15):

First, as can be observed in the case study buildings, the existing high-temperature radiators are preserved where possible, still equipped with the analogue radiator valve. Due to the renovation, the supply temperature can be lowered, so that these radiators provide the necessary heating power of that room with a supply temperature of 75°C and a delta of around 10°C, a temperature regime of 75/65/20. Outdoor design conditions have been revised so a higher outdoor temperature can be selected in the design. For Ghent, this would be -7°C for example. In the case that new rooms become heated (e.g. the attic is renovated to become a bedroom) or that the whole building use changes (a single-family house becomes a multi-family house or an office), new radiators are installed, again with a temperature regime of 75/65/20. A wood-based fireplace is still present in the living room. From the analysis of the cases, it is clear that the heating system is still controlled by a central thermostat in the living room, although a more refined control is feasible. An outdoor temperature sensor would allow the system to adjust heating output based on actual weather conditions, rather than maintaining a constant level throughout the heating season. The thermostatic radiator valves make a more local control possible.

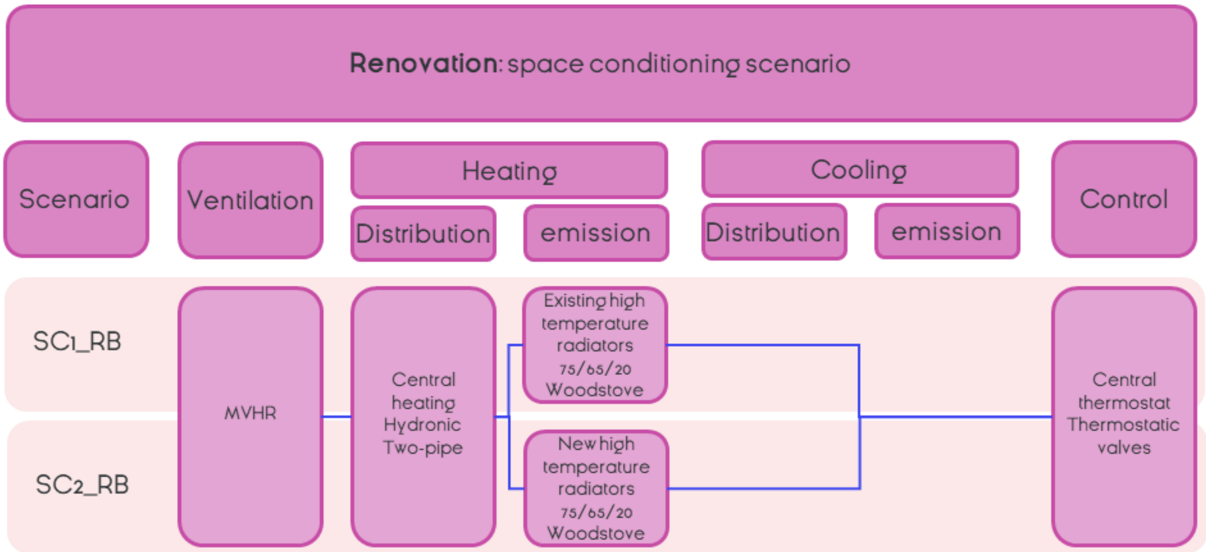


Figure 2-15 Schematic overview of the Belgian Renovation Baseline (RB) Space Conditioning (SC) scenarios for the Belgian archetypes.

In a contemporary renovation, cooling systems are usually not installed, as can be observed in case analysis. Meanwhile, with the current Belgian EPBD legislation, a ventilation system for the supply and exhaust of air is required. Although, a full ventilation system is rarely present in the cases that are studied, it is included in the renovation baseline, to take into account national requirements. A mechanical ventilation system with heat recovery is applied according to NBN-D50-001 (BIN, 1991): fresh air is provided in the 'dry' rooms and polluted air is extracted in the 'wet' rooms, such as the bathroom and kitchen. Mechanical supply is chosen over natural supply because this way the valuable windows or facade do not have to be impacted. Constant flow rates are assumed.

The same comfort baseline is assumed as in the pre-renovation baseline, to make a fair comparison possible. The same temperature levels for heating are adopted, and for newly heated rooms (e.g. the renovation of the attic), the temperature settings of the corresponding function are supposed.

3 Norway

3.1 Equipment and set-up

Measurements of temperature, relative humidity, CO_2, formaldehyde, TVOC, and $PM_{2.5}$ were carried out in various rooms across five case-study buildings, labelled Occ A to E. The four apartments featured open kitchen–living room layouts. In OccA and OccD, the bedroom was connected to other spaces, allowing a single measurement point. In OccB and OccC, bedroom data could not be collected due to lack of space in the room. In OccB, the living room served also as a bedroom throughout the summer.

All cases involved a single permanent occupant, except OccA, which operated as an Airbnb during the summer and reverted to single occupancy from January 2025. OccE, a café, was monitored only in the accessible area; however, data collection was inconsistent due to frequent sensor unplugging to access power outlets.

Additionally, local weather data from the Meteorologisk institutt (Norwegian Meteorological Institute)(Met, 2024) were used to relate indoor conditions to the outdoor climate. This enabled the assessment of thermal comfort, perceived indoor air quality, and moisture load.

The measurements were done using a combination of four types of sensors. The data were collected every five minutes and logged into the internal memory of the Raspberry Pi and sent to an Influx database. More information about the sensor's calibration and intra-unit consistency can be found in (Justo Alonso, Madsen, et al., 2022; Justo Alonso, Moazami, et al., 2022). Table 3-1 provides an overview of the sensor specifications.

Table 3-1 Sensor specifications of used devices for Norway.

Sensor model	Parameter measured	Interval of measurement	Accuracy
Sensirion SCD30 (Sensirion, 2020)	Temperature	−40 °C – 70 °C	± (0.4 °C + 0.023 x (T [°C] - 25 °C))
	Relative humidity	1-100 %	±3%RH at 25 °C
	CO_2	400–10000 ppm	±30 ppm ± 3% (500–1500 ppm)
DART WZ-S formaldehyde (Dart, 2019)	Formaldehyde	0.03–2 ppm	≤0.02 ppm formaldehyde equiv. < ±2%
Sensirion SVM30 (Höhener, 2019)	TVOC	0–60’000 ppb	15% of MVa
Sensirion SPS30 (Sensirion, 2018)	PM2.5	Resolution 1 μg/m³	0–100 μg/m³ ≥ ±10 μg/m³ 100–1000 μg/m3 ≥ ±10 %

Apart from the long-term measurements, the space conditioning devices and ventilation provisions were noted.

3.2 Observations and data analysis

3.2.1 EPBD building temperature

The indoor temperature has a substantial impact on the building heat losses and thus the energy use. Within the EPC/EPBD calculation frameworks, the entire building volume is assumed to be isothermal, with standard indoor temperatures for Belgium of 18 °C in winter and 23 °C in summer. For international comparability, the standard EPC temperatures for Belgium are used in all countries.

Figure 3-1 presents the distribution of the measured volume-weighted average indoor temperature during the winter (December–February) and summer (June–August) periods. In Occ_C, D, and E, the selected summer—chosen for cross-country comparability—preceded the installation of sensors in these buildings. The volume-weighted temperature was calculated using Equation (1).

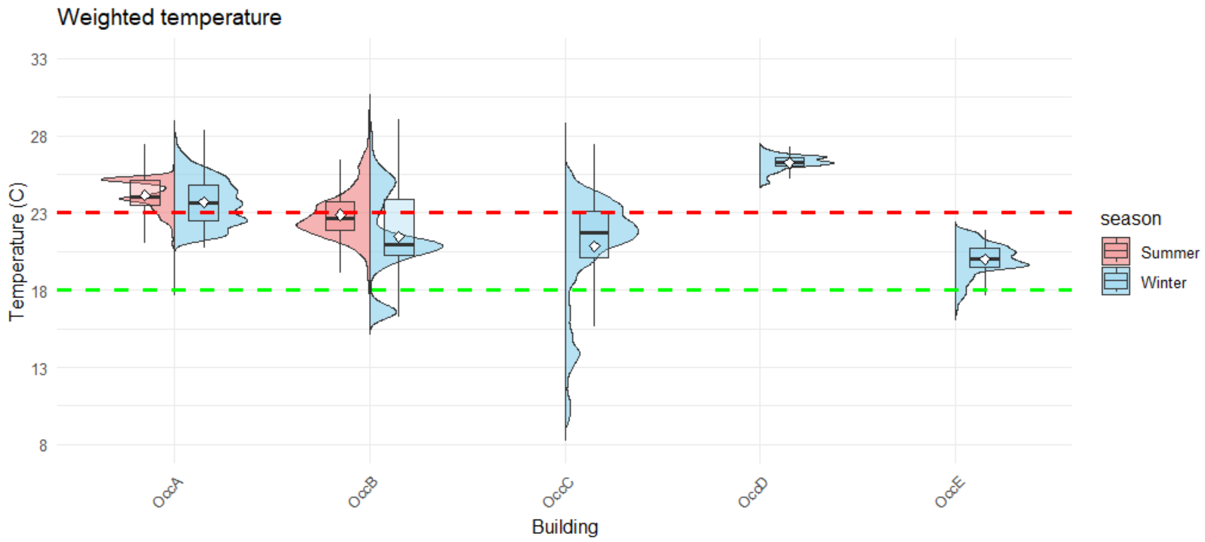


Figure 3-1 Distribution and boxplots of the volume-weighted average indoor temperature for summer (June–August) and winter (December–February for the Norwegian cases. Volume weighted temperature of all available temperature measurements of the case studies. The red dotted line indicates the assumed winter indoor temperature (18 °C) used in the EPBD calculations for belgium; the green dotted line marks the assumed summer indoor temperature (23 °C) for cooling energy use.

The data indicates that, in most cases, the average winter temperature exceeds the assumed baseline of 18°C. Occasional measurements below 18°C typically correspond to periods when the buildings were vacant or, if occupied, to times of “morning aeration.” Generally, average winter temperatures range between 21°C and 22°C, with the exceptions of OccA and OccD, which recorded averages of 23°C and 26°C, respectively. Notably, OccD exhibits a particularly tight distribution around its average winter temperature of 26°C, approximately 8°C higher than the value calculated using the EPBD method. This apartment is especially compact, featuring an open layout that combines the kitchen, living room, bedroom, and bathroom. In this case, the sensor in the living room was malfunctioning, and limited data was collected during the defined winter period from December to February. As a result, the temperature in the bathroom had a significant impact on the weighted average.

Interestingly, the difference between average summer and winter temperatures is less than three degrees for all cases. This small variation is likely due to the relatively cold and windy summer during the measurement period that made that several users kept their heating on.

3.2.2 Temperature variability

The variability in indoor temperatures between summer and winter provides insights into how occupants operate their buildings. All the buildings studied have the same orientation towards the sun; however, the exposure to wind is higher for OccA and OccB, with OccA located on the ground floor and OccB on the second floor. Figure 3-2 presents density plots of indoor temperatures during summer and winter. Missing plots indicate insufficient data.

The temperature variability within the 2.5th–97.5th percentile range is generally limited in both seasons. Regarding the living rooms, in OccB, a clear daily pattern is observed in the living room, where temperatures rise throughout the day and begin to decrease after 20:00. In OccA, summer temperatures remain stable around 22°C, which corresponds to the heating setpoint. In winter, when the dwelling is occupied by a single user, the temperature drops during working hours while the occupant is away and increases upon his return in the evening. In OccC, indoor temperatures remain stable around 23°C for most of the day. A second distinct temperature range, at lower levels, reflects the daily ventilation routines. In OccE, the temperature profile differs from the others: higher temperatures are observed before opening hours, likely due to oven use for baking, followed by a stable temperature throughout the rest of the day.

In the bathrooms, OccA shows two distinct heating setpoints for summer and winter. In contrast, OccB displays similar temperatures across both seasons. The profile in OccC indicates two clearly defined periods—lower temperatures before 08:00 and higher temperatures (above 25°C) from 08:00 to 20:00. In OccD, winter temperatures remain constantly around 25°C.

In the kitchen of OccB, temperatures remain low until the evening, rising between 18:00 and 20:00, likely due to meal preparation.

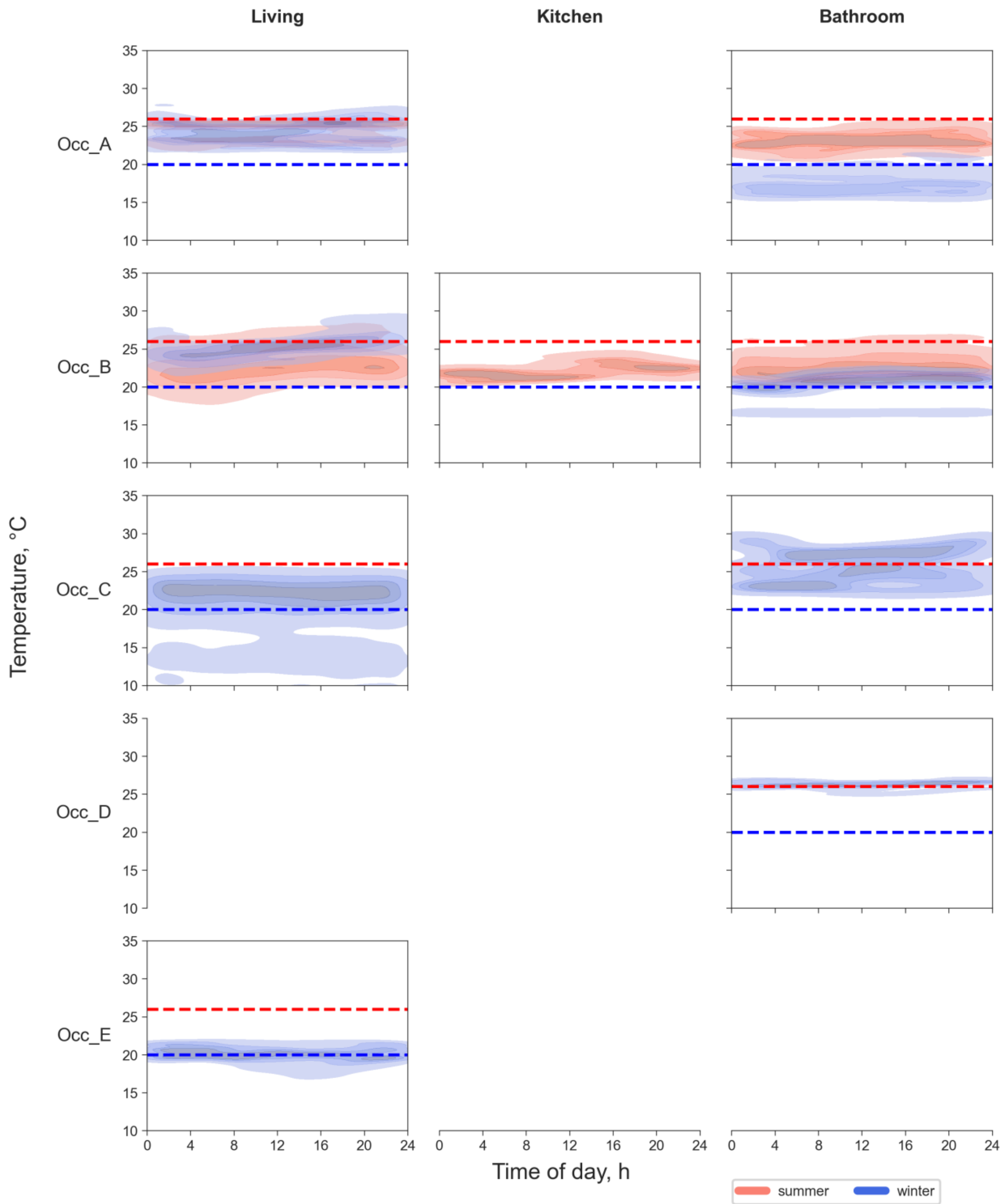


Figure 3-2 Indoor temperature distribution (density plots showing approximately the 2.5th–97.5th percentile range) as a function of time of day for the Norwegian cases. Display of summer (June–July–August) and winter (December–February) in living room, kitchen, and bathroom. Empty cells indicate insufficient data (e.g., for OccD, data from the living room are missing because the sensor stopped functioning in early January and was reset in March). The blue and red dashed reference lines represent the lower (20°C) and upper (26°C) temperature limits of the acceptable range for thermal indoor environmental quality (IEQ) Class II, as defined by EN 16798.

A more detailed analysis of the living rooms differentiating weekend and weekdays is presented in Figure 3-3. Figure 3-3 presents the mean temperature, along with the 5th and

95th percentiles, as a function of time of day, separately for weekdays and weekends. These profiles help illustrate the daily temperature dynamics of each space.

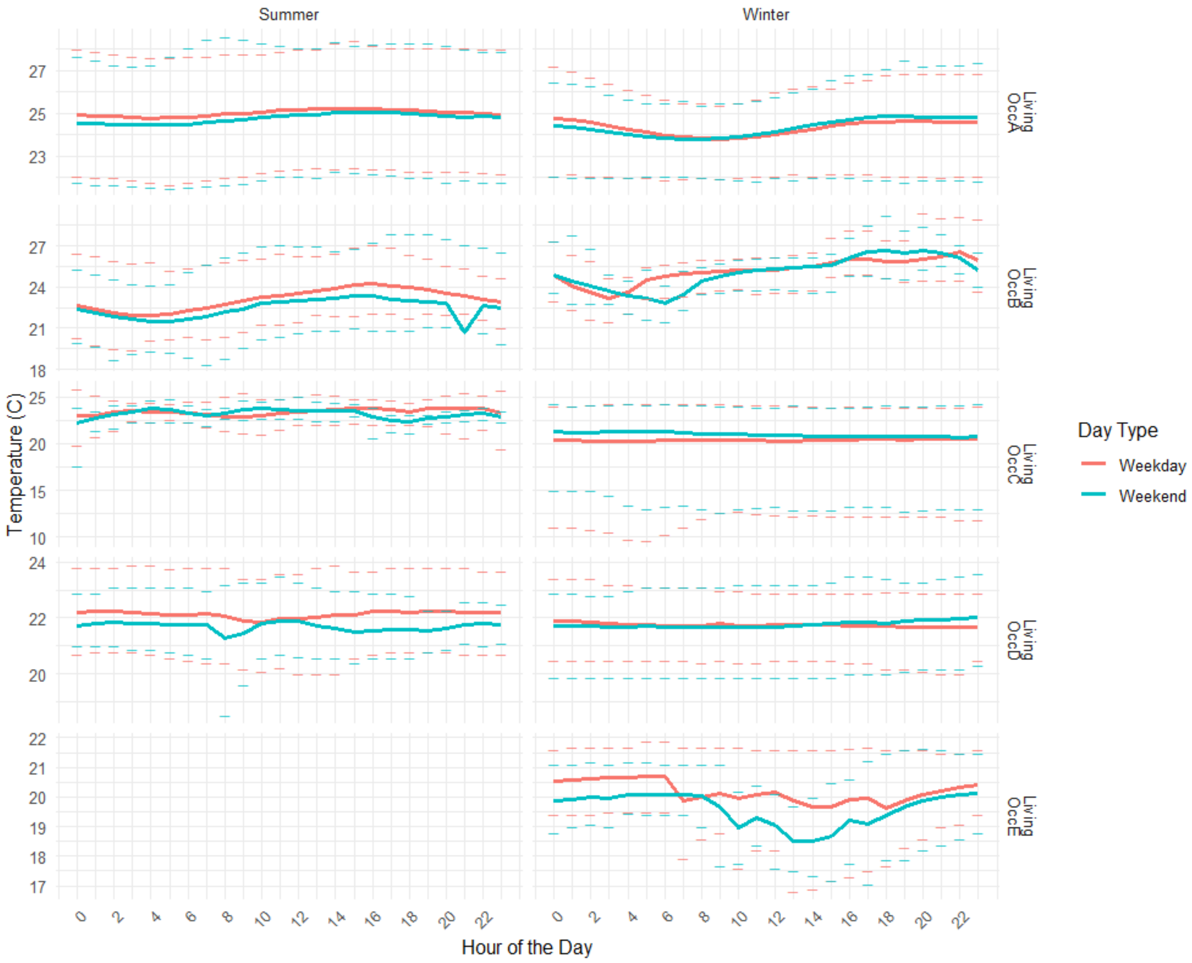


Figure 3-3 Temperature distribution in the specified rooms, comparing weekdays and weekends during summer and winter for the Norwegian cases. Solid lines represent the mean indoor temperature as a function of time of day, separately for summer and winter, and for weekdays and weekends. Dotted lines indicate the 5th and 95th percentiles of the corresponding data.

In OccA, a wide variability in indoor temperatures is observed within the 5th–95th percentile range during summer. This is likely due to the presence of different users and their varying comfort preferences. Nevertheless, the average temperature, despite accounting for diverse occupancy patterns, does not deviate significantly from those in the other cases. During summer, temperatures in OccA are consistently around 25 °C, while in winter, they range from approximately 24 °C when the dwelling is unoccupied to about 25 °C when the occupant is present. The temperature patterns between weekdays and weekends in this case are notably similar.

In contrast, OccB exhibits the most pronounced differences between summer and winter. Although the radiator setpoint profile remains unchanged across seasons, in winter the occupant uses a wood stove to enhance thermal comfort. This additional heating results in higher evening and nighttime temperatures, followed by a gradual decline as the temperature approaches the radiator setpoint. Distinct differences between weekday and weekend temperature profiles are also clearly visible in this case.

For the remaining cases, seasonal differences in temperature profiles are generally limited. Only in OccD is there a noticeable variation between weekdays and weekends during summer. In winter, however, all electric radiators operate under a constant setpoint, resulting in uniform temperature profiles across the week. In contrast, some other dwellings—such as OccB—use newer radiator models that allow for time-dependent variations in setpoints, contributing to the observed differences.

3.2.3 Duration of heating season

For the Norwegian cases, it is difficult to determine a precise date when heating was initiated. During the summer period (June to September), the average outdoor temperature was 13°C, with recorded extremes ranging from -1°C to 30°C. Notably, 75% of the temperature values during this period were below 12°C.

In most cases, the heating system operates with a fixed setpoint; only in the case of OccB is there any daily variation in the control setting. Nevertheless, the same setpoint is maintained throughout both summer and winter. This practice is common in Norway, where electric heaters are widely used in residential buildings (Kvaal & Tysnes, 2022). Across all examined cases, users confirmed that heating had already been activated by 15 September and remained in continuous use until at least 15 May.

3.2.4 EN 16798 Adaptive Thermal Comfort

The adaptive comfort model from EN 16798 serves as a useful benchmark for assessing thermal comfort. Figure 3-4 illustrates indoor temperatures against the exponentially weighted running mean outdoor temperature in the living rooms of OccA and OccB. The other cases show similar or better results.

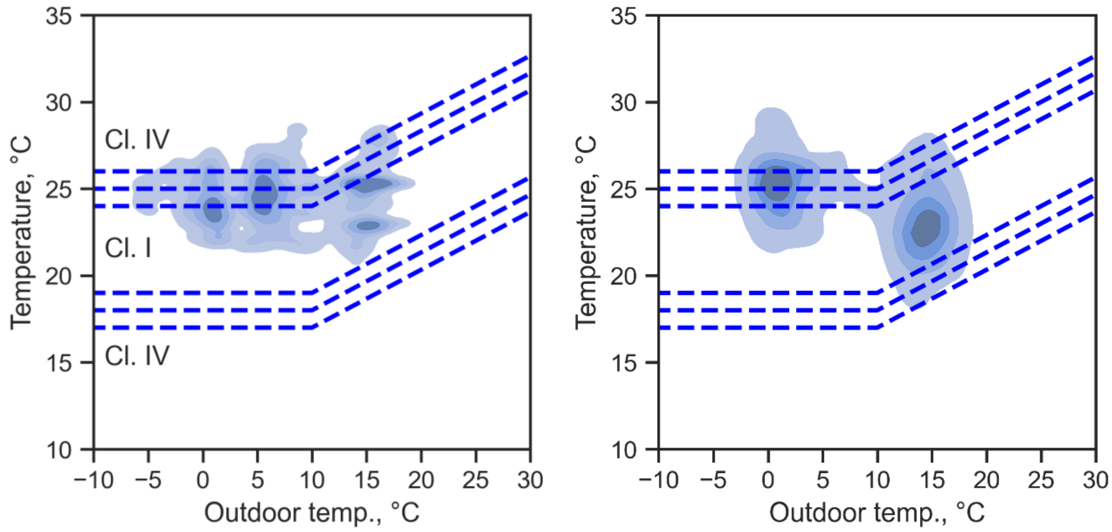


Figure 3-4 Temperature distribution of the measured indoor temperature as a function of the exponentially weighted outdoor temperature (density plot for the 25th-97.5th percentile data) for the living room of Norwegian cases OccA (left) and OccB (right). The dotted reference lines are based on the adaptive thermal comfort acceptability limits (Airspeed <0.6ms) as described in the EN-16798 standard.

In all cases, over 95% of the measured data fall within at least EN 16798 acceptability class III. The results are positioned at the upper end of the acceptable range. Indoor temperatures remain stable or increase slightly as outdoor temperatures decrease, showing little to no upward trend with rising outdoor temperatures. In some cases, temperatures appear flat or even lower than those recorded during winter, when heating was continuously used.

The adaptability analysis is summarized in Table 3-2 by calculating the percentage of measured data assigned to a certain class (including outside above or below). Note that not all cases have data on all seasons.

The results indicate that most living rooms achieve high levels of thermal comfort, with 70-89% of the measured hours falling within the highest comfort class (Class I) for the majority of cases. Overheating is generally minimal, except in one category (OccC), which exhibited elevated overheating (17.1%) and a significant portion of time in lower comfort classes. In all the cases the occupants were healthy individuals with ages ranging 30 to 60 years old that had the means to decide the setpoints of their heaters. These findings suggest that occupant control over heating setpoints generally supports optimal comfort, though specific cases differ from the expected comfort setpoints.

Table 3-2 Percentage of datapoints in or outside adaptive temperature class for the living room, All data of Norwegian cases

	OccA	OccB	OccC	OccD	OccE
Hours of data considered	3510 h	231	1130 h	764h	288 h
Start-end of data	2024-06-21 2025-05-13	2024-06-21 2024-12-16	2024-10-02 2025-02-28	2024-10-02 2024-11-18	2024-10-02 2024-12-31
Overheating	2.1%	0.9%	17.1%	0.4%	0%
Class I	69.9%	88.7%	35.8%	80.1%	84.4%
Class II	21.3%	9.1%	23.2%	17.1%	15.3%
Class III	6.6%	0.9%	18.9%	2.4%	0.3%
Below	0.1%	0.4%	5%	0.%	0%

Since thermal comfort is only relevant when occupants are present, it is logical to focus the analysis on periods with a higher likelihood of occupancy as presented in Table 3-3. To achieve this, indoor temperature data was filtered to include only those hours when the CO_2 concentration in the living room exceeded 600 ppm—a commonly used proxy for human presence. While this threshold does not perfectly capture all instances of occupancy (as CO_2 levels may lag behind actual entry or exit, and high ventilation rates can mask presence), it substantially increases the probability that the analysed data reflects times when someone was actually in the room, compared to using the full dataset.

A high proportion of hours fall within Class I comfort – the optimal range – across nearly all cases. This is particularly evident in OccB, OccD, and OccE, where more than 85% of hours meet this standard, indicating consistent indoor comfort. Overheating is virtually absent in most scenarios, with the exception of OccC, which experiences overheating during 22% of the occupied hours and has the lowest share of Class I comfort (30.1%). Importantly, no cases show occupied hours falling below the minimum acceptable thermal threshold, suggesting that even in suboptimal conditions, environments remain within tolerable limits.

Seasonal patterns and case-specific anomalies offer further insight. OccC, monitored during winter, exhibits a combination of elevated overheating and reduced comfort, potentially pointing to issues with the building's heating system, envelope performance, or occupant behaviours.

Table 3-3 Percentage of datapoints in or outside adaptive temperature class for the living room, data of Norwegian cases when CO2 level is above 600ppm

	OccA	OccB	OccC	OccD	OccE
Hours of data considered	3059 h	208 h	690 h	155 h	66 h
Start-end of data	2024-06-21 2025-05-13	2024-06-21 2024-12-16	2024-10-02- 2025-02-28	2024-10-02 2024-11-18	2024-10-02 2024-12-31
Overheating	1.9%	1%	22%	0%	0%
Class I	76.1%	86.5%	30.1%	85.1%	95.5%
Class II	16.4 %	11.1%	17.7%	14.3%	4.5%
Class III	5.5. %	1.4%	1.9%	0.6%	0%
Below	0%	0%	0%	0%	0%

3.2.5 CO2 variability

Figure 3-5 presents the density plots of indoor CO_2 concentrations for summer and winter across the four monitored cases. While data for OccD are available, they do not cover the specific winter period analysed here.

In all cases except OccA, the variation between the 2.5th and 97.5th percentiles are minimal, likely due to regular window opening. For OccA, the plot shows two distinct zones: one in summer with concentrations around 2000 ppm, and another spanning both summer and winter with levels between 600–800 ppm. During summer, room occupancy was higher. This apartment is well-insulated and airtight, with only wall vents for ventilation. Many of the summer occupants were tourists and reported feeling cold, avoiding window opening. In contrast, the winter occupant opened windows more frequently and consistently used the exhaust fan while cooking.

Overall, CO_2 levels were low across all cases in both seasons, except for OccA in summer. This is likely due to air leakage and common practices of natural ventilation through window opening, and very high number of m^2 per person. Diurnal variation is minimal. However, OccE exhibits a distinct midday peak in winter, likely due to its use as a café, with higher visitor traffic during those hours. In general, daily patterns are flat for all the other cases.

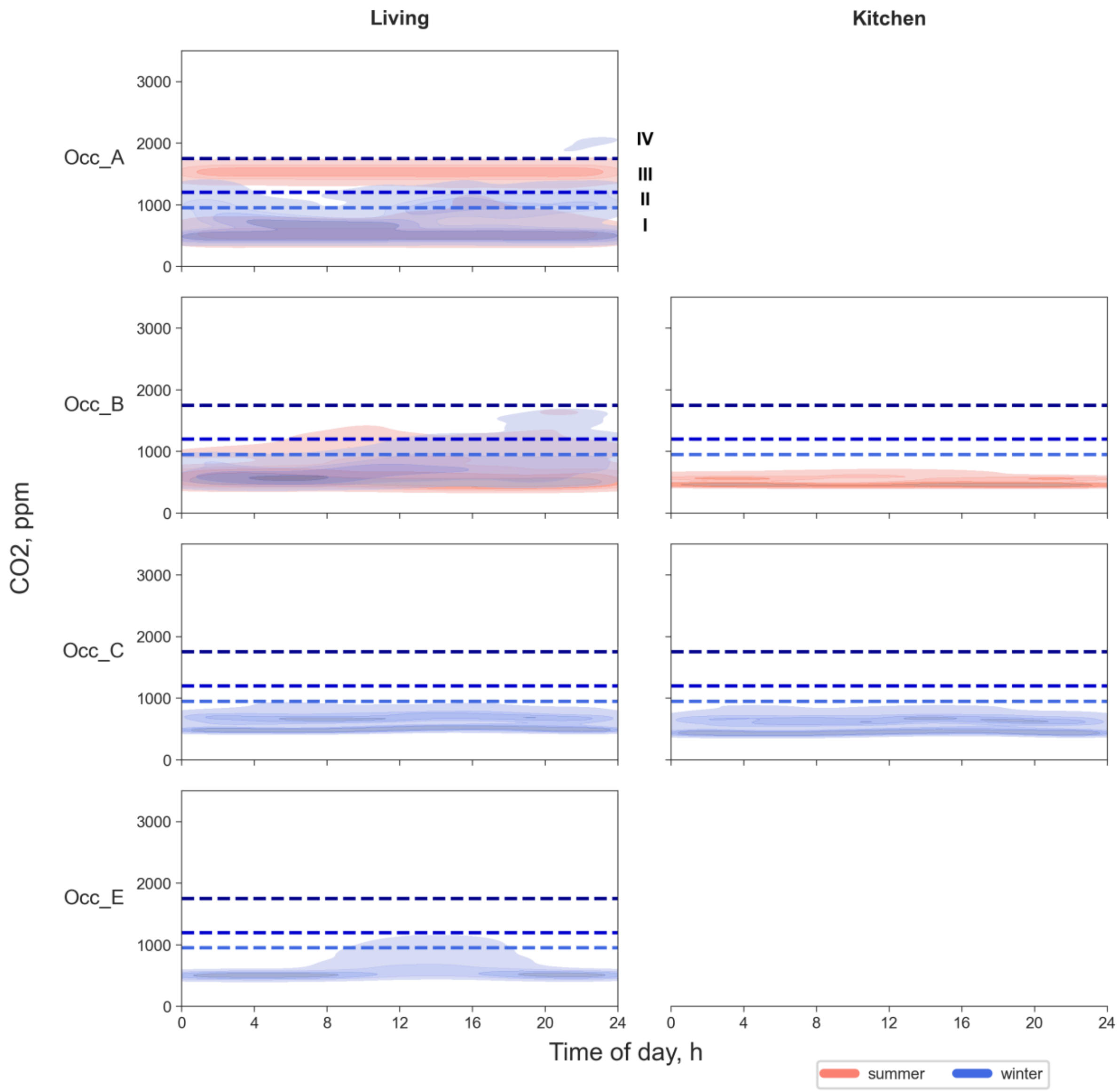


Figure 3-5 CO_2 concentration distribution (5th–95th percentile density plots) as a function of time of day for the Norwegian cases. Display of summer (June–July–August) and winter (December–January–February) in living rooms and kitchens. Empty time slots indicate the absence of relevant data. Blue dotted reference lines represent the CO_2 threshold values for indoor environmental quality (IEQ) classes as defined in EN 16798.

These results also agree with the ones presented in Figure 3-6. In general, CO_2 levels remain relatively stable throughout the day in most cases, with only slight differences between weekdays and weekends. Nevertheless, large variations up to 2000ppm can be found between average and percentiles 95th The most notable exception is OccA in summer, where concentrations exceed 2000 ppm during nighttime and early morning hours, then gradually decline during the day. This pattern likely reflects high occupancy combined with limited ventilation, as previously discussed.

In contrast, OccB, OccC, and OccE maintain CO_2 levels predominantly below 1000 ppm across all hours and seasons. Minor peaks can be observed during daytime hours, particularly in OccC and OccE, which may reflect increased activity or visitors, especially during weekends.

Winter profiles across all cases show less diurnal variation, with flatter trends and lower peak values, suggesting more consistent ventilation or reduced occupancy during the colder months.

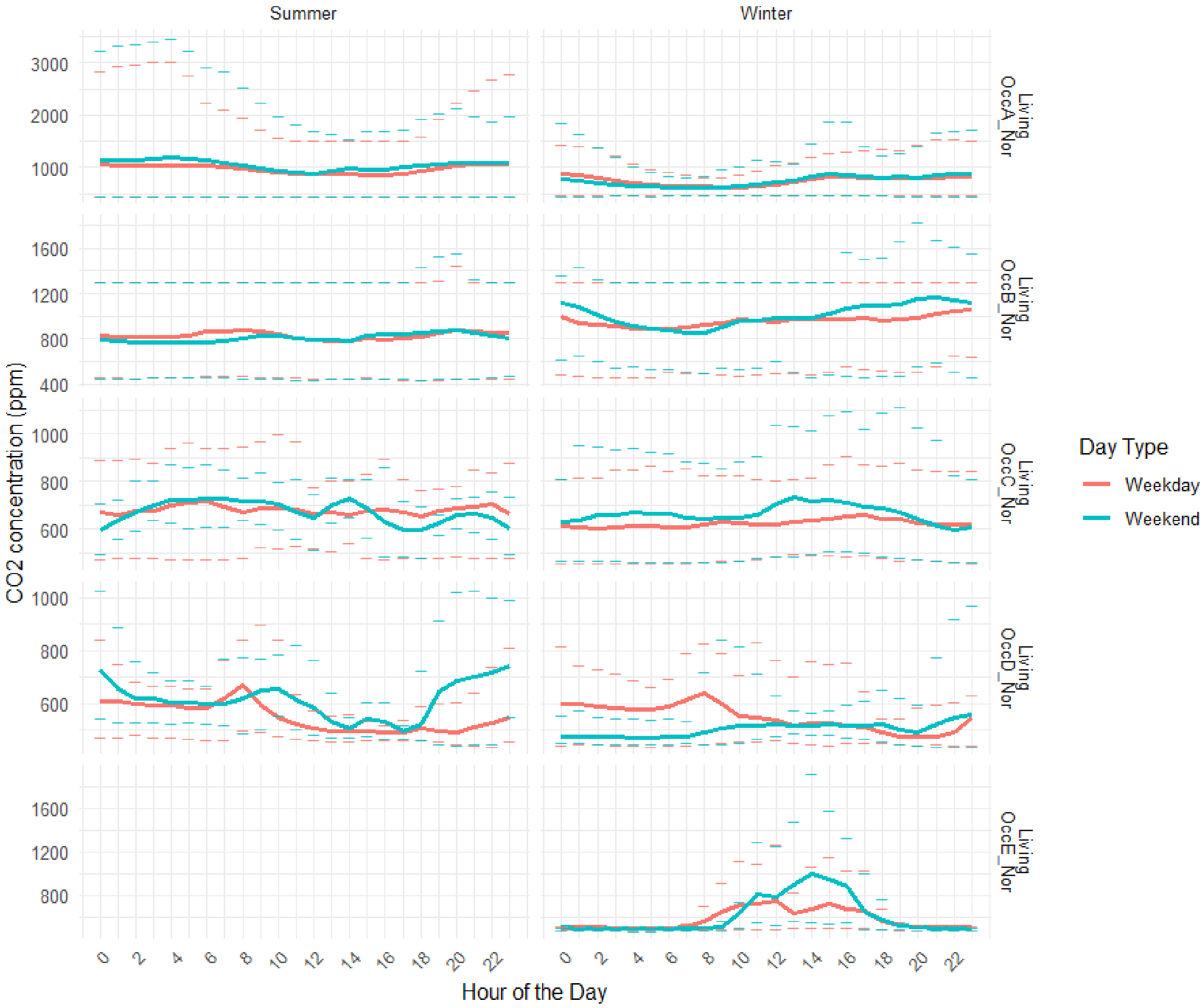


Figure 3-6 CO_2 concentration distribution in the specified rooms, comparing weekdays and weekends during summer and winter for the Norwegian cases. Solid lines represent the mean indoor CO_2 concentration as a function of time of day, separately for each season and day type. Dotted lines indicate the 5th and 95th percentiles of the corresponding distributions.

3.2.6 EN 16798 IEQ categories

We refer to the IEQ classification system from EN 16798-1:2029, as described in Chapter 7.2.6. The CO_2-based classification, derived from perceived air quality, uses the design ΔCO_2 values in Table B.12 to define class limits shown in Table 2-5.

IEQ class analysis was conducted for living rooms in all cases as we don't have measurements for the bedrooms. Each day was categorized based on its 95th percentile CO_2 concentration, and the percentage of days per class is shown in Table 3-4

Table 3-4 CO_2 based IEQ categorisation for the living rooms of all Norwegian cases. Limits are based on Table 2-5

% of days in Cat. #	OccA	OccB	OccC	OccD	OccE
Days in dataset	295 days	157 days	121 days	48 days	22 days
Start-end of data	2024-06-21 2025-05-13	2024-06-21 2024-12-16	2024-10-02- 2025-02-28	2024-10-02 2024-11-18	2024-10-02 2024-12-31
Category I	37 %	39%	88%	95%	41%
Category II	17 %	19%	8%	5%	50%
Category III	36 %	40%	3%	0%	9%
Category IV	9 %	2%	0%	0%	0%

Regarding the IEQ categories, it is important to note that the distribution of time across categories differs between the two measured seasons. In the case of OccA, the proportion of time spent in Category III is significantly higher in summer than in winter, as shown in Figure 3-7 (left). A similar pattern is observed for OccB. In OccB, OccC, and OccD, the highest CO_2 concentrations consistently occur at around 5°C.

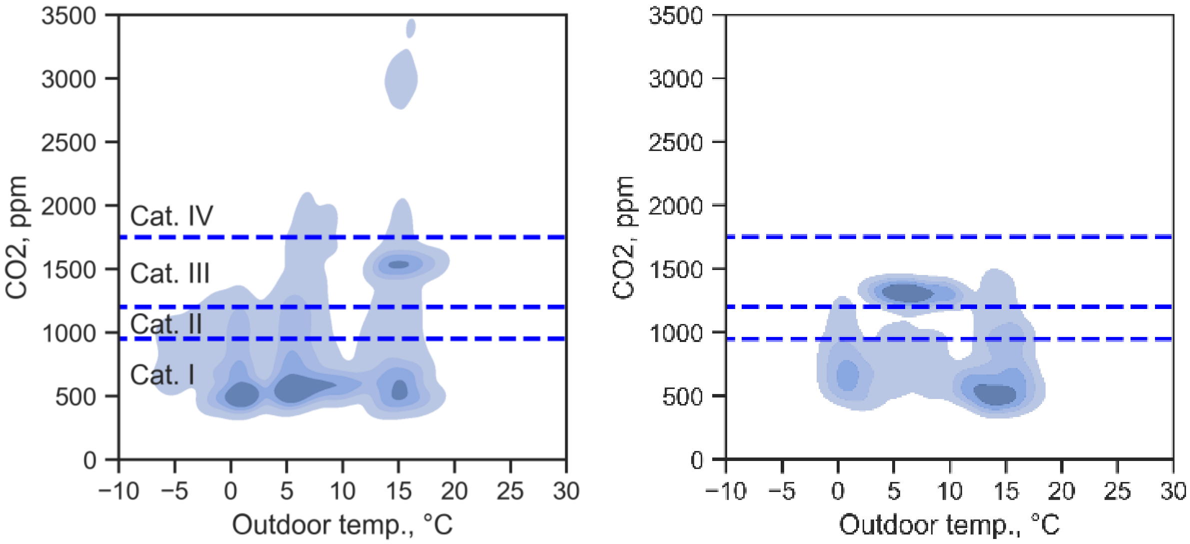


Figure 3-7 Distribution of the measured CO_2 as a function of the exponentially weighted outdoor temperature (density plot for the 2.5th-97.5th percentile data) for the living room of Norwegian cases OccA (left) and OccB (right). The dotted reference lines are the limits of the IEQ categories.

3.2.7 Relative humidity variability

Figure 3-8 presents an overview of relative humidity (RH) in the living room, kitchen, and bathroom. In cold climates, such as Trondheim, indoor humidity can drop to very low levels during winter due to the combined effects of low outdoor absolute humidity and increased indoor heating. Studies have shown that indoor RH values below 10% are not uncommon in Nordic regions during January (Geving & Holme, 2012). While such low humidity may be considered unusual in milder climates, it is typical for Trondheim, especially when indoor temperatures are maintained at comfortable levels over 22°C throughout the winter. The pronounced seasonal variation in RH, largely driven by outdoor air conditions and ventilation practices, aligns with established findings for cold-climate buildings.

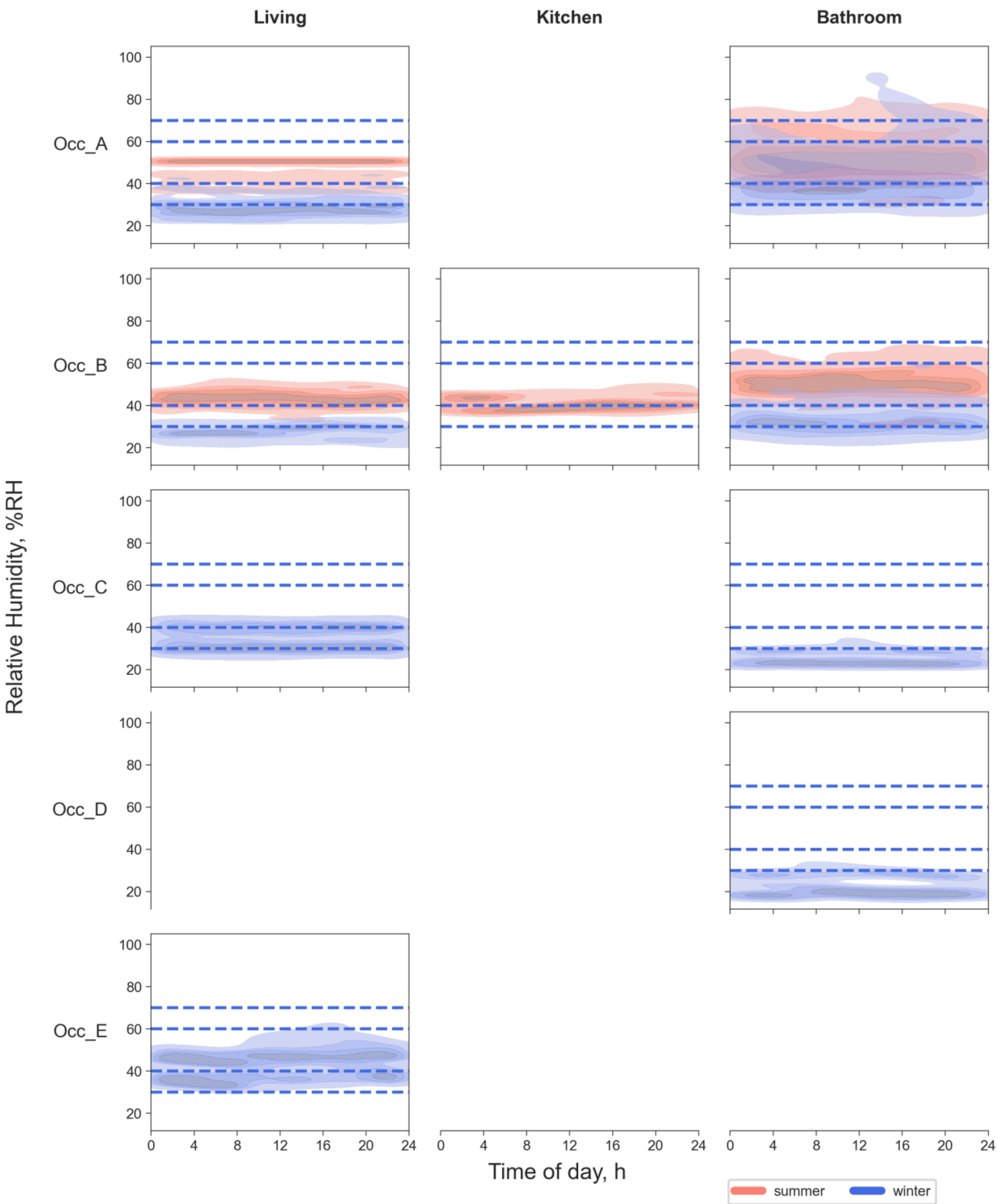


Figure 3-8 Relative humidity distribution (density plot for the 5th-95th percentile) as a function of the time of day for the Norwegian cases. Display of summer (Jun-Jul-Aug) and winter (Dec-Jan-Feb) in living, kitchen and bathroom. Empty slots mean no relevant data was available. The blue dotted reference lines at 30-40% and 60-70% indicate typically used intervals considered to be perceived as comfortable by people.

A notable difference in RH is observed between OccA and OccB, which may be partly attributed to the improved insulation in OccA. Enhanced insulation reduces air leakage and heat loss, thereby stabilizing indoor temperature and humidity levels (Geving & Holme, 2012). This effect is well documented in literature, where retrofitting with better insulation has been shown to moderate indoor humidity fluctuations (Mikola et al., 2017).

In the kitchen of OccB, a high density of nighttime RH values above 40% is observed. This kitchen lacks mechanical ventilation and relies solely on window airing, while also being open to both the stairway and living room. The absence of dedicated exhaust ventilation in kitchens can result in elevated humidity, particularly during cooking or periods of limited air exchange, but in this case the high values happen outside cooking hours.

Despite some variability, no significant discomfort due to excessively high or low humidity is expected for most occupants. However, both OccA and OccB show a considerable number of instances with RH above 70% in the bathrooms, which is not observed in OccC and OccD in a different building but with similar number of occupants and showering profiles. High humidity in bathrooms is common due to showering and limited ventilation, and persistent RH above 70% can increase the risk of mold growth and associated health concerns.

3.2.8 Moisture load - internal humidity classes

Moisture excess, Δv [g/m³], the difference between indoor and outdoor water vapour content, was calculated from measured indoor and outdoor temperature and relative humidity. To examine its dependence on outdoor climate and identify critical values, data were grouped by outdoor temperature in 1 °C intervals.

As expected, there is an inverse relationship between indoor moisture and outdoor temperature (Figure 3-9). For the case of OccA the data show that most observations cluster around 2–4 g/m³ of moisture excess when outdoor temperatures are in the range of 0–10 °C. This is consistent with typical indoor moisture generation from activities such as cooking, bathing, and respiration, combined with moderate ventilation rates (Liu et al., 2023).

Instances of higher moisture loads (6–8 g/m³) are relatively infrequent and are primarily observed when outdoor temperatures drop below 5 °C. Recent studies indicate that a 90th percentile value of approximately 2.6 g/m³ in bathrooms is typical in well-ventilated Nordic apartments without humidifiers (Stavanger, 2021). These events can be attributed to increased indoor moisture production coupled with reduced ventilation and higher airtightness in this building. Such conditions can lead to a temporary accumulation of indoor moisture, but overall, the trend remains dominated by the strong dependence of indoor moisture excess on outdoor temperature and ventilation practices.

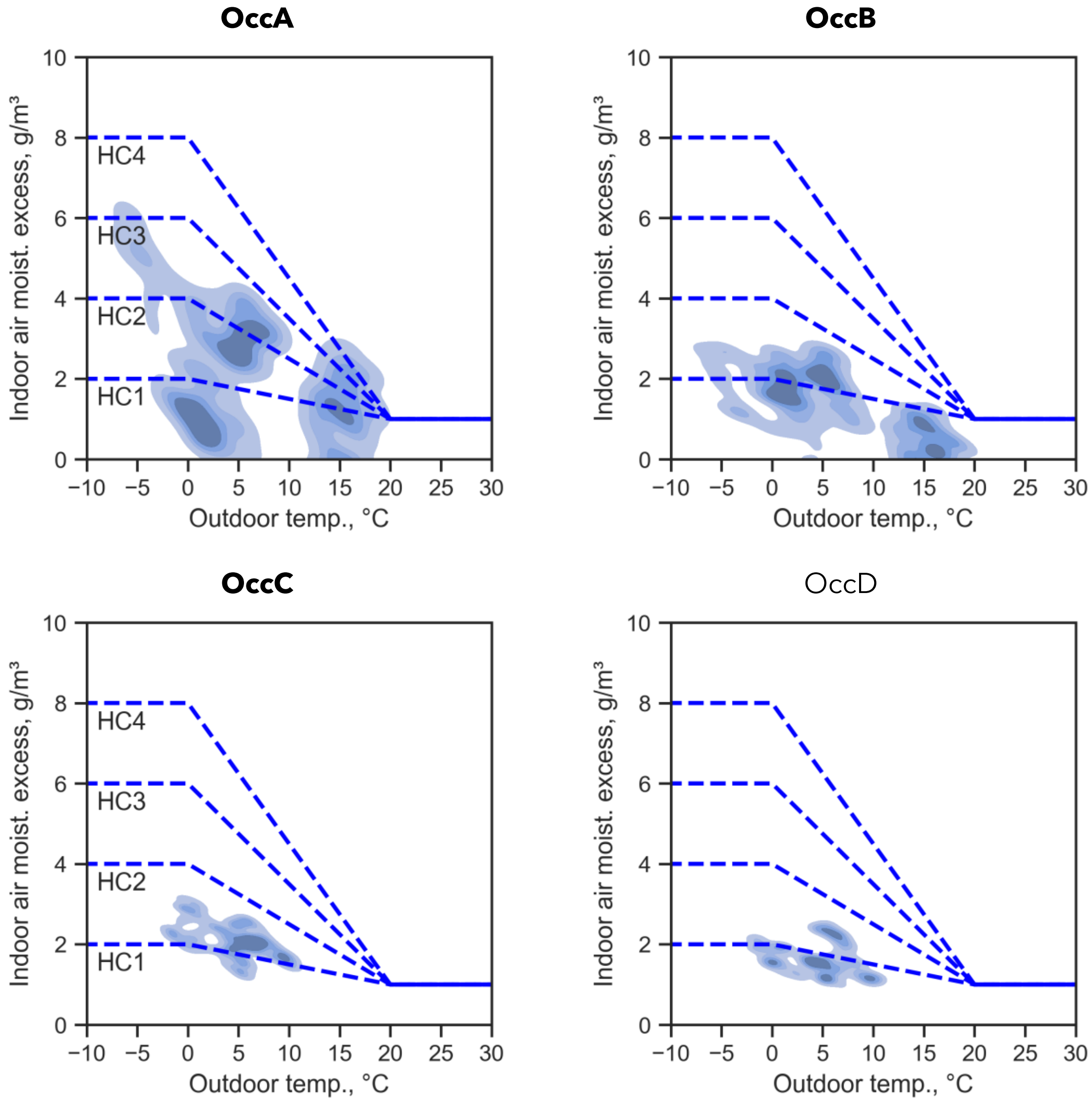


Figure 3-9 Weekly average indoor air moisture excess distribution as a function of the exponentially weighted outdoor temperature (density plot for the 5th-95th percentile data) for the bathrooms of Norwegian cases OccA, OccB, OccC and OccD. The dotted reference lines represent the threshold values defined by the internal humidity classes as described in the EN ISO 13788:2013 standard.

For the three other cases, moisture excess in the bathroom typically clusters between 2 and 3 g/m³ during cold periods, decreasing towards zero as outdoor temperatures rise above 15 °C.

3.2.9 Insights

The analysis of indoor environmental quality and space conditioning in the five Norwegian heritage townhouse case studies highlights a complex relationship among building typology, occupant behaviour, and seasonal climate. Despite their age and architectural constraints, these buildings generally maintain thermal comfort within or close to the boundaries defined by European standards (EN 16798 and EN ISO 13788). In summer, indoor temperatures typically remain below the upper comfort threshold of 25 °C. In winter, temperatures often average between 23 °C and 25 °C—values that, while within the comfort range, may be considered relatively high and potentially energy-intensive to sustain. This performance is largely attributed to occupant control over heating systems, simple yet effective ventilation practices, and moderate space conditioning strategies.

A key finding is the limited seasonal variability in indoor temperature, with most spaces showing a difference of less than 3°C between summer and winter. This outcome is partly attributed to Norway's relatively cool summer climate during the monitoring period, but it also reflects the continued use of heating into the warmer months and the consistent setpoint strategies employed by the occupants.

The use of electric radiators and wood stoves, often operating with fixed or minimally adjusted setpoints, aligns with traditional Norwegian heating practices. This contributes to stable thermal conditions but also results in elevated average indoor temperatures in winter, often exceeding EPBD assumptions (18°C) by several degrees. For example, OccD maintained an average winter temperature of 26°C, well above the regulatory reference.

Regarding ventilation and IAQ, CO_2 concentrations remained within acceptable limits in most cases, reflecting common practices of window airing, low building airtightness and the low occupant density typical of these buildings. However, OccA—operated as an Airbnb in summer—experienced prolonged CO_2 levels above 2000 ppm, highlighting the challenges posed by variable user behaviour and limited mechanical ventilation in more airtight renovations.

Relative humidity and moisture load analyses confirm typical cold-climate profiles: low indoor RH in winter due to dry outdoor air and high heating, with occasional humidity spikes in bathrooms that may pose mold risks if not addressed through effective ventilation. Nevertheless, the majority of RH readings remained within the comfort range, indicating generally successful moisture management practices.

In terms of adaptive thermal comfort, the majority of cases meet or exceed Class I and II thresholds, even when considering only occupied periods (based on CO_2 >600 ppm). Overheating is rare and, when present (e.g., OccC), appears linked to system or envelope limitations rather than external climate alone.

From a broader perspective, these heritage townhouses demonstrate several key trade-offs:

- Advantages: Compact size, high user control, low occupant density, and behavioural adaptation (e.g., window airing, limited night heating) contribute to surprisingly robust IEQ performance.
- Challenges: Limited mechanical ventilation, uneven space conditioning, and a reliance on user intervention can create inconsistencies, particularly under atypical use (e.g., tourist rental).
- Opportunities: Targeted improvements—such as thermostatic zoning, modest ventilation upgrades, or enhanced bathroom exhaust—could significantly enhance performance without compromising historical integrity.

Looking forward, these findings suggest that renovation strategies should prioritize thermal zoning, moisture management, and occupant awareness over wholesale mechanical system replacement. Future work should explore how to scale these lessons across similar building stocks, especially as climate change introduces greater extremes in temperature and humidity, and as building use becomes more diverse (e.g., shared, or seasonal occupancy).

3.3 Space conditioning and IAQ management

For the five cases where long time measurements were carried out, a detailed inventory of the space conditioning systems present in those dwellings was carried out. In Table 3-5, the focus is on the distribution and emission systems (with the corresponding control system), alongside with the ventilation systems. The overview of the energy systems can be found in 'D4.1 R²ES-Based Energy Supply Concepts for Heritage Buildings in Historical Neighbourhoods'.

Table 3-5 Overview of space conditioning systems of the Norwegian townhouse buildings

Building code			Nygata _1	Nygata _2	Nedre1 _1	Nedre1 _2	Nedre1 _3
Heated area, m²			30.2	48.3			
Distribution	Heating	central/local	Central elec. boiler	Local	Local	Local	Local
		Transport medium	Hydronic	Electric	Electric	Electric	Electric
		Type of distribution system	Underfloor pipes	n/a	n/a	n/a	n/a
	Cooling	central/local	n/a	n/a	n/a	Local	n/a
		Transport medium	n/a	n/a	n/a	Refrigera nt	n/a
		Type of distribution system	n/a	n/a	n/a		n/a
Emission	Heating	Main type	Floor heating	Radiator, Wood stove	Radiator s	Radiators	Radiators
	Cooling	Main type	n/a	n/a	n/a	n/a	n/a
	Ventilation	Central ventilation system	n/a				
		Toilet extraction, m³/h	Extraction fan with light				
		Range hood, m³/h	Existing ca. 300 m³/h	None	Existing ca. 300 m³/h	Existing ca. 300 m³/h	Existing
	Temperature control	Control type	Central thermostat, Thermostati c valves.	Time-based schedule	Thermostatic valves		
		Night setback, °C	No setback				
		Day setback, °C	No setback				

3.4 Defining space conditioning pre-renovation baselines and renovation baselines

3.4.1 Pre-renovation baseline

In line with typical Norwegian practice for urban wooden townhouses and apartment buildings from the late 19th and early 20th centuries the pre-renovation baseline for Bakklandet buildings is characterized by the use of central hydronic heating systems (SINTEF & Niku, 2021; Stavanger, 2021). Most buildings were equipped with a central boiler, often oil- or wood-fired, though frequently replaced by electric boilers by the time of the EPBD, which distributed hot water to cast iron or steel radiators in each main room. A woodstove is often still present in the living room and bathroom can be heated through electric radiators. A summary of this scenario is indicated as SC1_PB in Figure 3-10.

During the 1990s, however, many renovated buildings replaced the original iron radiators with electric radiators in each room. In bedrooms, electric heating was often left turned off or not installed at all, while underfloor electric heating became the preferred solution in bathrooms. Living rooms commonly retained woodstoves or fireplaces, which provided additional heating and ambiance. Heated spaces included living rooms, kitchens, and bathrooms. Unheated spaces included bedrooms, attics, cellars, and often hallways.

Given that most renovation cases followed this pattern, SC2_PB (Figure 3-10) is selected as the main pre-renovation baseline.

The original waterborne systems were typically designed for high supply temperatures, with common operating regimes such as 90/70/20°C or 80/60/20°C (supply/return/room temperatures), and temperature drops across the radiators generally ranged from 15–20°C.

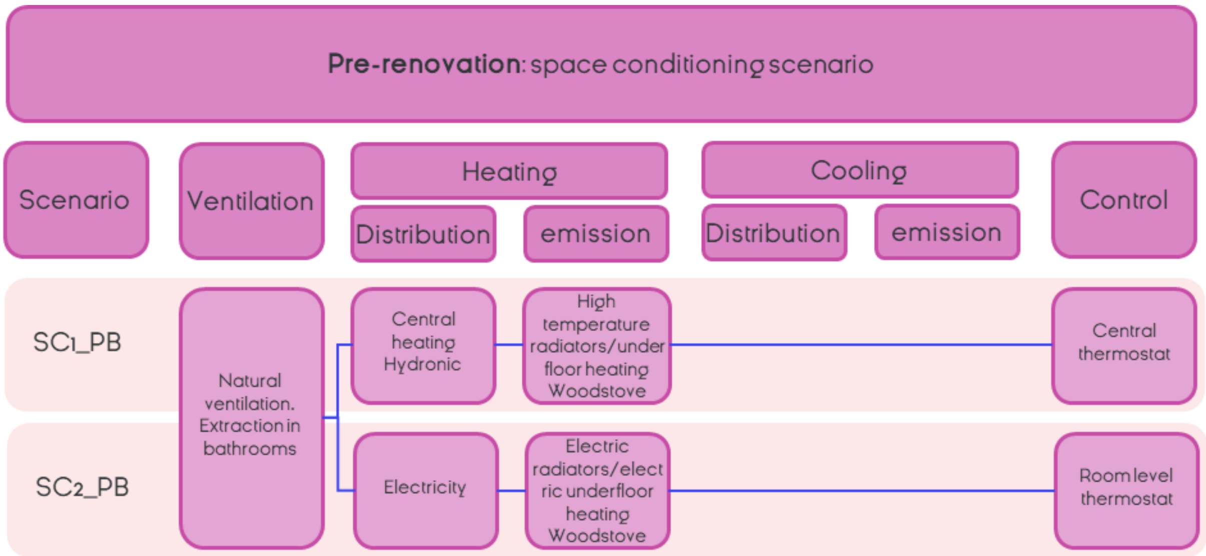


Figure 3-10 Schematic overview of the Pre-renovation Baseline (PB) Space Conditioning (SC) scenario for the Norwegian archetype.

Regarding the control, in the case of a central electric boiler supplying waterborne radiators, control is typically centralized, regulating the boiler output based on building or zone demand. The sensor is typically placed in the living room, controlled the electric boiler operation (on/off) with a typical bandwidth of ±1°C. There was minimal zoning; the central thermostat dictated the heating for the entire system. De woodstove is manually operated.

For underfloor electric heating and electric radiators, each system uses a room-level thermostat for temperature regulation—these thermostats may be manually operated or programmable with time-based schedules but often set to fixed positions. So for the pre-renovation baseline, the room-level thermostat with a single set point will be used.

Ventilation was primarily via window airing and natural infiltration. Mechanical ventilation was rare, except for kitchen and bathroom exhaust fans. This led to variable and often insufficient air exchange, especially during cold periods when windows remained closed.

In pre-renovation heritage wooden buildings in Baklandet, Norway, before the implementation of the EPBD (TEK07, (Kommunal-og regionaldepartementet, 2007)), space conditioning practices reflected both technical limitations and user habits. Oil boilers and wood stoves were common for heating before their phase-out, with electric panel heaters later supplementing or replacing these systems. Comfort and temperature settings were typically pragmatic, balancing energy costs with comfort, and often varied by room and occupancy patterns.

The main heated space, the living room, was often kept at 18–21°C during use. Night setbacks were uncommon, but temperatures could drop to 16–18°C when not in use, especially if heating was manually controlled or based on wood stoves (Storvolleng, 2013). Bedrooms were frequently kept cooler for sleeping comfort, with temperatures around 16–18°C. Nighttime heating was often reduced or turned off, especially in older buildings without central heating. The kitchen was often heated to similar levels as living rooms (18–20°C) but often benefited from additional heat during cooking. Setback during non-use was not systematic but could drop to 15–17°C, especially overnight or when the house was empty. The hallways were typically among the coolest areas, maintained at 14–16°C, mainly to prevent freezing and moisture issues rather than for comfort. The bathrooms were heated more than other rooms, often to 20–22°C during use. Night setback was rare in pre-renovation settings, but temperatures could fall to 16–18°C when unoccupied, depending on the heating system (Storvolleng, 2013).

Table 3-6 Overview of the design guidelines according to Norwegian practices

Room	Day Setpoint	Night Setback	Notes (CEN, 2019; SINTEF Byggforsk., 2017)
Living room	21°C	17°C	Central thermostat location; main heated zone
Bedrooms	16°C	8°C	Lower comfort expectation, especially at night. There is commonly no heater and window opening during the night. It is common to keep the door closed
Kitchen	19°C	16°C	Often heated via adjacent rooms
Hallways	16°C	14°C	Typically, unheated, or indirectly heated
Bathroom	24°C (in use)	18°C	Heated only during use; electric floor heating common

However, user behavior played a significant role in actual indoor temperatures, with energy costs and the technical state of the building envelope influencing choices (Storvolleng, 2013).

A comfort baseline is proposed in Table 3-6 based on typical Norwegian design guidelines and NS-EN 16798-1:2019 (Category II), as well as SINTEF Byggforsk (SINTEF Byggforsk., 2017) and common practices.

Both scenarios involve natural ventilation, with mechanical extraction in the bathroom and kitchen. Kitchen extraction is typically activated during cooking periods, while bathroom extraction is generally controlled by the light switch. The electric radiators in the living room, kitchen, and hallways are regulated as outlined in Table 3-6. In the bedroom, heating remains off at all times. The window is assumed to be minimally open throughout the night, except when outdoor temperatures drop below approximately -5 °C, and the bedroom door remains closed.

3.4.2 Renovation baseline

In practice, renovations of historic buildings in Bakklandet rarely achieve the full technical standards of new construction (such as TEK17). Instead, the approach prioritizes preservation of historic character, practical improvements, and selective upgrades for comfort and energy efficiency.

Existing hydronic radiator systems are often retained and refurbished during building upgrades. In such cases, outdated boilers are typically replaced with more efficient heat sources, such as modern electric boilers or, where applicable, air-to-water heat pumps—though the latter are not found in the streets studied. Complete conversions to low-temperature systems remain rare unless the building envelope has undergone substantial thermal improvements. Radiators are usually preserved or replaced with models that replicate the original design to maintain the building's historic interior character. These systems typically operate at moderate to high supply and return temperatures (e.g., 70/50°C or 80/60°C). The original double-pipe hydronic circuit is generally kept, resulting in limited thermal zoning. While thermostatic radiator valves are sometimes added, more advanced zoned control systems are seldom implemented. Central thermostats may be upgraded or newly installed, but room-by-room temperature control remains basic. Woodstoves are still operated manually.

An alternative approach involves replacing the original cast iron radiators with electric heaters. This option is often favored by users due to historically low electricity prices and the increased flexibility in temperature control. Consistent with pre-renovation practices, bedrooms were frequently left without a heating source, while living rooms typically combined electric heaters with woodstoves. In many cases, older coal-burning or inefficient wood stoves and open fireplaces were replaced by modern, high-efficiency woodstoves that emit fewer particulate emissions and offer improved combustion performance. Electric heaters are commonly installed in kitchens and hallways, while bathrooms are usually equipped with electric underfloor heating.

Both electric radiators and underfloor systems are generally controlled by room-level thermostats. These may be manually adjustable or programmable with time-based schedules, although they are most often left at fixed settings. For the renovation baseline used in simulations, the assumed configuration includes electric radiators in all rooms except the bedroom, electric underfloor heating in the bathroom, and a woodstove in the living room. All electric heaters are assumed to be regulated by room-level thermostats with a single fixed setpoint. Woodstoves are still operated manually.

Mechanical ventilation with heat recovery is seldom installed. In wet rooms (kitchens, bathrooms) local exhaust fans are added for moisture control since renovations after 1997. General ventilation relies on natural infiltration and window airing, as in the original state, to avoid intrusive interventions in historic fabric.

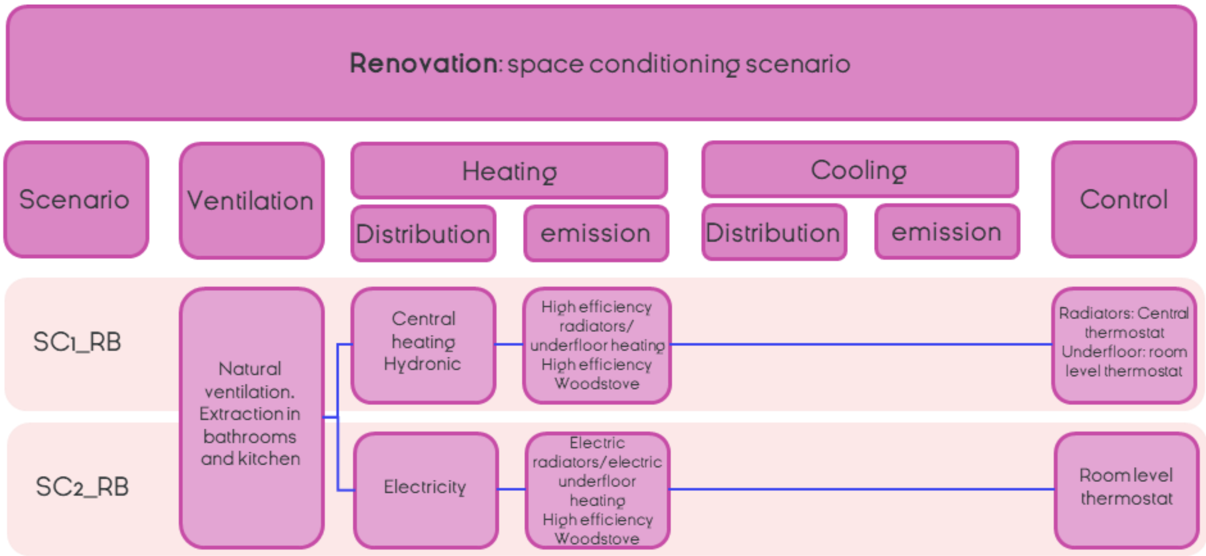


Figure 3-11 Schematic overview of the Belgian Renovation Baseline (RB) Space Conditioning (SC) scenarios for the Norwegian archetype.

Table 3-6 gives an overview of the normal design guidelines. Regarding indoor comfort temperatures, the primary heated space—the living room—was typically maintained at 20–22 °C during periods of use. However, when wood stoves were in operation, peak temperatures could rise to 24–26 °C. Nighttime temperature setbacks were uncommon; instead, heating was often turned off, especially when manually operated or reliant on wood stoves, leading to temperature drops to around 17–18 °C during unoccupied periods (Storvolleng, 2013).

Bedrooms were frequently kept cooler to support sleeping comfort. In the absence of active heating, bedroom temperatures could fall to approximately 8 °C during winter nights and fluctuate between 16–20 °C during the rest of the year. When bedrooms were used during the day, electric radiators were sometimes installed, allowing temperatures to reach levels comparable to those in living rooms. For simulations, a daytime setpoint of 16 °C and a nighttime setpoint of 10 °C are proposed to reflect this variability.

Kitchen temperatures were generally like those in living rooms, typically ranging from 18–20 °C, and often experienced additional heat gains during cooking. Temperature setbacks during periods of non-use were not systematically applied but could lead to reductions to 15–17 °C, especially overnight or when the dwelling was unoccupied.

Hallways were usually among the coolest areas in the home, maintained at approximately 14–16 °C. Heating in these spaces was primarily intended to prevent freezing and moisture accumulation rather than to ensure thermal comfort. Bathrooms were typically the warmest rooms, often heated to 20–22 °C during periods of use.

4 Estonia

The study concentrates on the historic apartment buildings described in deliverable D5.1.

4.1 Background information: Literature and Databases

Several prior studies and surveys provide valuable insights into the construction quality, service life, and indoor environmental conditions of residential buildings in Estonia and the Baltic region.

A comprehensive condition assessment of wooden apartment buildings in Estonia was conducted by Kalamees et al. (Kalamees et al., 2010), highlighting structural issues and estimating service life projections. Similarly, the technical condition and expected longevity of brick apartment buildings were analysed by Kalamees et al. (Kalamees et al., 2011), offering a comparative basis for evaluating older multifamily dwellings.

Further research by Arumägi et al. (Arumägi et al., 2015) explored indoor climate conditions and hygrothermal loads in historic wooden apartment buildings in cold climates. The study encompassed 29 buildings and 41 apartments and included long-term measurements of temperature, relative humidity, CO_2 concentrations, and air change rates, along with occupant surveys. Results showed that during winter, indoor temperatures were above acceptable comfort range (class III, EN 15251:2007) in 83% of the apartments, and in 25% during summer (CEN, 2007).

Occupants frequently reported discomfort due to unstable temperatures and cold floors in winter. The average daily indoor temperature variation reached up to 3.8 °C in buildings where complaints were noted, suggesting insufficient heating capacity and poor airtightness. Moisture excess and low ventilation rates were also identified, with air-change rates below the recommended minimum in over half the bedrooms studied. Based on the measurement data, the authors developed a stochastic hygrothermal load model tailored for renovation and risk analysis of historic wooden buildings

Additionally, Alev et al. (Alev et al., 2016) studied indoor hygrothermal conditions and occupant satisfaction in naturally ventilated historic buildings across the Baltic Sea region. The findings inform renovation strategies that respect heritage values while improving living conditions.

Ilomets et al. (2018) investigated hygrothermal loads for both deterministic and stochastic envelope design approaches in cold climates, providing a methodological foundation for performance-based design.

These studies, supported by both field investigations and simulation-based methods, form a solid empirical and analytical foundation for assessing existing building stock and guiding renovation decisions.

4.2 Equipment and set-up

In five case-study buildings, environmental monitoring was carried out in two apartments per building, with the exception of the case Wood A, where data collection was limited to a single apartment. Measurements included temperature, relative humidity (RH), and carbon dioxide (CO_2) concentrations, which were recorded in multiple rooms within each dwelling.

Outdoor climate data was obtained from a meteorological station located approximately 5 km from the case study site.

The temperature, relative humidity and CO_2 were measured at 5-minute intervals. The indoor loggers were located on separating walls in the main bedroom and in the living room.

The measurements were done using a wireless, portable device for measuring air quality. The device measures carbon dioxide (CO_2) concentration, temperature, relative humidity, and atmospheric pressure. Table 4-1 provides an overview of the sensor specification.

Table 4-1 Sensor specification of used devices for Estonia.

Datalogger Model	Parameter measured	Measurement range	Accuracy
Aranet4 PRO (indoor climate)	Temperature	0-50 °C	+/-0.3 °C
	Relative humidity	0-85 %	+/- 3 %
	CO_2	0-9999 ppm	± (30 ppm + 3 % of reading)
LSI Lastem DMA672.1 (outdoor climate)	Temperature	-50–100 °C	+/-0.1 °C
	Relative humidity	0-100 %	+/- 1 %

CO_2 levels were measured in the living rooms and bedrooms during the summer and winter period for the assessment of the IEQ in the apartments. The CO_2 levels were measured at 5-minutes intervals during 32…35 weeks using CO_2 monitors (measurement range 0…9999 ppm, with an accuracy of ±30ppm +3% of reading).

Target values from the indoor climate category "class III" were selected to assess indoor thermal conditions: +18…25 °C during winter months and +22…27°C during summer months.

Indoor climate category "class III" represents an acceptable moderate level of expectation used for existing buildings. In thermal evaluation, an hourly criterion is used, based on the calculation of the percentage of time when the criteria are met or are outside a specified range.

4.3 Observations and data analysis

4.3.1 EPBD building temperature

This section provides an overview of indoor temperature conditions in the context of the Energy Performance of Buildings Directive (EPBD), which emphasizes the importance of maintaining adequate thermal comfort while ensuring energy efficiency.

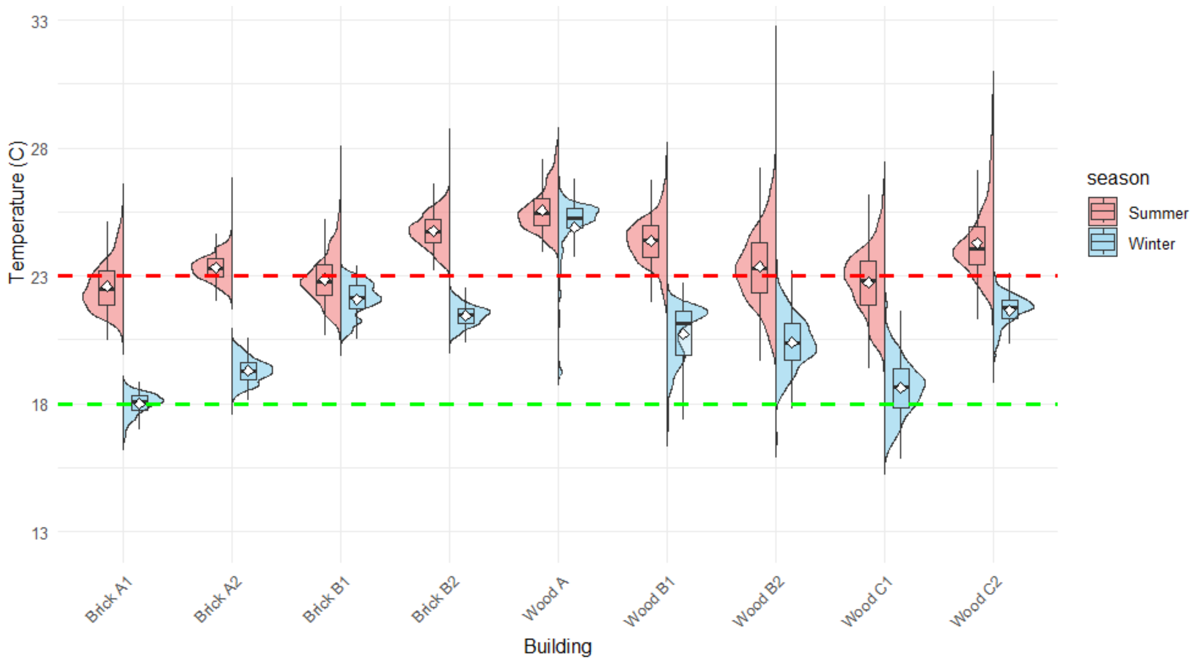


Figure 4-1 Distribution and boxplots of the building average temperature for summer (Jun-Jul-Aug) and winter (Dec-Jan-Feb) for the Estonian cases. Volume weighted temperature of all available temperature measurements of the case studies. The green dotted reference line (18 °C) is the assumed winter temperature in the Belgian EPBD calculations. The red dotted reference line (23 °C) is the assumed summer indoor setpoint temperature for cooling energy

Within the EPC/EPBD calculation frameworks, the entire building volume is assumed to be isothermal, with standard indoor temperatures for Belgium of 18 °C in winter and 23 °C in summer. For international comparability, the standard EPC temperatures for Belgium are used in this graph as well. Belgium is chosen as it represents a mild climate.

The analysis in Figure 4-1 shows that mean weighted indoor temperatures during winter varies with approximately 7°C between the highest and lowest with the lowest being around 18°C. Relatively high indoor temperatures exceeding the 18°C reference is thus common in the investigated Estonian townhouse buildings. This suggest high temperature setpoints of the occupants and an underestimation of the heat losses if one would use 18°C as winter indoor temperature.

For the summer temperature data mean temperatures differ by approximately 5°C only, with the lowest around 22.5°C. Occupants seem to accept these higher temperatures since later additions of active cooling devices was limited. This indicates that assuming a summer-comfort temperature of 23°C would be too negative for the Estonian townhouse cases.

In both seasons, the narrower distribution spread observed for the brick archetype compared to the wooden archetype indicates the influence of construction type on indoor temperature regulation, primarily attributable to differences in thermal mass. Additionally, the characteristics of the heating system contribute to this variation, as centrally heated brick buildings typically exhibit more stable indoor temperatures, while stove-heated wooden buildings are subject to greater fluctuations driven by intermittent heat supply and occupant behaviour.

The following subsections present a detailed evaluation of adaptive thermal comfort based on EN 16798 and observed temperature levels in relation to EPBD requirements and expectations.

4.3.2 Temperature variability

In most apartments, the heating setpoint is typically around 21 °C, which is generally used as the reference temperature for both thermal comfort assessment and energy performance evaluations in Estonia. During colder periods, there is a tendency among occupants to maintain slightly higher indoor temperatures. Lower temperatures are occasionally observed in rooms with intermittent use, such as spare bedrooms or storage areas, where heating demand is naturally reduced.

In certain living rooms and bedrooms where lower temperatures were recorded, the cause appeared to be related to the technical characteristics or operational state of the heating system. In timber-framed apartment buildings, this was often due to uneven heat distribution inherent to the system design, while in some masonry buildings, low temperatures were attributed to malfunctioning or improperly adjusted heating systems. In the latter case, occupants reported dissatisfaction and discomfort due to insufficient indoor temperatures.

The overall indoor temperature range was wider in apartments with stove-based heating systems, reflecting greater temporal fluctuations. In contrast, apartments with water-based central heating exhibited narrower temperature variations and more stable indoor conditions. In a few cases, underheated rooms were identified, where low temperatures were likely a result of heating system limitations rather than intentional occupant behaviour.

The following statement provides a descriptive summary of average indoor temperatures across all monitored rooms and seasons. The average indoor temperature of all rooms during the winter (Dec-Jan-Feb) period was +20.5 °C (standard deviation: 1.97 °C, min. +16.7 °C and max +25.7 °C) and during the summer (Jun-Jul-Aug) period +23.6 °C (standard deviation: 0.95 °C, min +21.9 °C and max +25.8 °C).

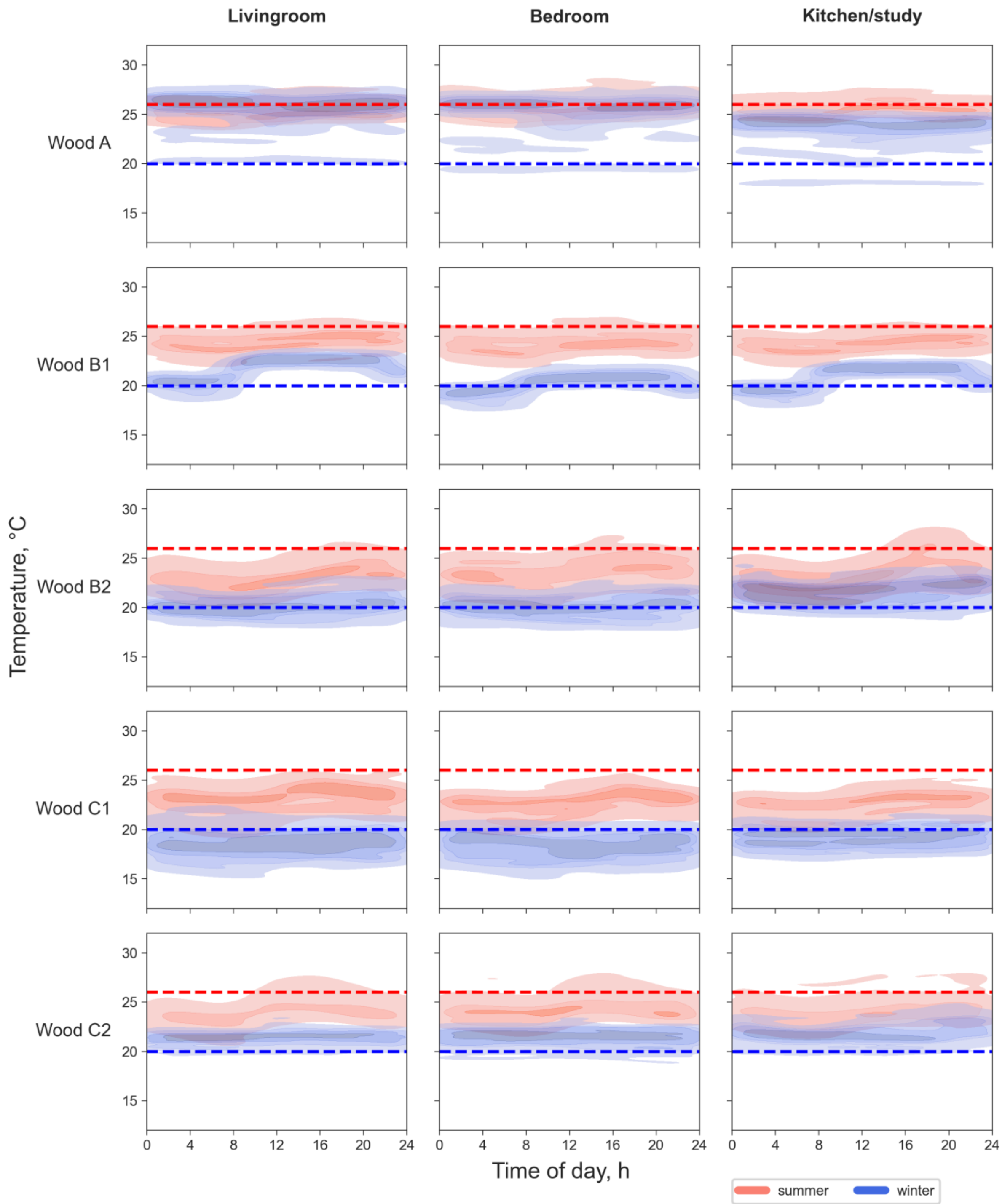


Figure 4-3 show a density plot of the indoor temperatures for the summer and winter in main rooms in brick and in wooden apartment buildings.

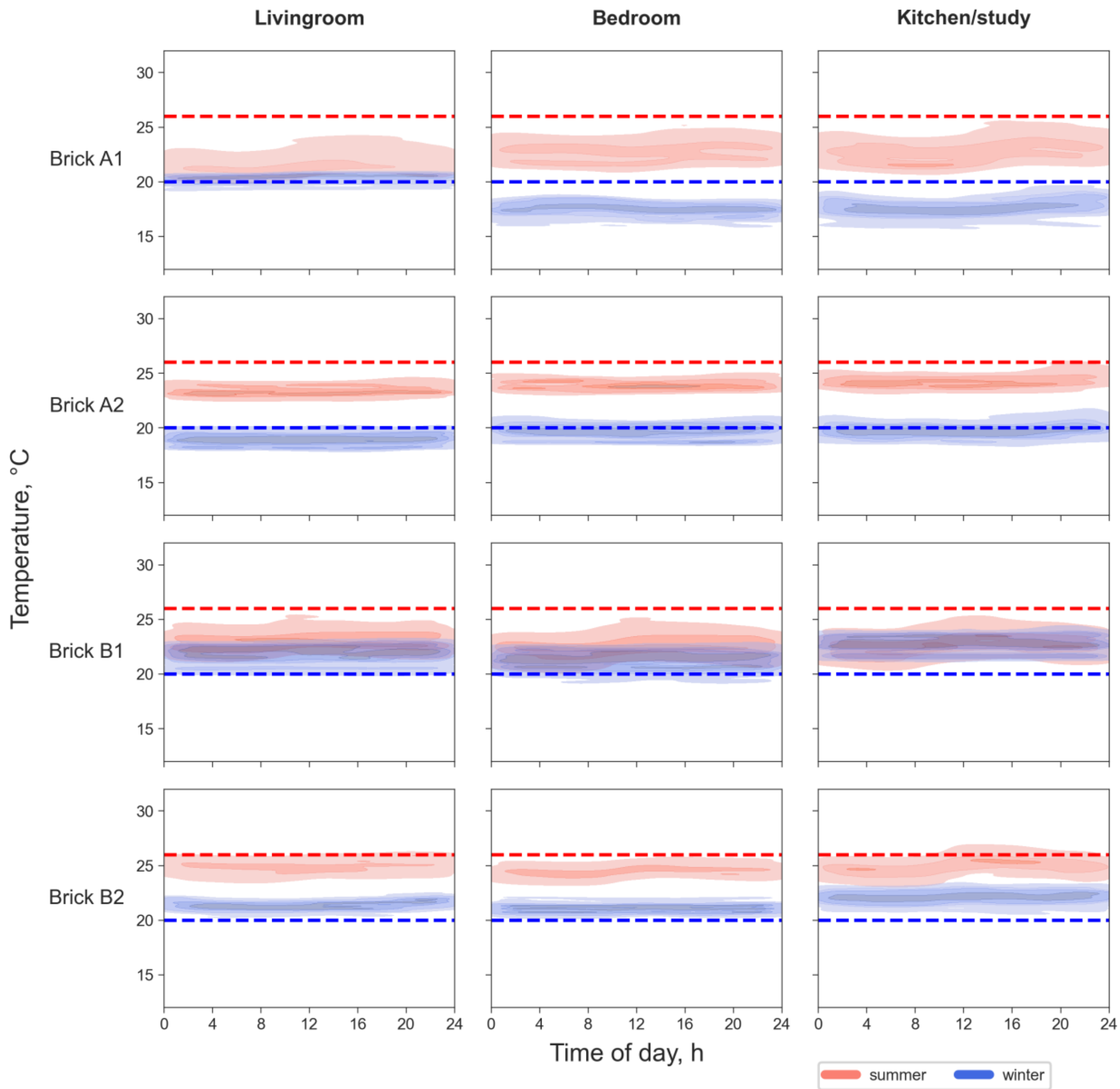


Figure 4-2 Indoor temperature distribution (density plot for the 2.5th-97.5th percentile) as a function of the time of day for summer (Jun-Jul-Aug) and winter (Dec-Jan-Feb) in main rooms in Estonian brick apartment buildings. The blue and red dotted reference lines are the temperature levels at the lower (20°C) and higher end (26°C) of the allowed temperature range for the thermal IEQ class II according to EN-16798.

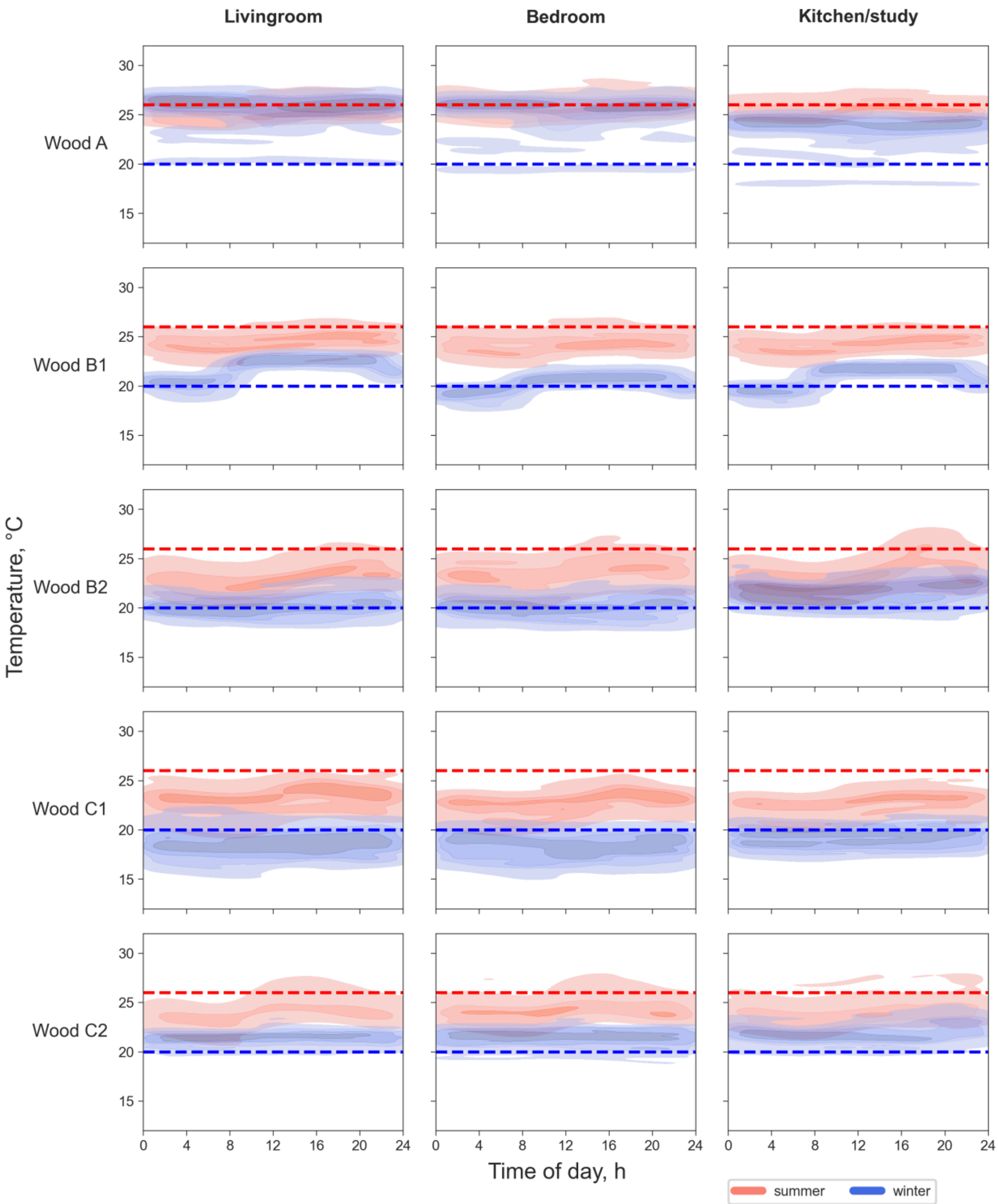


Figure 4-3 Indoor temperature distribution (density plot for the 2.5th-97.5th percentile) as a function of the time of day for summer (Jun-Jul-Aug) and winter (Dec-Jan-Feb) in main rooms in Estonian wooden apartment buildings. The blue and red dotted reference lines are the temperature levels at the lower (20°C) and higher (26°C) end of the allowed temperature range for the thermal IEQ class II according to EN-16798.

In large brick apartment buildings with central heating systems, the indoor temperature is generally more stable due to centralized control (see Figure 4-4Figure 4-4). The heating system is regulated at the building's heat substation based on the outdoor air temperature, which ensures a relatively uniform thermal environment throughout the building. Within individual apartments, occupants can adjust room temperatures using thermostatic radiator valves, allowing for local fine-tuning without significantly disturbing the system's balance. This effect is reflected, for instance, in bedroom temperature measurements, where a temperature difference of approximately one degree Celsius between rooms within the same apartment indicates user-level adjustments rather than limitations of the heating system itself.

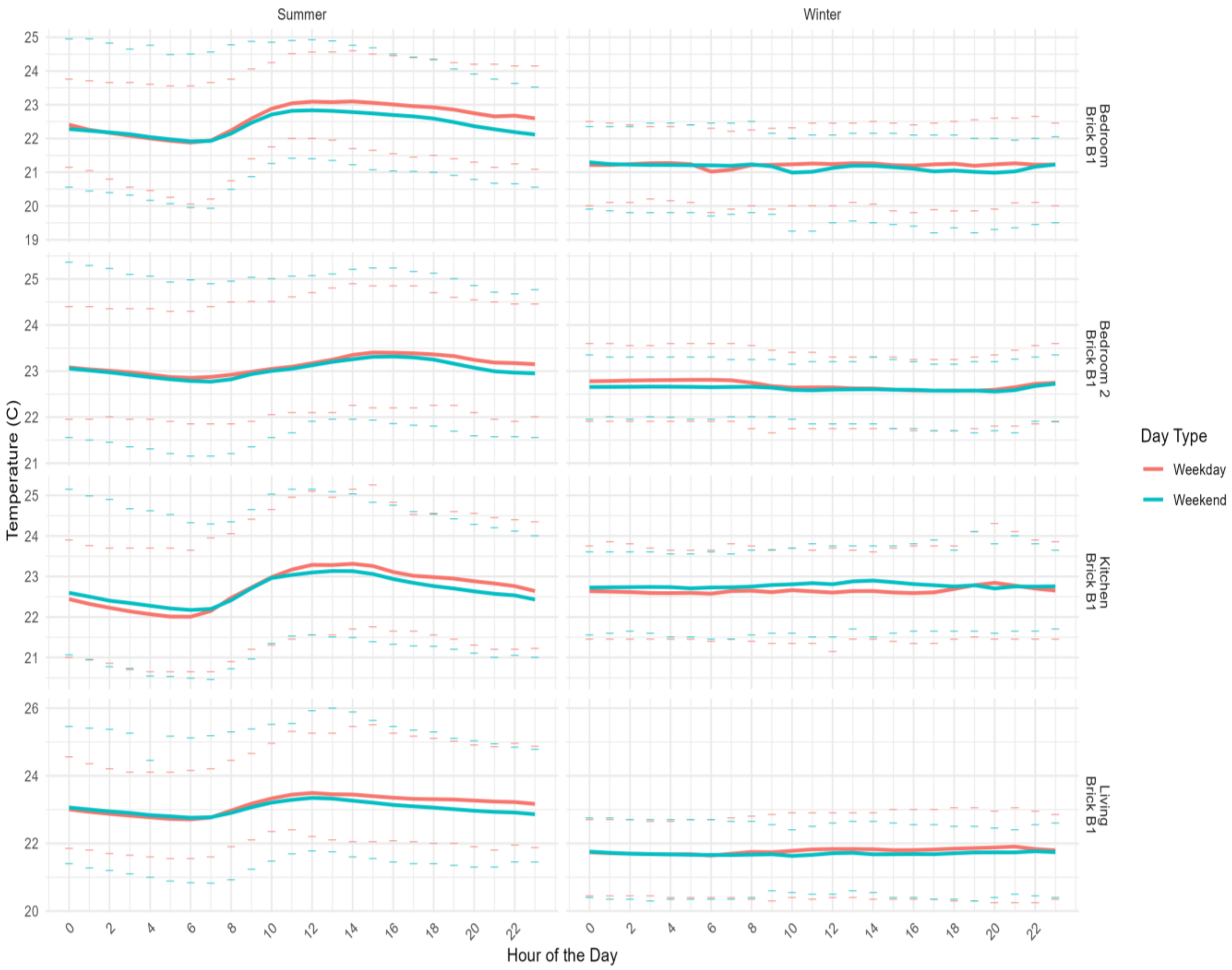


Figure 4-4 Temperature distribution in the specified rooms, comparing weekdays and weekends during summer and winter for the Estonian case Brick B1. Solid lines represent the mean indoor temperature as a function of time of day, separately for summer and winter, and for weekdays and weekends. Dotted lines indicate the 5th and 95th percentiles of the corresponding data.

In apartments equipped with individual heating systems, occupants have greater flexibility to implement personal heating strategies, including night-time temperature setback. In such cases, the user can deliberately lower the setpoint temperature during the night to reduce energy consumption without compromising comfort. This practice is made possible by apartment-level heating controls, which allow for independent scheduling and room-specific temperature regulation. Temperature data from these apartments often show a clear diurnal pattern, with noticeably lower temperatures during night hours, reflecting conscious occupant behaviour aimed at improving energy efficiency. A good example of this behaviour is illustrated in Figure 4-5.

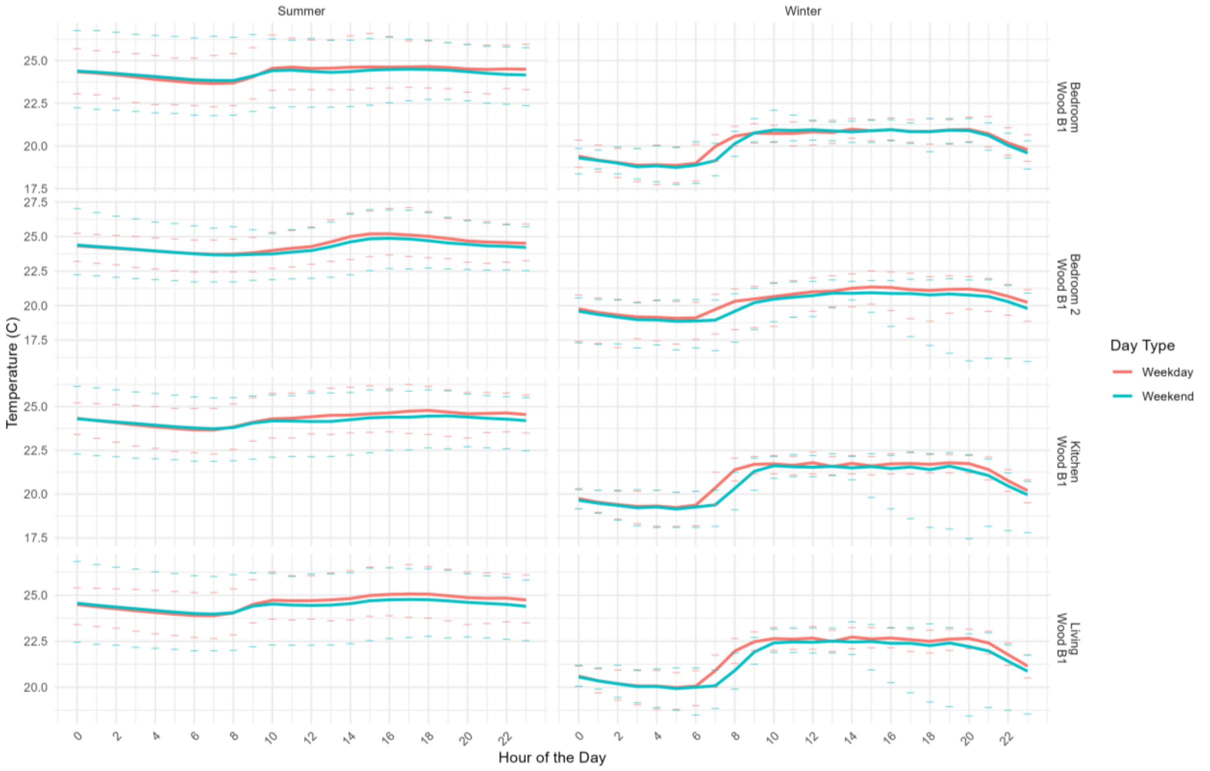


Figure 4-5 Temperature distribution in the specified rooms, comparing weekdays and weekends during summer and winter for the Estonia case Wood B1. Solid lines represent the mean indoor temperature as a function of time of day, separately for summer and winter, and for weekdays and weekends. Dotted lines indicate the 5th and 95th percentiles of the corresponding data.

4.3.3 EN 16798 Adaptive Thermal Comfort

The recorded indoor temperature data were analysed in accordance with the adaptive comfort model for periods when the outdoor air temperature was at or below 10 °C. Although the applicability of the adaptive model is typically oriented toward warmer seasons and free-running buildings, this analysis provides valuable insight into indoor thermal performance during colder conditions.

This paragraph presents an aggregated overview of measured indoor temperature distributions across the full sample. On average, indoor temperatures fell within Category I limits for 67% of the observed time, with variation across monitored apartments ranging from 2% to 100%. Conditions corresponding to Category II were observed for an average of 10% of the time, with a range between 0% and 38%, while Category III was applicable for approximately 8% of the time, varying between 0% and 51%. In addition to these comfort classifications, indoor temperatures fell below the minimum threshold of Category I (19 °C) for an average of 19% of the time, with values ranging from 0% to as high as 94%, indicating that in some apartments indoor conditions were frequently colder than recommended comfort levels.

These findings suggest that while indoor environments generally met the highest thermal comfort expectations during colder outdoor conditions, there were notable deviations in some cases. The variability between apartments points to the influence of individual building characteristics, heating control strategies, and occupant behaviour, highlighting the importance of tailored thermal management during the heating season.

Instances where the indoor temperature exceeded 27 °C were rare. On average, this occurred during only 1% of the observation time, with a variation from 0% to a maximum of 7%. These exceedances were primarily observed in a single apartment located in a wooden apartment building, suggesting that overheating was not a widespread issue across the monitored sample.

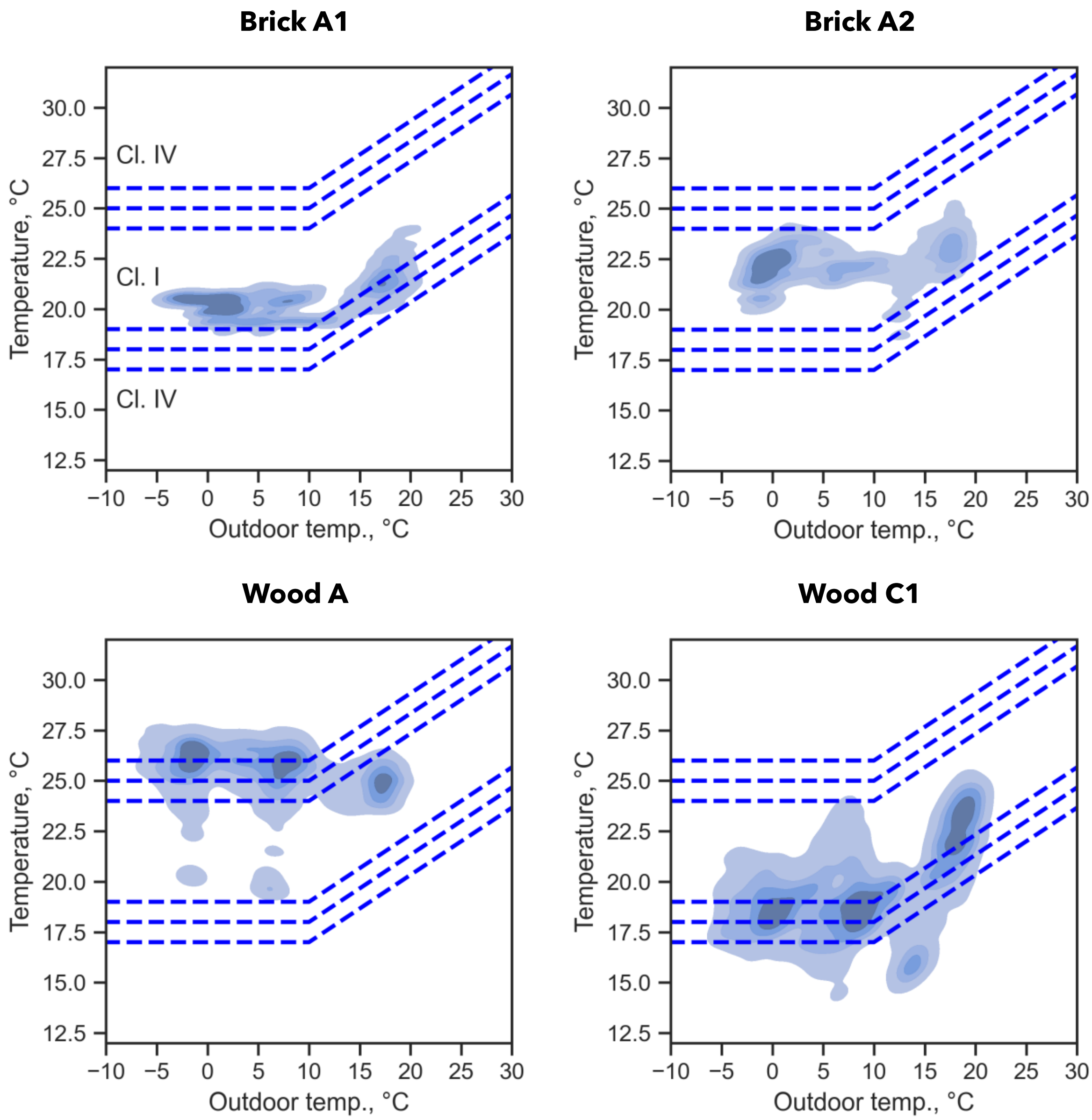


Figure 4-6 Temperature distribution of the measured indoor temperature as a function of the exponentially weighted outdoor temperature (density plot for the 2.5th-97.5th percentile data) for living rooms in Brick A1 (top-left), Brick B1 (top-right), Wood A (bottom-left) and Wood C1 (bottom-right) Estonian brick and wooden apartment buildings. The dotted reference lines are based on the adaptive thermal comfort acceptability limits as described in the EN-16798 standard.

Figure 4-6 shows the adaptive comfort graphs for the Living room of case Brick A1, Brick B1, Wood A and Wood C1.

The percentage of time of the living room in a certain category is shown in Table 4-2 and the percentage of days of the bedroom in a certain category is shown in Table 4-3.

Table 4-2 Percentage of datapoints in or outside adaptive temperature class for the living room, All data of Estonian cases.

% of time in Cat. #	Brick_A1	Brick_B1	Brick_B2	Wood_A	Wood_B1	Wood_B2	Wood_C1	Wood_C2
Hours of data considered	7874	7677	7340	7012	7698	7674	6675	6673
Start-end of data	Jun - May							
Below	1%	0%	0%	0%	1%	8%	52%	1%
Class I	99%	99%	100%	11%	99%	92%	35%	84%
Class II	2%	0%	0%	0%	2%	9%	27%	1%
Class III	0%	0%	0%	0%	0%	1%	18%	0%
Overheating	0%	0%	0%	7%	0%	0%	0%	2%

Table 4-3 Percentage of datapoints in or outside adaptive temperature class for the bedrooms of all Estonian cases.

% of time in Cat. #	Brick_A1	Brick_A12	Brick_A2	Brick_A22	Brick_B1	Brick_B12
Hours of data considered	7845	7745	7410	7410	7677	7677
Start-end of data	Jun - May					
Below	87%	94%	25%	13%	1%	0%
Class I	13%	6%	75%	87%	99%	99%
Class II	30%	13%	27%	11%	1%	0%
Class III	51%	37%	2%	3%	0%	0%
Class IV	0%	0%	0%	0%	0%	0%
Overheating	0%	0%	0%	0%	0%	0%
	Brick_B2	Wood_A	Wood_B1	Wood_B2	Wood_C1	Wood_C2
Hours of data considered	7340	7012	5001	7674	6674	6673
Start-end of data	Jun - May					
Below	0%	2%	6%	11%	56%	1%
Class I	87%	11%	45%	89%	31%	84%
Class II	12%	2%	5%	11%	25%	1%
Class III	3%	0%	1%	2%	21%	0%
Class IV	1%	5%	0%	0%	0%	2%
Overheating	0%	5%	0%	0%	0%	2%

4.3.4 CO2 variability

A clear seasonal difference can be observed in the measured data, particularly in relation to window ventilation practices. During summer, higher outdoor temperatures promote frequent window opening, resulting in better natural ventilation and lower CO_2 levels. During winter, windows are more likely to remain closed due to cold weather, which reduces air exchange and contributes to higher indoor CO_2 concentrations. These behavioural patterns play a significant role in shaping the seasonal variation in indoor air quality.

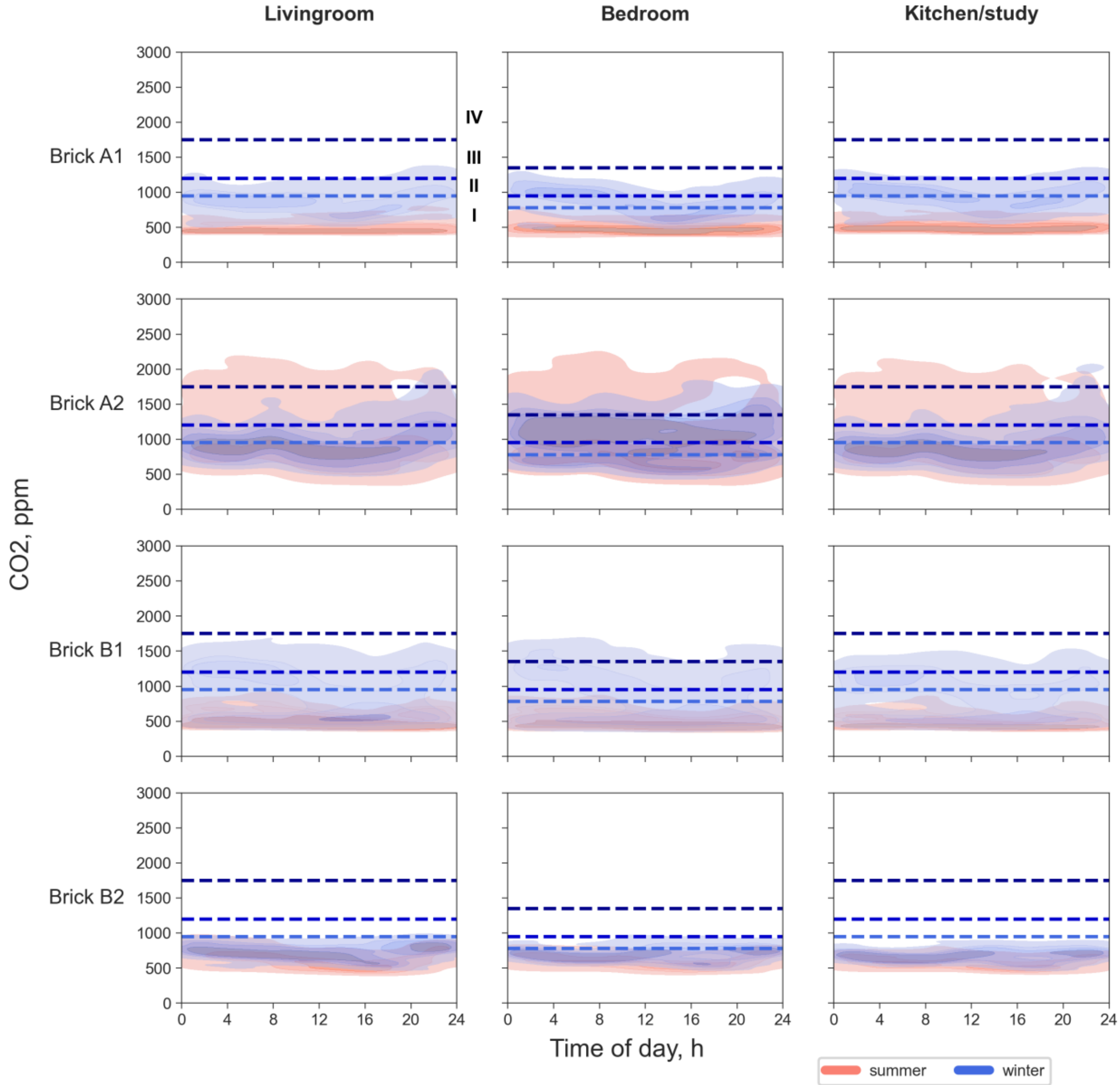


Figure 4-7 and Figure 4-8 show a density plot of the CO_2 concentration for the summer and winter in the main rooms of the brick and in wooden apartment buildings.

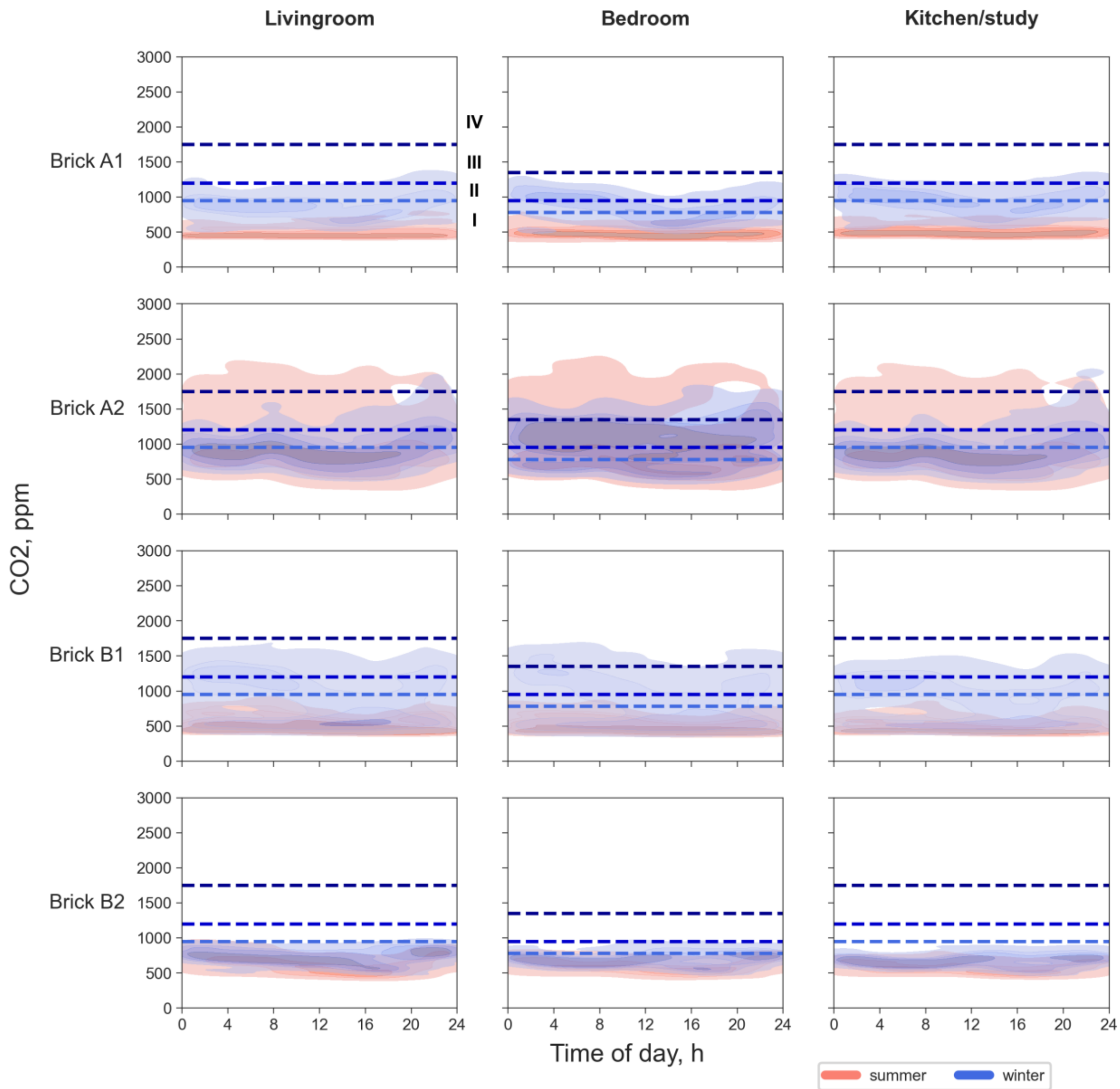


Figure 4-7 CO_2 concentration distribution (5th–95th percentile density plots) as a function of time of day for summer (June–July–August) and winter (December–January–February) in Estonian brick buildings. Blue dotted reference lines represent the CO_2 threshold values for indoor environmental quality (IEQ) classes as defined in EN 16798.

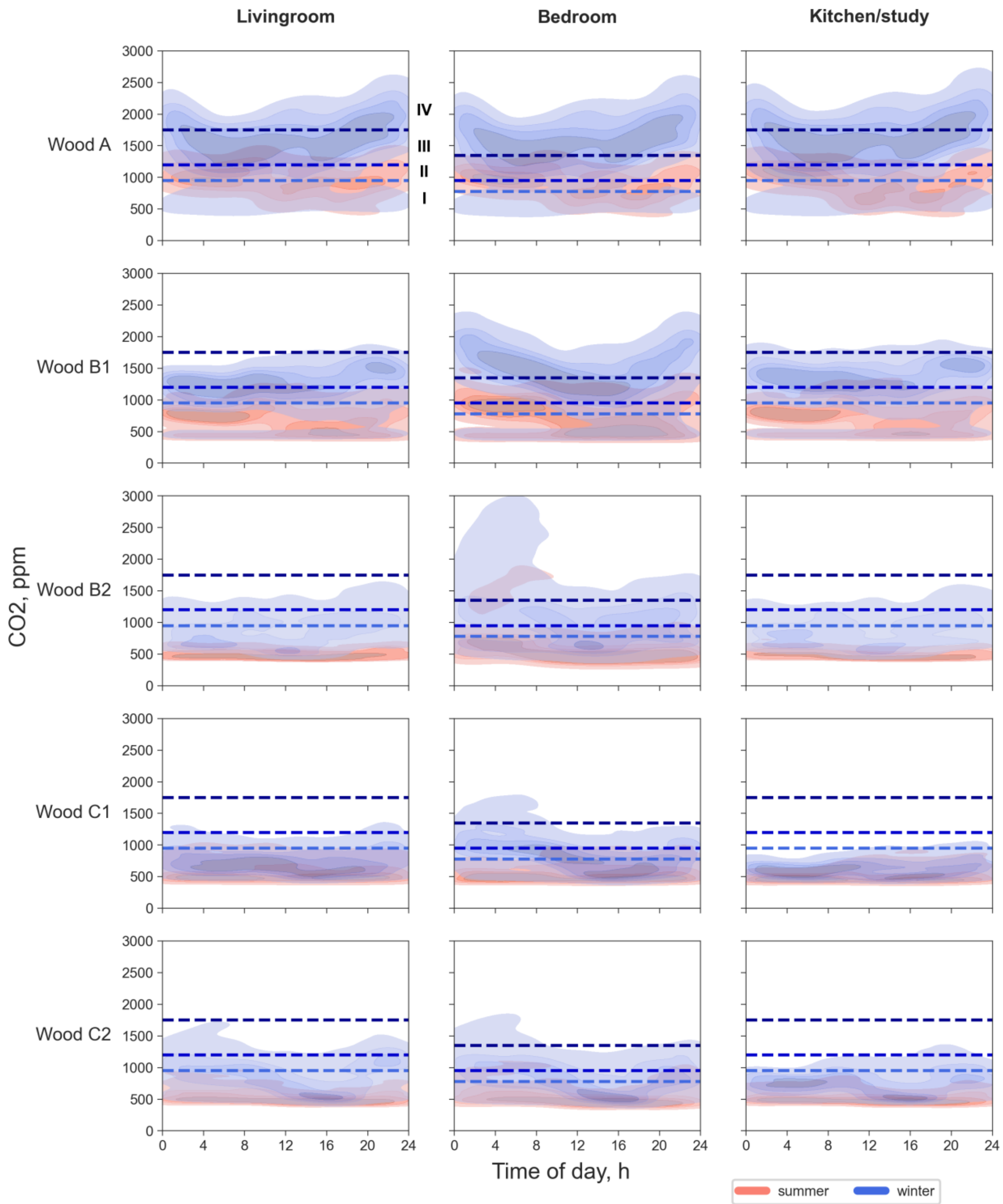


Figure 4-8 CO_2 concentration distribution (5th–95th percentile density plots) as a function of time of day for summer (June–July–August) and winter (December–January–February) in Estonian wooden apartment buildings. Blue dotted reference lines represent the CO_2 threshold values for indoor environmental quality (IEQ) classes as defined in EN 16798.

Figure 4-9 shows the CO_2 concentration distribution in a selection of rooms, comparing weekdays and weekends during summer and winter for the Estonian cases. In general, CO_2 levels remain relatively stable throughout the day in most apartments, with no significant differences observed between weekdays and weekends. Instead, the variation is more pronounced between daytime and nighttime periods, reflecting typical occupancy patterns—higher concentrations during the night when bedrooms are in use, and lower levels during the day due to reduced presence or improved ventilation. CO_2 concentrations can exceed 2000 ppm during nighttime and early morning hours before gradually declining as the day progresses. This pattern likely results from a combination of high occupancy and limited ventilation during sleeping hours. The figure also clearly illustrates the seasonal contrast between warm and cold periods: nighttime CO_2 concentrations in bedrooms are generally higher during the heating season, when windows are more likely to remain closed, and lower in warmer periods, when window ventilation is more common.

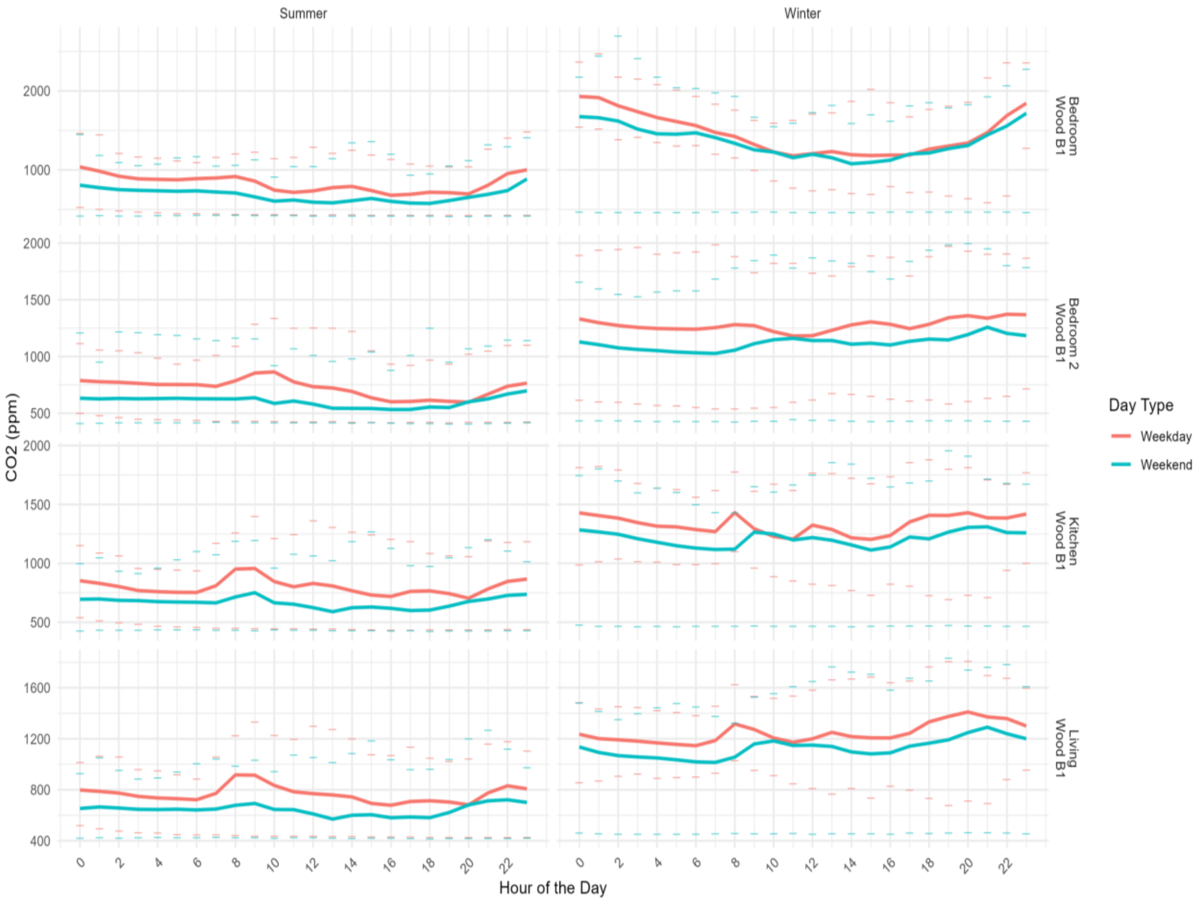


Figure 4-9 CO_2 concentration distribution in the specified rooms, comparing weekdays and weekends during summer and winter for the Estonian case Wood B1. Solid lines represent the mean indoor CO_2 concentration as a function of time of day, separately for each season and day type. Dotted lines indicate the 5th and 95th percentiles of the corresponding distributions.

4.3.5 EN 16798 IEQ categories

The indoor CO_2 concentration was used as an indicator of indoor air quality since occupants are the main pollution sources in dwellings. During our measurements, the peak values varied between 1728 ppm to 3869 ppm in the wintertime. During the winter period, the average value of all the bedrooms was 987 ppm (varied between 400…3869 ppm) at the nighttime. During the summer period, the average value of all the bedrooms was 690 ppm (varied between 400…3470 ppm). Measured CO_2 concentrations were above 950 ppm 25% of the measurement time during winter period and 13% of measurement time during summer period. Measured CO_2 concentrations were above 1350 ppm 14% of the measurement time during winter and summer periods in bedrooms.

The IEQ-classes analysis was done for the living rooms and bedrooms of all cases. Each day in the dataset was assigned a category based on its 95th percentile CO_2 concentration value. The percentage of days of the living room in a certain category is shown in Table 4-4 and the percentage of days of the bedroom in a certain category is shown in Table 4-5.

Table 4-4 CO_2 based IEQ categorisation for the living rooms of all Estonian cases.

% of days in Cat. #	Brick_A1	Brick_B1	Brick_B2	Wood_A	Wood_B1	Wood_B2	Wood_C1	Wood_C2
Days in dataset	327	320	306	292	321	320	278	278
Start-end of data	Jun - May							
Category I	82%	64%	95%	17%	37%	65%	91%	70%
Category II	15%	17%	4%	17%	29%	21%	7%	21%
Category III	3%	19%	1%	45%	33%	13%	2%	9%
Category IV	0%	0%	0%	21%	1%	0%	0%	0%

Table 4-5 CO_2 based IEQ categorisation for the bedrooms of all Estonian cases.

% of days in Cat. #	Brick_A1	Brick_A12	Brick_A2	Brick_A22	Brick_B1	Brick_B12	Brick_B2
Days in dataset	327	323	309	309	320	320	306
Start-end of data	Jun - May						
Cat I	58%	48%	68%	25%	56%	48%	85%
Cat II	22%	16%	21%	18%	11%	12%	13%
Cat III	18%	25%	11%	33%	23%	22%	1%
Cat IV	0%	10%	0%	24%	10%	18%	0%
	Wood_A	**Wood_B1**	**Wood_B12**	**Wood_B2**	**Wood_B22**	**Wood_C1**	**Wood_C2**
Days in dataset	292	208	321	320	320	278	278
Start-end of data	Jul - May						
Cat I	12%	24%	29%	45%	48%	59%	51%
Cat II	8%	14%	17%	13%	14%	18%	17%
Cat III	29%	32%	34%	28%	24%	17%	25%
Cat IV	51%	31%	19%	15%	13%	6%	7%

The following figures present CO_2 concentration measurement results, providing a visual illustration of how the previously discussed tables came to be. The graphs show the distribution of measured values in relation to outdoor air temperature for the living room and main bedroom of Brick A1 and Wood A, highlighting how indoor air quality varies under different seasonal and environmental conditions (Figure 4-10 and Figure 4-11).

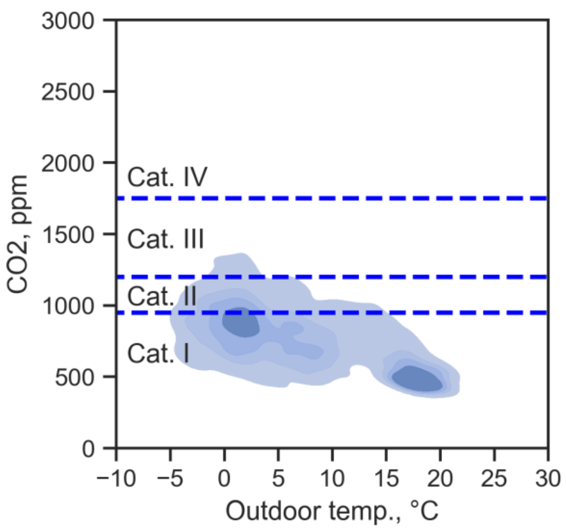


Figure 4-10 Distribution of the measured CO2 as a function of the exponentially weighted outdoor temperature (density plot for the 2.5th-97.5th percentile data) for living room the Estonian apartments Brick A1 (left) and Wood A (right). The dotted reference lines are the limits of the IEQ categories.

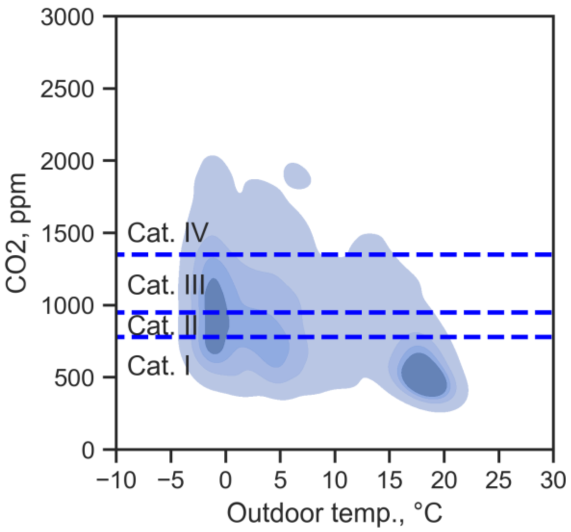


Figure 4-11 Distribution of the measured CO_2 as a function of the exponentially weighted outdoor temperature (density plot for the 2.5^{th}-97.5^{th} percentile data) for the main bedroom of Estonian apartment s Brick A1 (left) and Wood A (right). The dotted reference lines are the limits of the IEQ categories.

4.3.6 Relative humidity

Figure 4-12 and Figure 4-13 presents an overview of relative humidity (RH) in the living room, kitchen, and bathroom.

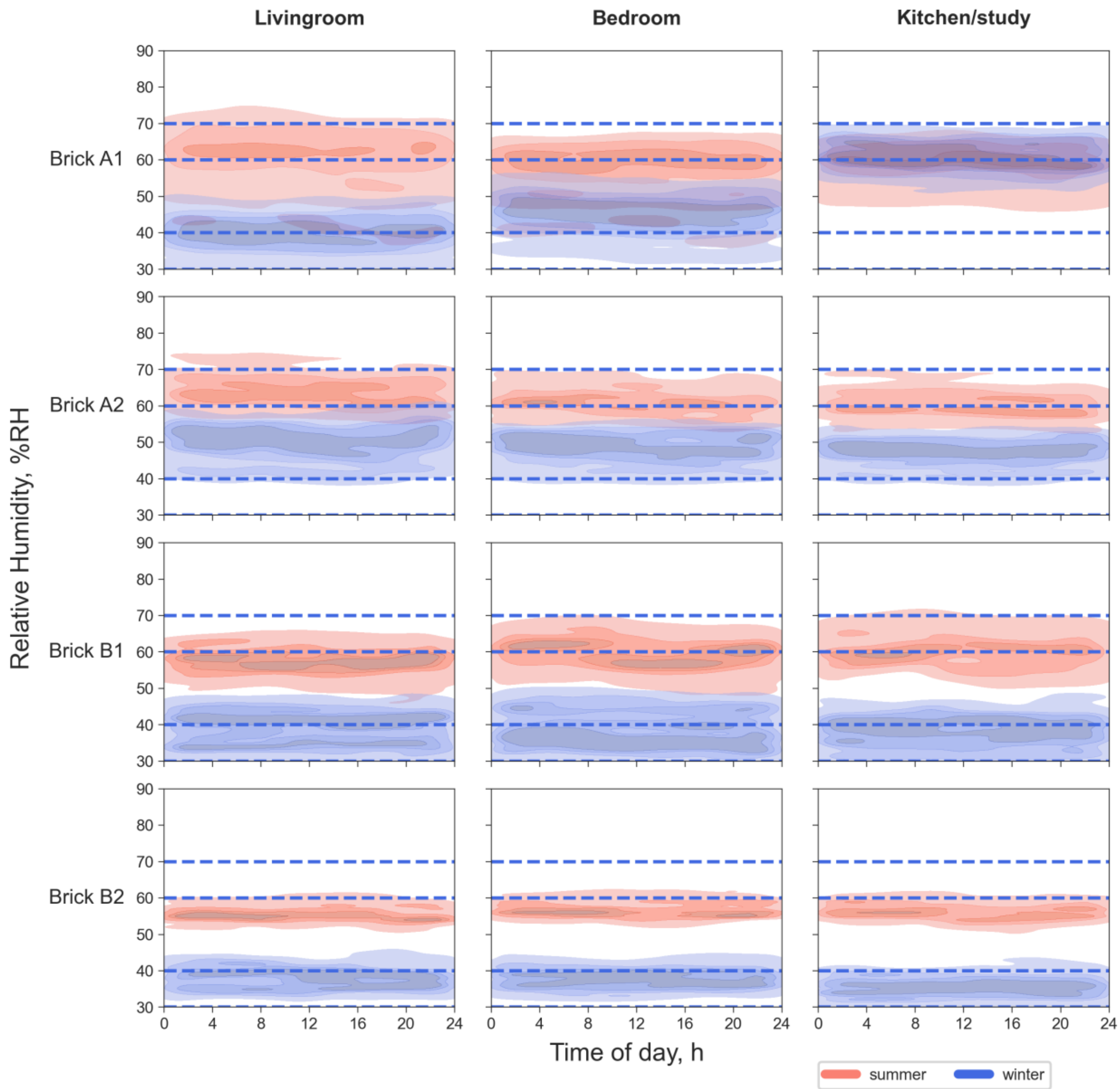


Figure 4-12 Relative humidity distribution (density plot for the 5th-95th percentile) as a function of the time of day for summer (Jun-Jul-Aug) and winter (Dec-Jan-Feb) in four spaces: living, main bedroom, kitchen and bathroom in Estonian brick apartment buildings. Empty slots mean no relevant data was available. The blue dotted reference lines at 30-40% and 60-70% indicate typically used intervals considered to be perceived as comfortable by people.

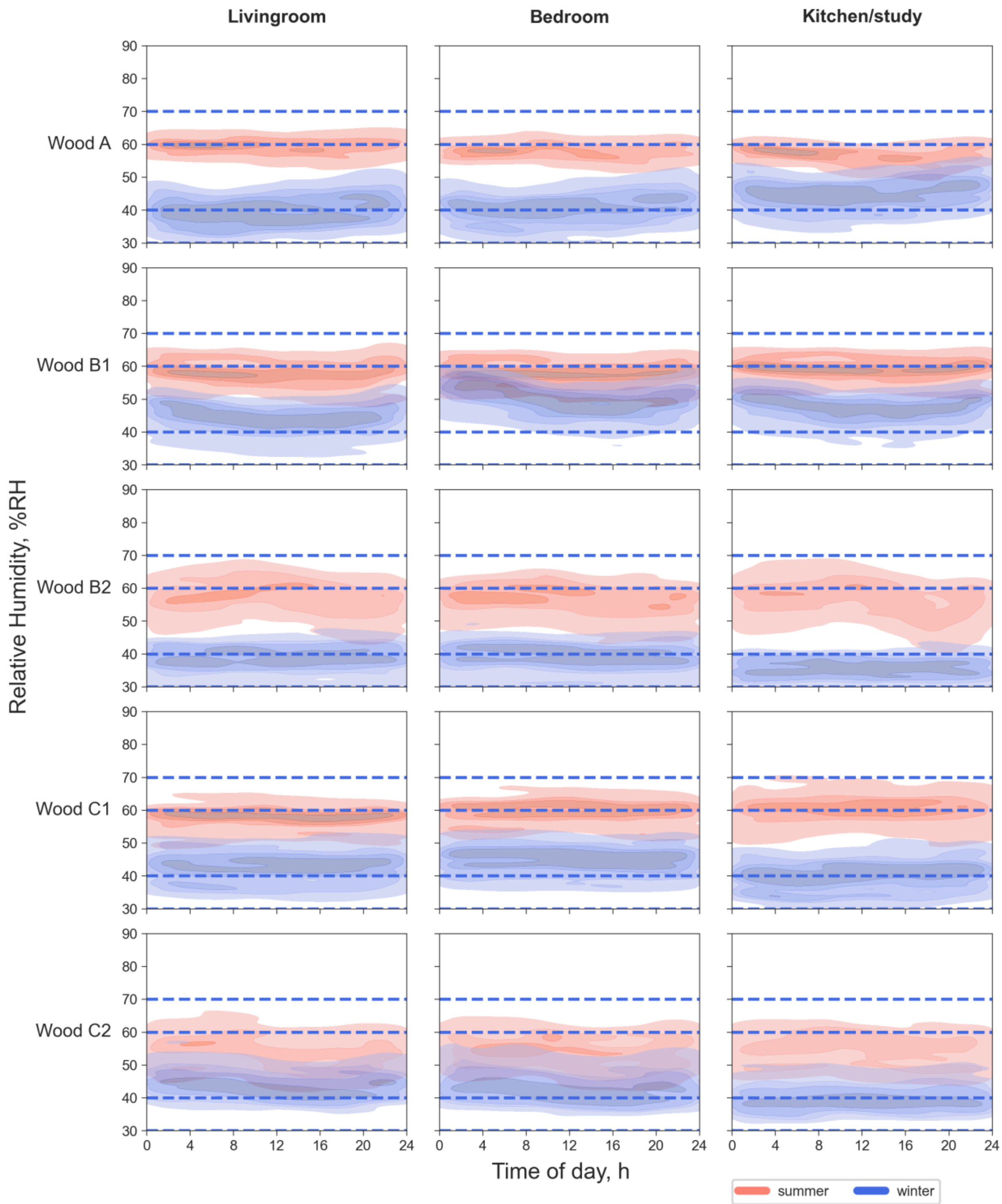


Figure 4-13 Relative humidity distribution (density plot for the 2.5th-97.5th percentile) as a function of the time of day for summer (Jun-Jul-Aug) and winter (Dec-Jan-Feb) in four spaces: living, main bedroom, kitchen and bathroom in Estonian wooden apartment buildings. Empty slots mean no relevant data was available. The blue dotted reference lines at 30-40% and 60-70% indicate typically used intervals considered to be perceived as comfortable by people.

In cold climate conditions, during the heating season and at low outdoor temperatures, it is generally expected that indoor relative humidity levels remain low due to the combined effects of cold outdoor air and indoor heating. However, the measurements conducted in the case-study apartments during this study tended to show higher relative humidity levels than typically expected under such conditions. Indoor relative humidity levels observed during both summer and winter did not indicate any consistent discomfort for occupants, remaining generally within the range considered acceptable for human well-being. However, during the winter period, relative humidity levels occasionally rose to high values which, if sustained over time, may become critical from the perspective of building envelope hygrothermal performance. While such conditions may not directly affect perceived indoor comfort, they can increase the risk of condensation and moisture accumulation within structural components. Elevated humidity levels during cold periods often indicate insufficient ventilation, where moisture generated by occupants and daily activities—such as cooking, washing, or drying laundry—is not effectively removed and accumulates in the indoor air. This concern is more clearly illustrated in the moisture surplus graphs presented in the following chapters.

4.3.7 Moisture load – Internal humidity classes

The moisture excess Δv [g/m³] (the difference between the indoor and the outdoor air water vapour content) was calculated based on the measured results of the indoor and outdoor temperatures and RH. To provide an overview of the temperature and humidity loads the dependency of the indoor temperature and moisture excess on the outdoor temperature was analysed.

The analysis of indoor moisture excess (difference between indoor and outdoor absolute humidity) further supports these findings. During colder periods, when the outdoor temperature was 0 °C or below, the average moisture excess across the monitored apartments was 3.3 g/m³, with values ranging from 1.4 to 6 g/m³. In milder conditions, with outdoor temperatures between 0 °C and 20 °C, the average moisture excess was slightly lower at 2.6 g/m³, with a variation between 0.7 and 5 g/m³.

Figure 4-14 and Figure 4-15 show the results of the moisture excess analysis for cases Brick A1 and Wood A of the living room and main bedroom of respectively.

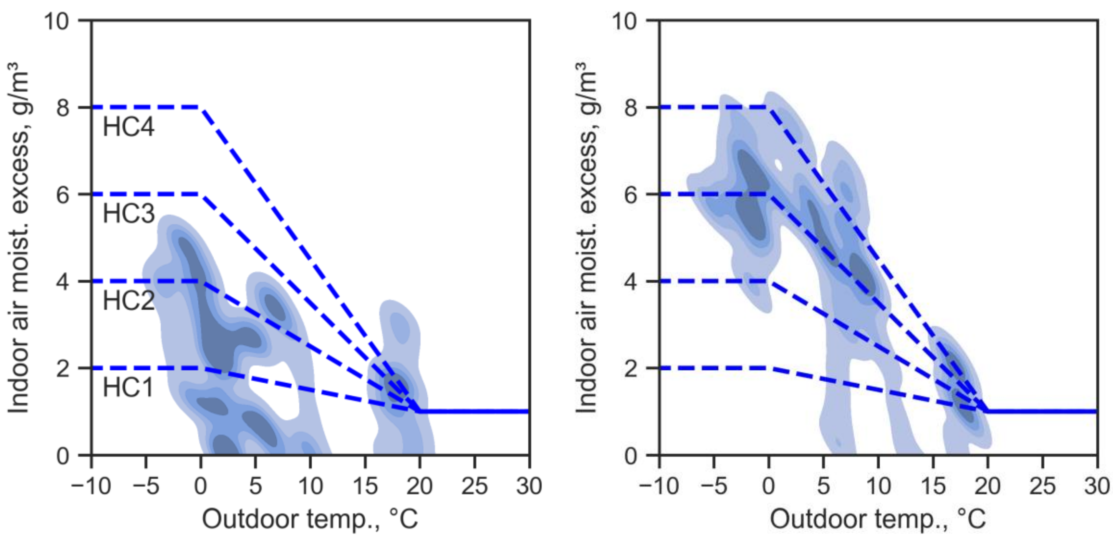


Figure 4-14 Weekly average indoor air moisture excess distribution as a function of the exponentially weighted outdoor temperature (density plot for the 2.5th-97.5th percentile data) for the living rooms in Estonian apartments Brick A1 (left) and Wood A (right). The dotted reference lines represent the threshold values defined by the internal humidity classes as described in the EN ISO 13788:2013 standard.

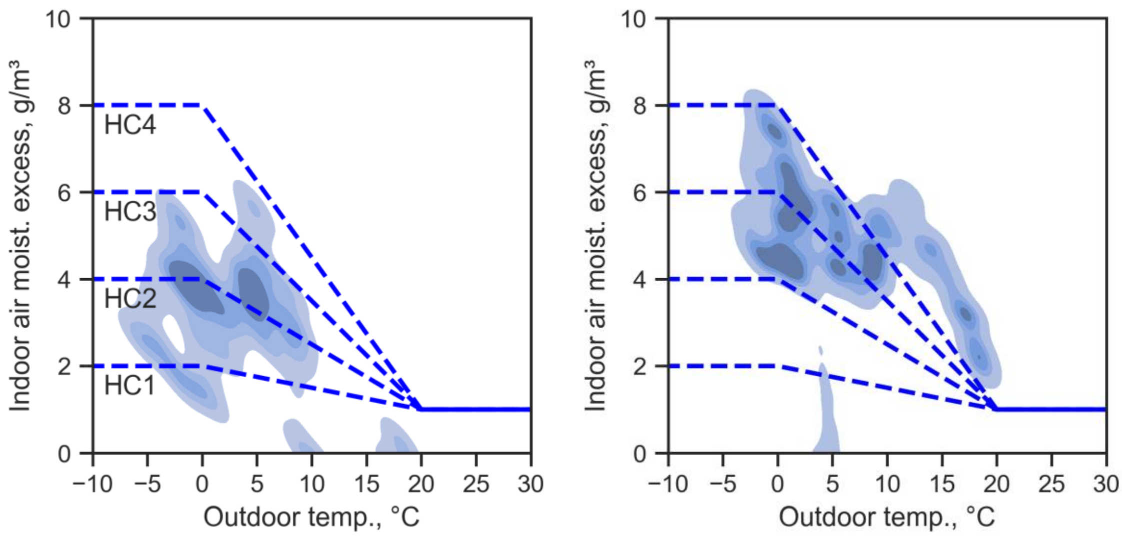


Figure 4-15 Weekly average indoor air moisture excess distribution as a function of the exponentially weighted outdoor temperature (density plot for the 5th-95th percentile data) for the main bedroom in Estonian apartments Brick A1 (left) and Wood A (right). The dotted reference lines represent the threshold values defined by the internal humidity classes as described in the EN ISO 13788:2012 standard.

Table 4-6 provides an overview of the assigned internal humidity classes for the bedrooms and living rooms of all investigated cases.

Table 4-6 Internal humidity classification of the main bedrooms and living rooms for the Estonian cases.

	Bedroom 1	**Bedroom 2**	**Livingroom**
Brick_A1	Class III	Class III	Class III
Brick A2	Class III	Class III	Class III
Brick_B1	Class II	Class II	Class III
Brick B2	Class II		Class II
Wood A	Class IV		Class IV
Wood B1	Class III	Class III	Class III
Wood B2	Class II	Class III	Class II
Wood C1	Class II		Class II
Wood C2	Class III		Class III
* Compared to the cold period (with outdoor temperatures below 0 °C), the moisture excess during the transitional period (0 to 20 °C) was generally one humidity class higher, and in some cases even two classes higher. This elevated level of indoor moisture load during milder outdoor conditions represents a particularly increased risk for mould growth in building components.			

An analysis of the measured moisture excess values reveals that both wooden and brick apartment buildings include rooms where moisture excess reaches critically high levels. These elevated values indicate conditions where moisture generated indoors is not sufficiently removed, posing a risk to building envelope durability and increasing the potential for condensation-related damage. In rooms with such high moisture levels, there is a significant risk of mould growth, especially in cases where internal insulation is present. The presence of such high moisture loads across different building types suggests that local ventilation performance and occupant behaviour play a significant role in indoor moisture accumulation.

4.3.8 Insights

Key findings indicate that wooden and brick apartment buildings have comparable indoor climates in terms of CO_2 levels and moisture load. Across all buildings, problems with inadequate air exchange were evident, often resulting in elevated CO_2 concentrations—especially during the cold season, when window ventilation causes thermal discomfort. In apartments with medium to high occupancy density, residents frequently reported a sense of stuffiness in rooms.

One of the main issues is that the construction of proper ventilation systems is perceived by residents as prohibitively expensive, and there is a lack of good examples of functioning solutions.

High indoor humidity levels and a realized risk of mould were observed particularly in structures with high thermal transmittance. In many apartments, internal insulation has been added to exterior walls in an effort to reduce heating costs and improve thermal comfort. However, such insulation significantly increases the risk of mould growth, especially when applied without adequate moisture control. As the building elements were not opened during the study, the extent of potential moisture damage remains unknown and requires further investigation.

Despite the elevated moisture load, measurements showed that relative humidity levels stayed within the comfort range for indoor climate. However, this is largely due to the combination of high indoor humidity generation and lower indoor air temperatures.

The stability of indoor temperatures also varied depending on the heating system. Central heating systems with water radiators typically maintained stable indoor temperatures, while systems relying on wood stoves showed greater fluctuations. In some apartments, due to faults or lack of a heating system, it was not possible to adequately heat certain rooms or reach the desired temperatures.

Notably, greater variability in indoor climate conditions was observed between different apartments within the same building, rather than between rooms within a single apartment. This suggests that resident behaviour, apartment orientation, and local heating or ventilation solutions play a more significant role in indoor climate differences than room-level factors.

4.4 Space conditioning and IAQ management

For the five cases where long time measurements were carried out, a detailed inventory of the space conditioning systems present in those dwellings was carried out. In

Table 4-7, the focus is on the distribution and emission systems (with the corresponding control system), alongside with the ventilation systems. The overview of the energy systems can be found in 'D4.1 R²ES-Based Energy Supply Concepts for Heritage Buildings in Historical Neighbourhoods'.

Table 4-7 Overview of space conditioning installations for Estonian brick and wood buildings

<table>
<tr><th colspan="5">Building code</th><th colspan="2">KRIST.</th><th>SIKUP.</th><th>KOIDU</th><th>KOME.</th><th>PILVE</th></tr>
<tr><td colspan="5">Heated area, m²</td><td colspan="2">2311.7</td><td>554.3</td><td>303</td><td>158.0</td><td>453.8</td></tr>
<tr><td colspan="5">Archetype</td><td colspan="3">BRICK</td><td colspan="3">WOOD</td></tr>
<tr><td rowspan="6">Distribution</td><td rowspan="3">Heating</td><td colspan="3">central/local</td><td>Central</td><td colspan="2">Local</td><td>Local</td><td>Local</td><td>Local</td></tr>
<tr><td colspan="3">Transport medium</td><td>Hydronic</td><td colspan="2">Hydronic</td><td>Hydronic, Air</td><td>Air</td><td>Hydronic, Air</td></tr>
<tr><td colspan="3">Type of distribution system</td><td>Two-pipe</td><td colspan="2">Two-pipe</td><td>Two-pipe, Electric radiator</td><td>Air to Air heat pump, wood stove</td><td>Two-pipe, Electric radiator</td></tr>
<tr><td rowspan="3">Cooling</td><td colspan="3">central/local</td><td colspan="2">n/a</td><td>n/a</td><td>n/a</td><td>Local</td><td>n/a</td></tr>
<tr><td colspan="3">Transport medium</td><td colspan="2">n/a</td><td>n/a</td><td>n/a</td><td>Refrigerant</td><td>n/a</td></tr>
<tr><td colspan="3">Type of distribution system</td><td colspan="2">n/a</td><td>n/a</td><td>n/a</td><td></td><td>n/a</td></tr>
<tr><td rowspan="2">Emission</td><td>Heating</td><td>Main type</td><td>Radiators</td><td>Radiators</td><td colspan="4">Radiators</td><td>Air to Air heat pump, Wood stove</td><td>Radiators</td></tr>
<tr><td>Cooling</td><td>Main type</td><td>n/a</td><td>n/a</td><td colspan="4">n/a</td><td>Air to Air heat pump</td><td>n/a</td></tr>
<tr><td colspan="2">Ventilati</td><td colspan="3">Central ventilation system</td><td colspan="6">n/a</td></tr>
</table>

	Toilet extraction, m³/h	n/a				n/a	Extraction fan with light	n/a	Extraction fan with light
	Range hood, m³/h	Existing							
Temperature control	Control type	Central thermostat, Thermostatic valves	Thermostatic valves	Thermostatic valves	Thermostatic valves	Thermostatic valves			
	Night setback, °C	No setback							
	Day setback, °C	No setback							

4.5 Defining space conditioning pre-renovation baselines and renovation baselines

Based on the observations made in the case-study buildings and considering expertise and experience of TalTech, for each Estonian archetype as described in 'D5.1 Case-study selection at building and neighbourhood levels' (Maton et al., 2024), a pre-renovation and renovation baseline for space conditioning are derived. The pre-renovation baseline is the condition in which these types of buildings were before the introduction of EPBD regulations (situation in '90-'00). The renovation baseline is the condition of these type of buildings as if they would be renovated today. In this report, only the baseline scenarios regarding the space conditioning systems (emission, distribution, and ventilation part of the HVAC systems) are described. The complete baseline scenarios (including heritage value, building envelope, energy systems and use scenarios) are described in 'D5.4 Baseline scenarios'.

4.5.1 Pre-renovation baseline

In original condition, wooden apartment buildings were typically heated using wood-burning stoves located in individual apartments. These stoves served as the primary source of space heating. Central heating systems were not present, and the heating relied on manual operation by residents. Ventilation was natural, occurring through air leaks in the building envelope and via openable windows, with no mechanical ventilation systems installed. In general, the discharge takes place through the chimneys and the compensation through the building body, which means that the air change rate in historic wooden buildings relates to the air tightness of the building because of the absence of the fresh air valves in most cases.

Brick buildings can generally be categorized into two subtypes based on size and heating configuration. Larger brick apartment buildings were commonly equipped with a one-pipe central heating system, delivering heat to apartments via radiators. These systems were usually connected to a district heating network or a local boiler house. Ventilation in these buildings was also predominantly natural, although some buildings may have incorporated simple gravity-based ventilation shafts.

Smaller brick buildings, on the other hand, often resembled wooden buildings in their heating approach. These structures also relied on wood-burning stoves for room heating, without centralized heating infrastructure.

Across all building types, mechanical ventilation was generally absent, and indoor air exchange relied heavily on occupant behaviour, such as window opening, and the natural permeability of the building envelope.

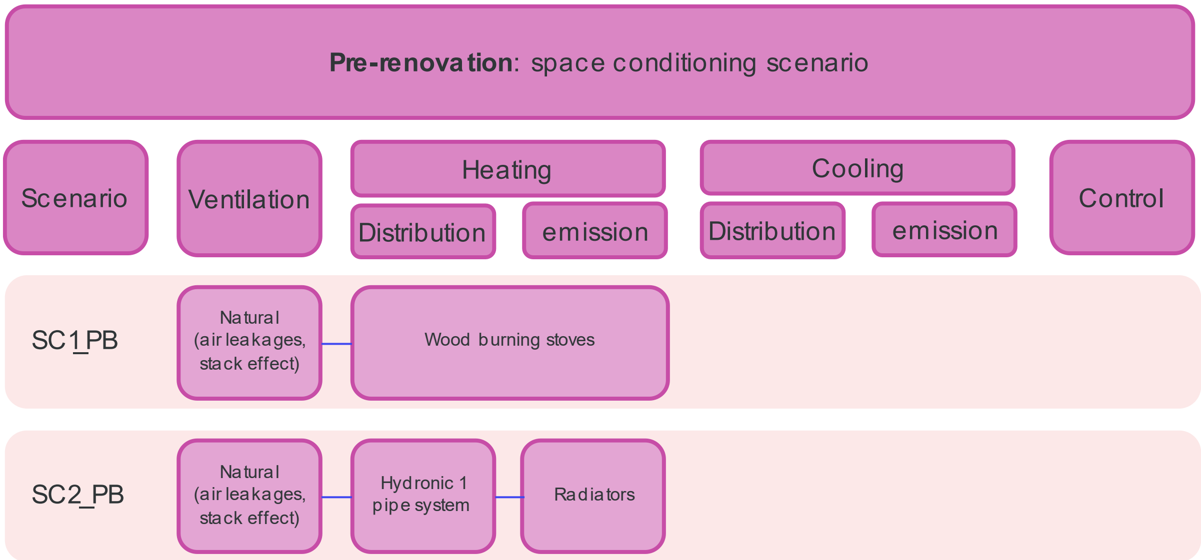


Figure 4-16 Schematic overview of the Pre-renovation Baseline (PB) Space Conditioning (SC) scenario for the Estonian archetypes.

As the stoves generally have low thermal mass, indoor temperatures fluctuate significantly throughout the day. Heating patterns depend heavily on occupant behaviour and vary with outdoor temperatures. For example, during colder periods, residents often heat their apartments in the morning and evening, while during milder weather, heating may occur only once per day. This leads to considerable variations in indoor thermal conditions, which have been clearly documented in previous studies on wooden apartment buildings.

Smaller brick apartment buildings that utilize wood-burning stoves behave similarly to wooden apartment buildings in terms of heating dynamics. Indoor temperatures in these buildings are subject to fluctuations due to the low thermal inertia of the stoves and the dependence on user habits. Heating typically occurs once or twice a day, depending on outdoor temperature, resulting in cycles of elevated indoor temperatures during and shortly after firing, followed by gradual cooling as the stove releases its stored heat and no additional energy input is provided—until the next heating cycle begins. As in wooden buildings, thermal comfort varies significantly across time and apartments.

In contrast, larger brick masonry apartment buildings are commonly equipped with one-pipe central heating systems. These buildings are typically connected to a district heating network via a substation, where the supply temperature to the building's internal heating circuit is regulated. The heating system operates on a 90/70/21°C regime, delivering hot water to radiators in each heated room. Control of the system is centralized: the supply water temperature is adjusted at the substation according to outdoor temperature or a fixed heating curve. In such buildings, temperature regulation within the system is inherently challenging. Due to the sequential nature of heat distribution—where hot water flows through all radiators in series—there are often significant discrepancies in room temperatures between different apartments. Units located closer to the heat source or at the beginning of the circuit may experience overheating and elevated indoor temperatures. Conversely, apartments located farther downstream may receive insufficient heat, resulting in cooler indoor conditions. These imbalances are a systemic characteristic of one-pipe systems and are further complicated by the limited individual control available to occupants over their radiators.

4.5.2 Renovation baseline

In recent decades, the heating and ventilation systems of wooden and brick residential buildings have undergone varying degrees of modernization, with significant differences between individual buildings depending on ownership, renovation history, and access to funding.

In many wooden apartment buildings, as well as smaller brick buildings originally equipped with wood-burning stoves, the traditional heating systems remain partially or full in use. Original stove heating is still common, particularly in buildings with minimal renovation. However, in response to rising comfort expectations and energy efficiency requirements, a range of supplementary or replacement heating systems has been introduced.

One of the most widespread upgrades has been the installation of apartment-based gas boilers, which supply heat to water-based radiator systems. These decentralized solutions allow individual apartments to control their heating schedule and indoor temperature independently. Gas boiler systems are especially prevalent in smaller brick buildings, where centralized heating infrastructure is often lacking.

Another common improvement is the installation of air-to-air heat pumps, which provide relatively efficient space heating with the added benefit of cooling during warmer months. These systems are popular due to their low installation costs and ease of use.

Despite the modernization of heating systems, ventilation remains predominantly natural in these buildings. Most rely on window airing and passive stack ventilation, which often proves insufficient, especially during the heating season when windows are kept closed. Only a small proportion of buildings that have undergone full-scale renovations have been equipped with mechanical ventilation systems, such as exhaust or heat recovery systems.

Larger brick buildings with one-pipe central heating systems mostly remain connected to district heating networks or communal boiler plants. In some cases, of both the wooden and Stalinist style brick apartment type, more extensive modernization measures have been implemented, such as converting the system to a two-pipe layout, which provides better control and balanced heating. While some of these systems have been modernized through the addition of thermostatic radiator valves and heat cost allocators.

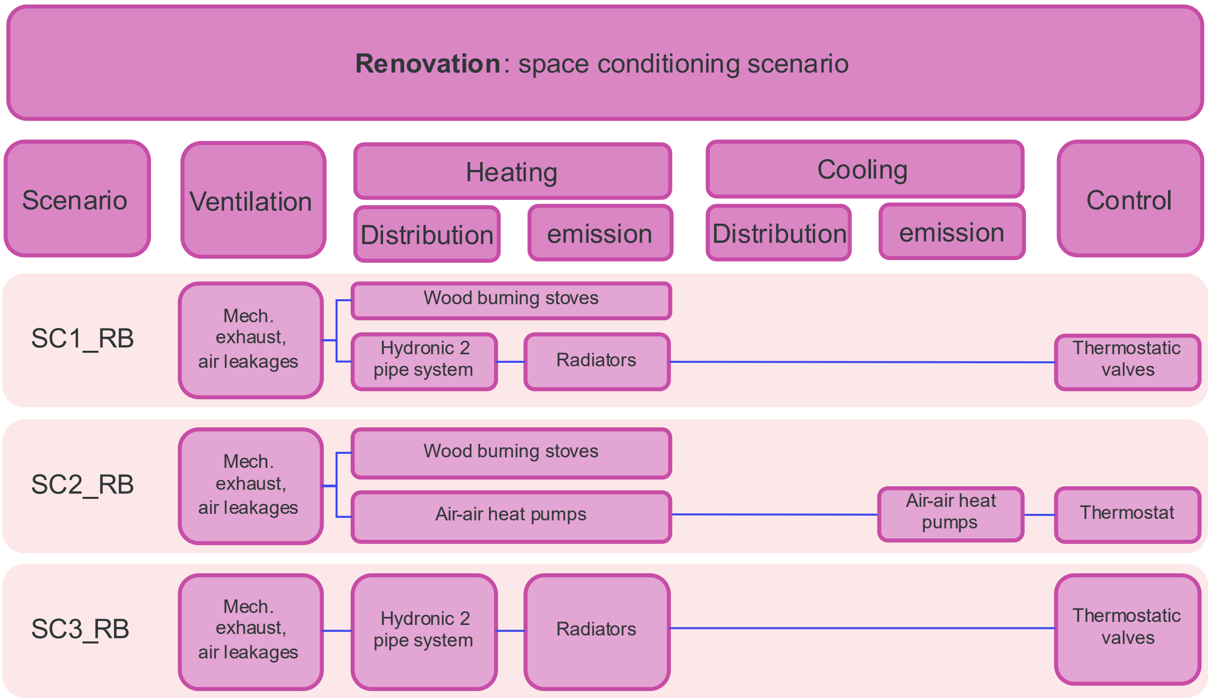


Figure 4-17 Schematic overview of the Renovation Baseline (RB) Space Conditioning (SC) scenario for the Estonian archetypes.

In large brick apartment buildings, energy renovation commonly includes central heating modernization. A key intervention is the replacement of the original high-temperature single-pipe system with a more efficient two-pipe hydronic distribution system, which improves hydraulic balance and enables better temperature control across different zones.

Thermostatic radiator valves (TRVs) have also been installed on radiators in each heated room, allowing occupants to adjust heating output locally based on individual comfort preferences. These measures have helped reduce thermal imbalances between apartments and improve overall energy efficiency.

Following such renovations, the reference indoor temperature used for space heating design and performance assessment in large brick buildings has increased. The minimum indoor temperature is now set at +21.5 °C, reflecting enhanced comfort standards and regulatory expectations.

In smaller buildings originally heated by stoves, renovations have introduced modern solutions such as gas boilers, heat pumps, or localized hydronic radiator systems. These upgrades provide more stable and controllable indoor temperatures compared to traditional stove heating.

Accordingly, the design baseline for indoor climate in such renovated buildings reflects both improved comfort and the inherent variability of these systems. The reference minimum indoor temperature is set at +20.5 °C, representing a balance between upgraded comfort and system-specific operational characteristics.

5 Italy

5.1 Equipment and set-up

In 3 case studies, environmental parameters such as temperature and relative humidity were monitored on an hourly basis and 15-minute time step for CO_2 in order to assess thermal comfort, perceived IAQ and humidity load. Two cases were unoccupied and unconditioned, one case was occupied and air-conditioned (Occ_C) during the monitoring. In particular:

In the first monitoring case (Palazzetto archetype), indicated as "Occ_A", n° 8 datalogger model DLRHT10 was installed from the 21st of June to the 24th of September. The climatic parameters monitored are the air temperature and relative humidity with hourly time steps.

In the second monitoring case (Gothic lot archetype), indicated as "Occ_B", n° 7 datalogger model DLRHT10 have been installed from the 21st of June to the 24th of September. The climatic parameters monitored are the air temperature and relative humidity.

In the third monitoring case (Extended building archetype), indicated as "Occ_C", n° 10 datalogger model Hobo MX1101 has been installed from the 21st of June to the 2nd of February, which collects temperature and relative humidity. On the 26th of November n° 6 of them were substituted with the datalogger model Hobo MX1102A, which collects temperature, relative humidity, and CO_2 each 15 min.

In the following figures, the position and type of datalogger installed are shown for each case.

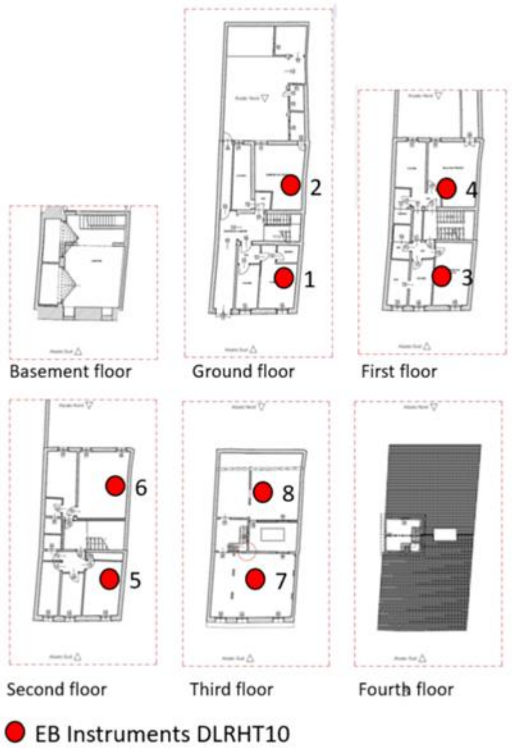


Figure 5-1 Position and type of datalogger installed in Occ_A, Italy

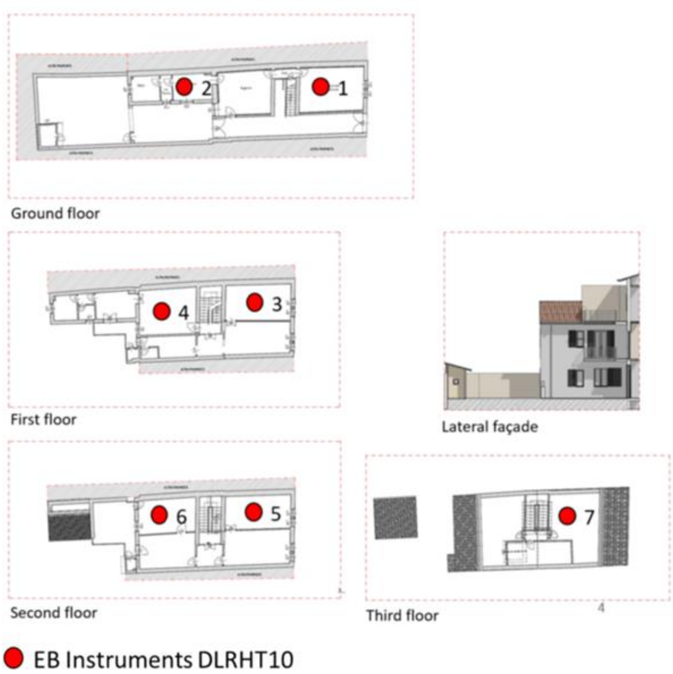


Figure 5-2 Position and type of datalogger installed in Occ_B, Italy

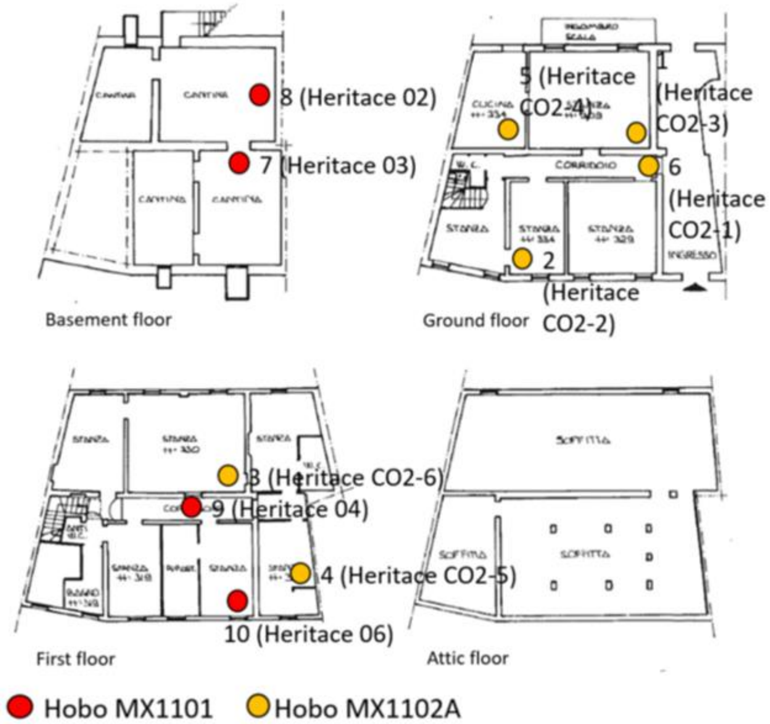


Figure 5-3 Position and type of datalogger installed in Occ_C, Italy

External climate data were collected from the Regional Environmental Protection Agency (ARPA) meteorological station located in the historic centre of Mantova. In more detail, this is the Mantova - S. Agnese meteorological station from which it was possible to retrieve temperatures, relative humidity, horizontal solar radiation, and wind speed/direction with hourly time step. The location of the meteorological station selected is shown in the figure below.

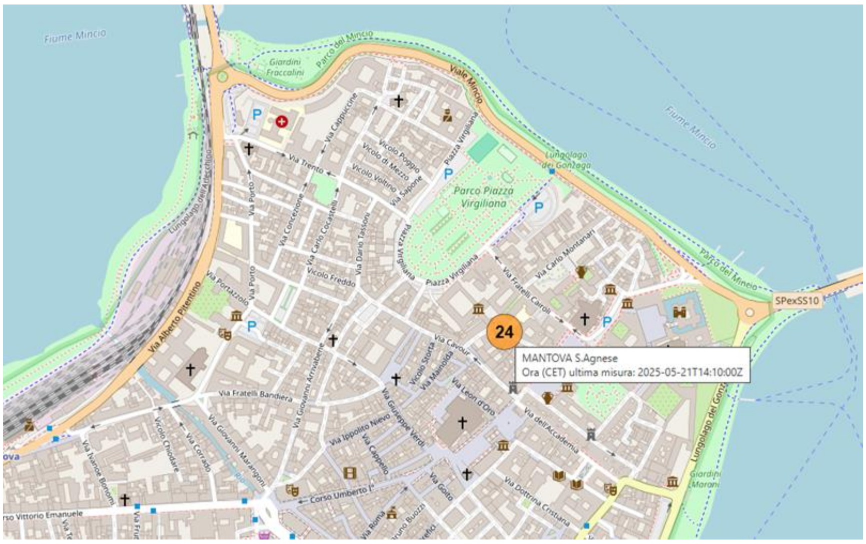


Figure 5-4 Location of the ARPA weather station adopted for the outdoor climatic data.

In the monitoring campaign three types of datalogger have been used. In detail, datalogger Hobo MX1101 and DRLRHT10 measure only temperature and relative humidity while Hobo MX1102A measure also CO_2. In the figure below is shown a view of the different datalogger adopted. The technical information of the dataloggers used are shown in Table 5-1.

Figure 5-5 Types of datalogger adopted in the monitoring campaign.

Table 5-1 Sensor specification of used devices for Italy.

Datalogger Model	Parameter measured	Interval of measurement	Accuracy
HOBO MX Temp/RH Data Logger (MX1101)	Temperature	-20-70 °C	+/-0.21 °C (0 … +50 °C)
	Relative humidity	1-90 %	+/- 2 % (20 … 80 %)
EB Instruments humidity and temperature USB datalogger DLRHT10	Temperature	-40-70 °C	+/-0.5 °C (-10 … +40 °C)
	Relative humidity	0-100 %	+/- 3.0 % (40 … 60 %)
HOBO Carbon Dioxide/Temp/RH Data Logger (MX1102A)	Temperature	0-50 °C	+/-0.21 °C (0 … +50 °C)
	Relative humidity	1-90 %	+/- 2 % (20 … 80 %)
	CO_2	0-5000 ppm	+/- 50 ppm +/- 5 % of reading at 25°C

5.2 Observations and data analysis

5.2.1 EPBD building temperature

As mentioned above, indoor air temperature has a large impact on the building heat losses and thus energy use. In the Italian national EPC/EPBD frameworks, the whole building volume is assumed to be isothermal with a temperature of 18°C in winter and 23°C in summer. Figure 5-6 shows the distribution of the measured volume weighted average indoor temperature during winter (dec-jan-feb) and summer (jun-jul-aug) for the three cases.

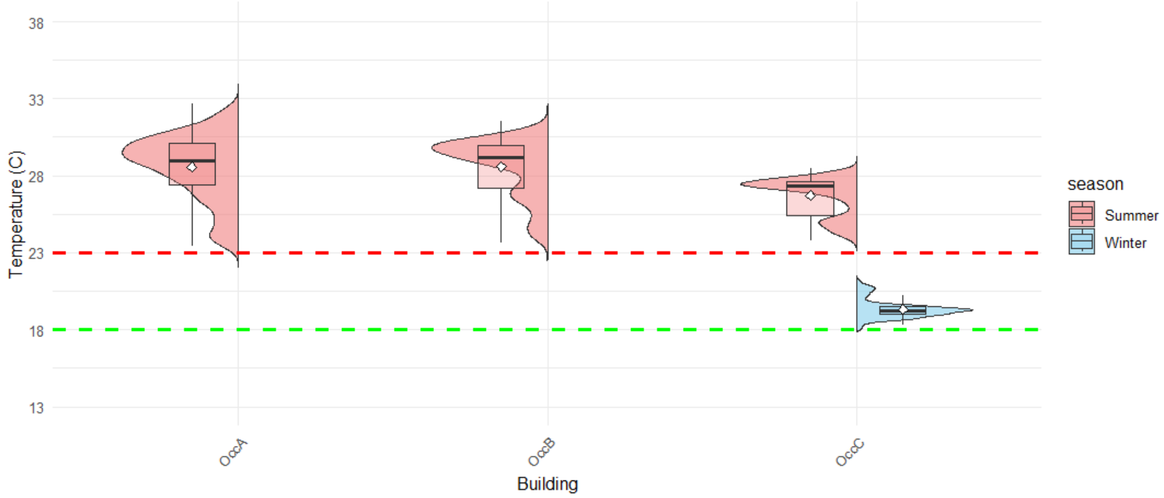


Figure 5-6 Distribution and boxplots of the building average temperature for summer (Jun-Jul-Aug) and winter (Dec-Jan-Feb) for the Italian cases. Volume weighted temperature of all available temperature measurements of the case-study. The red dotted reference line is the assumed winter temperature in the Italian EPBD calculations. The green dotted reference line is the assumed summer indoor temperature for cooling energy use.

According to the monitored data, it is evident that in the first two cases (Occ_A and Occ_B), which are unconditioned, temperatures peak above 33°C, with an average of about 29°C. These elevated temperatures, recorded during the summer period, highlight the necessity of implementing cooling strategies to ensure thermal comfort in Italian climatic context.

Moderate conditions are maintained in the Occ_C case, which is occupied and equipped with air conditioning system for cooling. The temperature data shows significantly lower variability and more compact temperatures, ranging from 23°C to 29°C, with an average of approximately 27°C.

Regarding the winter period in the occupied case, the thermal conditions appear to be relatively favourable. Temperatures range from approximately 18°C to 21°C, with an average around 19°C. These conditions are largely consistent with the typical winter setpoint temperature of 20°C established by Italian regulations.

5.2.2 Temperature variability

Related to the average indoor temperature and interesting to observe is how the building is being operated by its users. This can be done by analysing the variability of indoor temperatures in summer versus winter. Figure 5-7 shows a density plot of the indoor temperatures for the summer and winter in 3 main rooms of the cases.

An analysis of the temperature data for the two unconditioned cases reveals, as previously shown, that during the summer period, the majority of recorded temperatures are predominantly concentrated above the summer cooling setpoint temperature of 26°C (as defined by Italian regulations), with peak values occurring primarily during the hottest hours of the day. In contrast, the Occ_C case exhibits a lower concentration of temperatures exceeding 26°C, thereby confirming the positive impact of air conditioning systems.

During the winter period, temperature values tend to remain around the dashed blue line, which represents the winter setpoint temperature of 20°C, with the exception of the kitchen, where higher temperatures are observed probably due to the presence of greater internal heat gains.

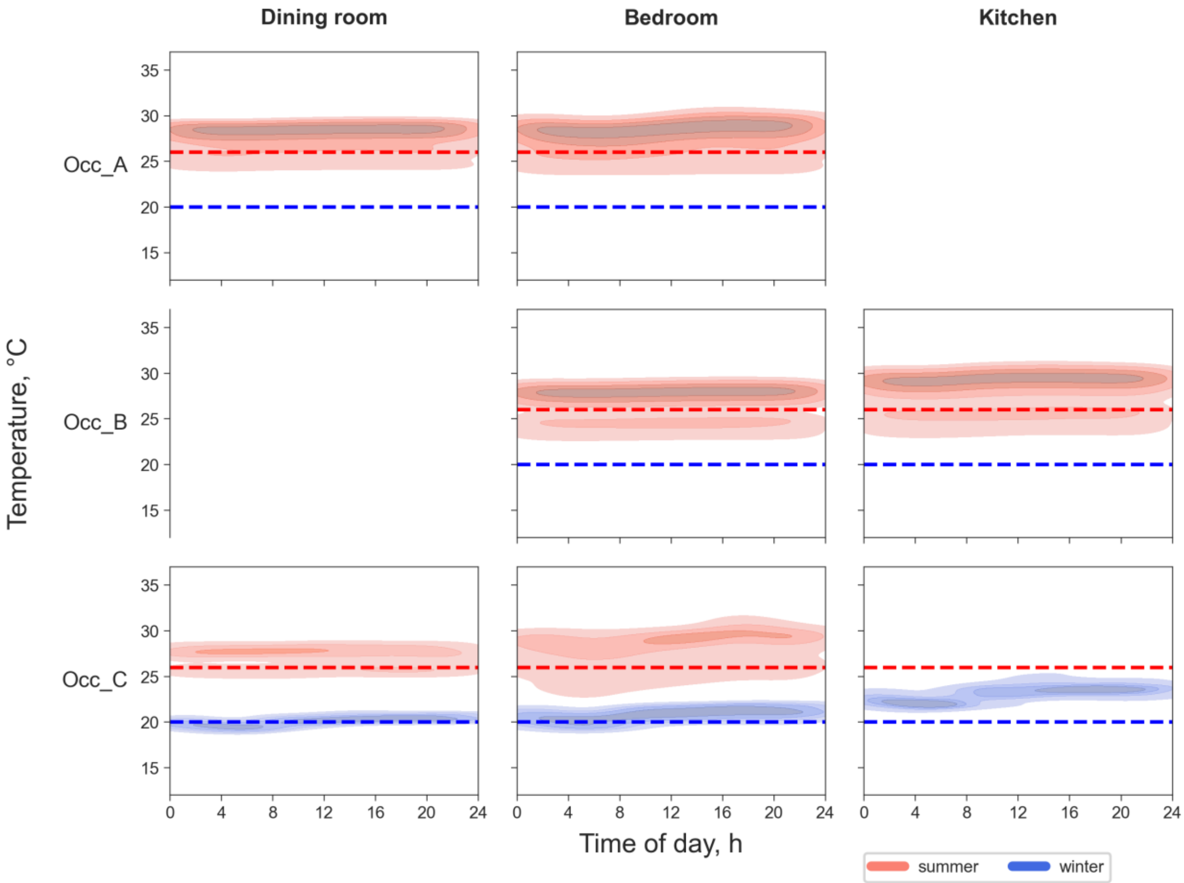


Figure 5-7 Indoor temperature distribution (density plot for the 2.5th-97.5th percentile) as a function of the time of day for the Italian cases. Display of summer (Jun-Jul-Aug) and winter (Dec-Jan-Feb) in three spaces: dining room, main bedroom and kitchen. Empty slots mean no relevant data was available. The blue and red dotted reference lines are the temperature levels at the lower and higher end of the allowed temperature range for the thermal IEQ class II according to EN-16798

Figure 5-8 shows an analysis on the week and weekend days of the occupied case: Occ_C.

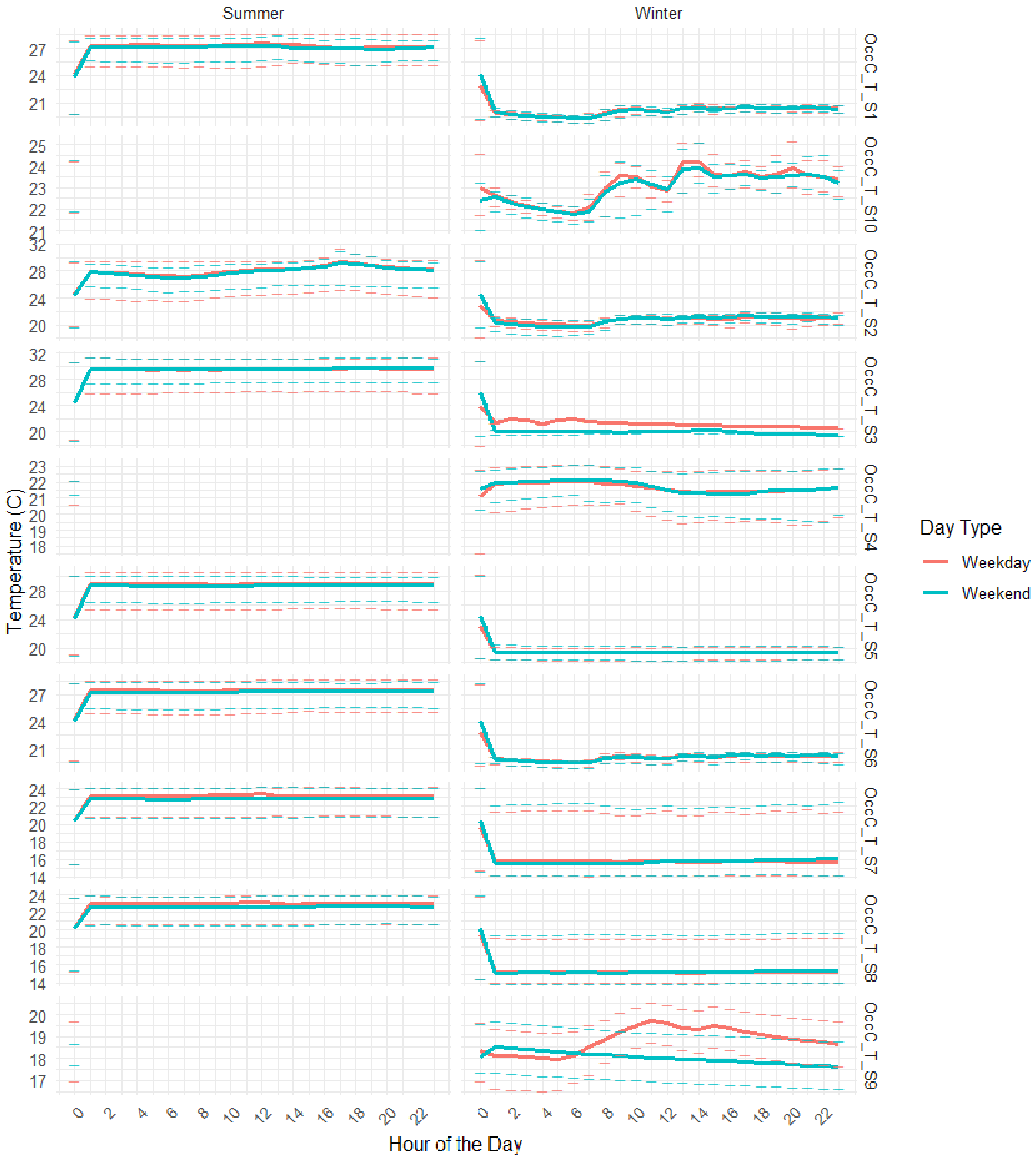


Figure 5-8 Temperature distribution in the specified rooms, comparing weekdays and weekends during summer and winter for the Italian case Occ_C. Solid lines represent the mean indoor temperature as a function of time of day, separately for summer and winter, and for weekdays and weekends. Dotted lines indicate the 5th and 95th percentiles of the corresponding data.

5.2.3 Duration of heating and cooling season

The heating periods for the various building case studies are presented in the table below. Specifically, only one case (Occ_C) was heated during the monitoring campaign, while the other buildings were not conditioned, as they were unoccupied due to ongoing renovation works.

The heating schedule for Occ_C closely follows the standard for Climate Zone E in Italy, which spans from October 15 to April 15, with heating activated for 14 hours per day, while for cooling no specific period is identified, as this can be activated when needed.

Table 5-2 Summary of the observed start and end of the heating season for the Italian cases

	Start	**End**	**Duration**
Case 1	Unconditioned during the monitoring		
Case 2	Unconditioned during the monitoring		
Case 3	15.10.2024	01.04.2025	14 hours/day
Case 4	Unconditioned during the monitoring		

5.2.4 EN 16798 Adaptive Thermal Comfort

The adaptive comfort theory and method described by the EN-16798 standard provide a valuable reference to benchmark the measurements in terms of thermal comfort. A visual representation of such analysis is shown Figure 5-9. It shows the indoor temperatures as a function of the exponentially weighted running mean outdoor temperature of the living room for Occ_A and Occ_C.

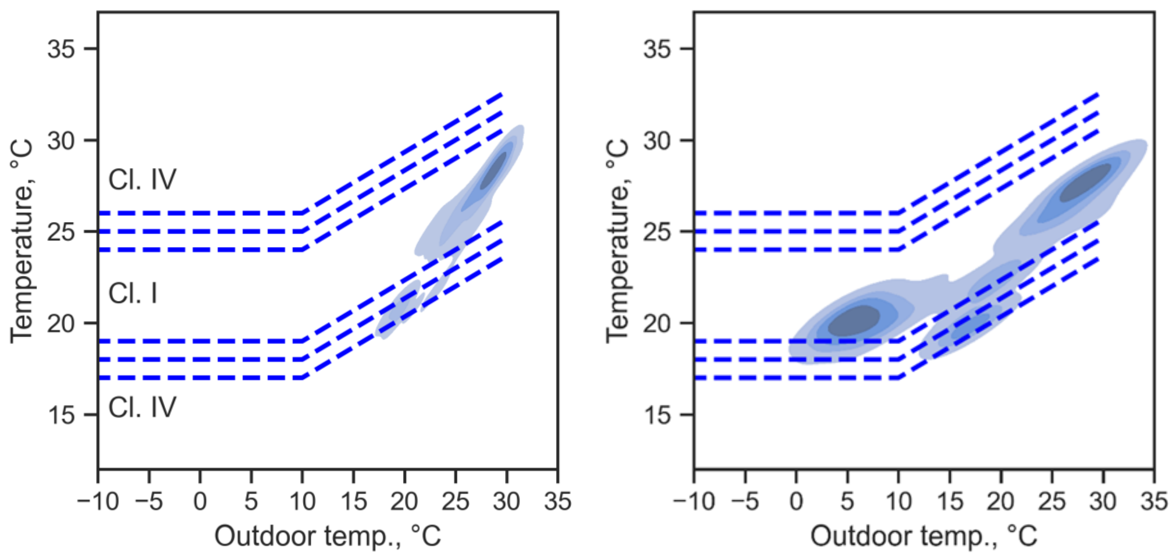


Figure 5-9 Temperature distribution of the measured indoor temperature as a function of the exponentially weighted outdoor temperature (density plot for approximately the 2.5th-97.5th percentile data) for the dining room of Italian cases Occ_A (left) and Occ_C (right). The dotted reference lines are based on the adaptive thermal comfort acceptability limits as described in the EN-16798 standard.

In the summer period, the measured data points in both cases analysed fall within the acceptability Class I for more than 90% of the time (see Table 5-3), while for the remaining time, the data points fall within the other classes. Such result indicates a positive condition during the summer season in both buildings analysed, even if the building Occ_A was not conditioned during the analysed period. However, it should be noted that the comfort conditions can be above the limits for some rooms that are closer to the roof. Figure 5-10 show two examples of this with high density regions around 30°C indoor temperature and significant portions above the upper limit of the comfort bands.

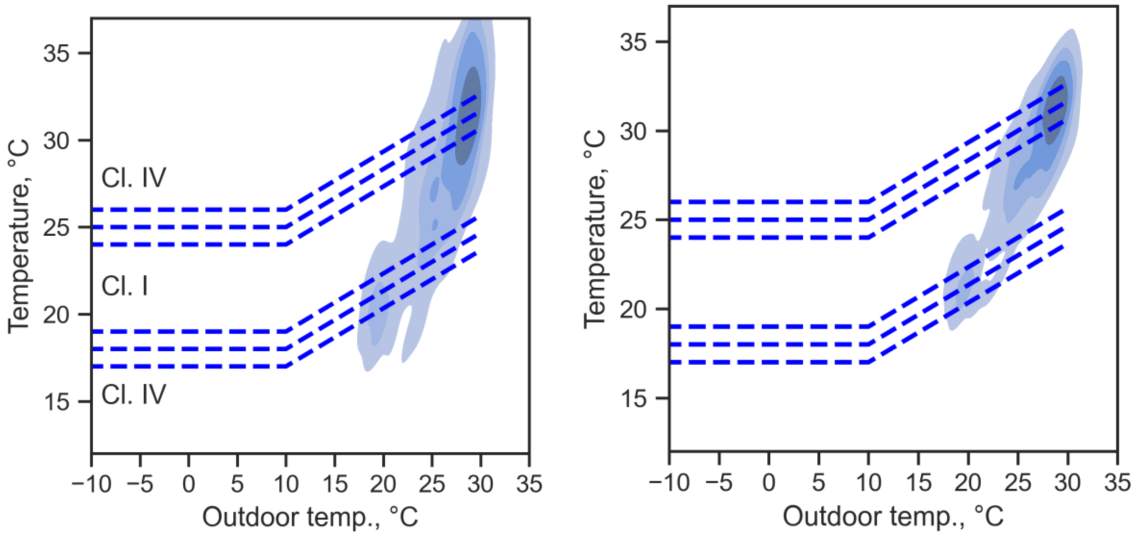


Figure 5-10 Temperature distribution of the measured indoor temperature for a room of case Occ_A (left) and case Occ_B (right) on the third floor of each building.

In the winter period, the data points monitored in case Occ_C fall within Class I for about half of the time, in Class II for about 42.8%, in Class III for 4.8% and below all the classes for about 1.8% of the time (during some hours in November). Such result indicates an overall good comfort condition in case Occ_C even during the winter period, however, the presence of some hours below the comfort ranges highlights to also have attention to heating need.

Table 5-3 Percentage of data points in or outside adaptive temperature class for the dining room (Occ_A and Occ_C), All data of Italian cases

% of data points in	**Occ_A**	**Occ_C**	
Hours of data considered	1719 h	2208 h	1719 h
Start-end of data	Summer	Winter	Summer
Overheating	0%	0%	0%
Class I	90.8%	50.6%	93.1%
Class II	7.7%	42.8%	6.7%
Class III	1.5%	4.8%	0.2%
Below	0%	1.8%	0%

Since thermal comfort is related to the occupants, it makes sense to only look at data with a higher likelihood of occupancy. In such regard can use the CO_2 data which is available in Dining room to only include the indoor temperature data when simultaneously the CO_2 concentration in that room is above 600ppm at that time. The results for the adaptive thermal comfort analysis filtered for CO2 > 600 ppm are summarized in Table 5-4, only for Occ_C, which is the occupied building.

Compared to the original table results are generally better in terms of the expected thermal comfort level in the dining room with a higher amount of data points inside the acceptability Class I (almost 70% of the data), while the remaining datapoints fall within Class II and III. Interventions by occupants and time-dependent controls of the heating system will lie at the basis of this improvement.

Table 5-4 Percentage of data points in or outside adaptive temperature class for the dining room. Data of Italian case Occ_C when CO_2 level is above 600ppm

% of datapoints in	Occ_C
Hours of data considered	740 h
Start-end of data	Winter
Overheating	0%
Class I	68.6%
Class II	30.3%
Class III	1.1%
Below	0%

5.2.5 CO_2 variability

Interesting to observe how the building is used and its impact on perceived IAQ is to look at the CO_2 concentration variability in winter period on the only case occupied. Figure 5-11 shows a density plot of the CO_2 concentration for the winter period in three rooms: dining room, bedroom, and kitchen.

In detail, the density plots indicate that CO_2 levels are generally low, with values mostly remaining below 1000 ppm, particularly in the bedroom. In contrast, during the summer period, higher concentrations are observed, especially in the dining room and kitchen, where values occasionally exceed 1500 ppm. The dashed blue lines represent reference thresholds, suggesting that while CO_2 levels remain within acceptable ranges for most of the day, there are peaks particularly in the afternoon and evening hours that may warrant attention in terms of ventilation.

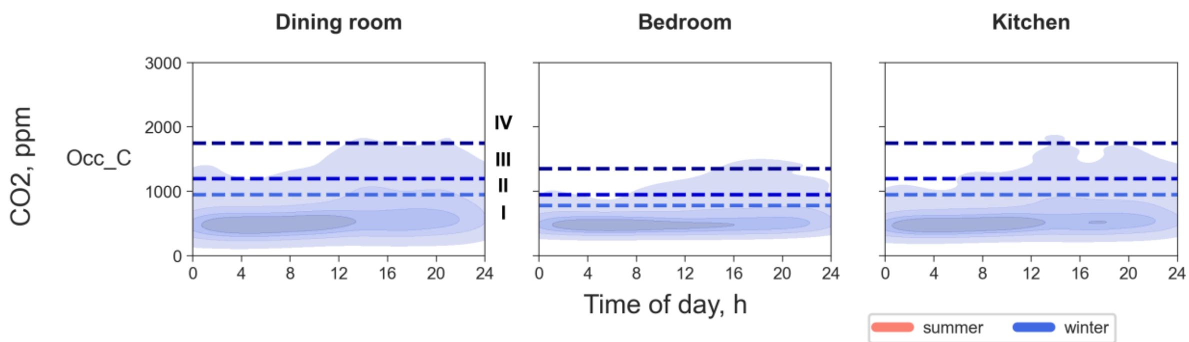


Figure 5-11 CO_2 distribution (density plot for the 2.5th-97.5th percentile) as a function of the time of day for the Italian case Occ_C. Display of summer (Jun-Jul-Aug) and winter (Dec-Jan-Feb) in three spaces: dining room, main bedroom and kitchen. The blue dotted reference lines are the threshold values of the CO_2 IEQ classes according to EN-16798.

Figure 5-12 presents the diurnal variation of indoor CO_2 concentrations across various rooms, comparing weekdays and weekends. The data are stratified by room and floor level, with CO_2 concentrations plotted against the hour of the day.

In general, higher CO_2 levels are observed during weekdays (red line), particularly in the first-floor dormitory and Room 2, where peaks exceed 2000 ppm and 1500 ppm respectively, likely due to higher occupancy. In contrast, weekend CO_2 concentrations (blue line) tend to be lower and more stable across most spaces, suggesting reduced human presence and activity.

Notably, in the dining room and kitchen on the ground floor, CO_2 levels also show distinct weekday peaks during mealtimes, reflecting patterns of use. The corridor and other rooms display more moderate fluctuations, with some overlap between weekday and weekend profiles.

Overall, the analysis underscores the influence of occupancy patterns on indoor air quality, emphasizing the potential for demand-controlled ventilation strategies tailored to temporal usage trends.

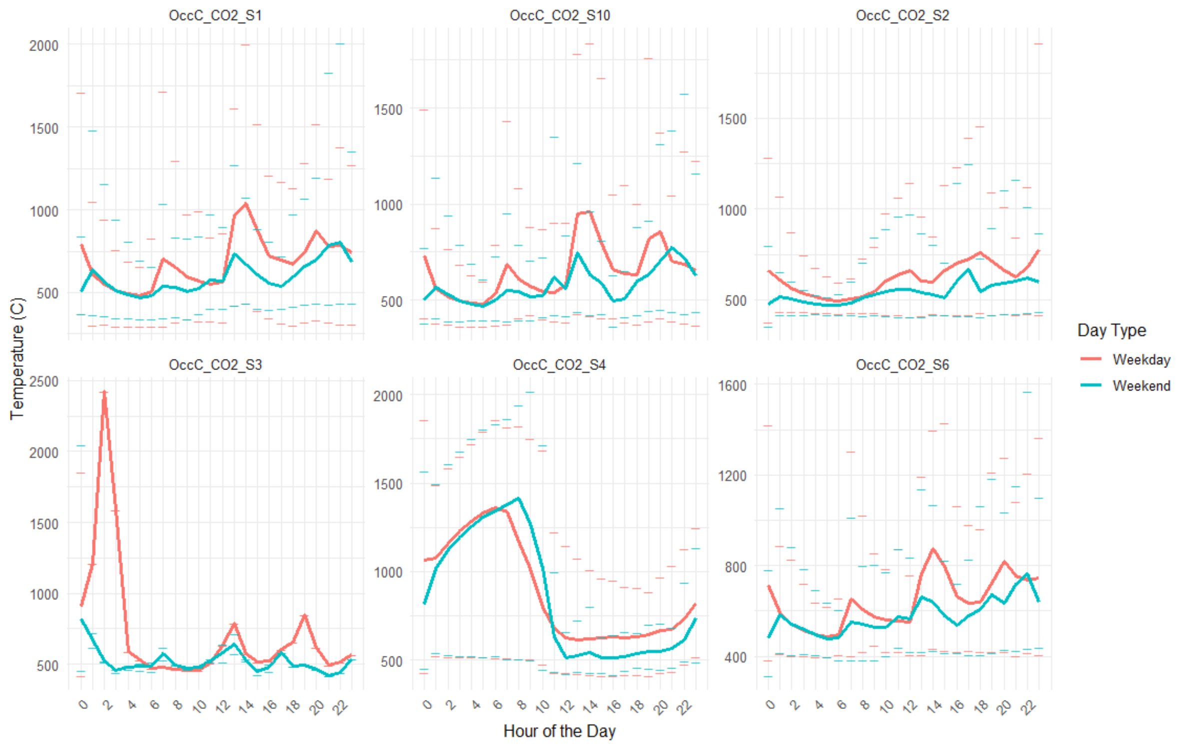


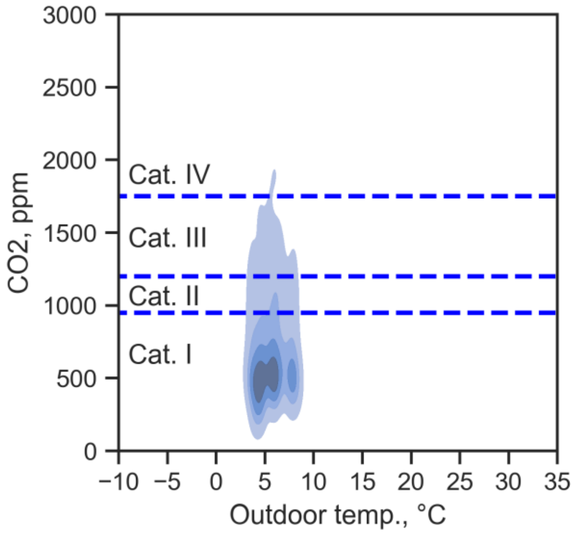
Figure 5-12 CO_2 concentration distribution in the specified rooms, comparing weekdays and weekends during summer and winter for the Italian case Occ_C. Solid lines represent the mean CO_2 concentration as a function of time of day, separately for summer and winter, and for weekdays and weekends. Dotted lines indicate the 5th and 95th percentiles of the corresponding data.

5.2.6 EN 16798 IEQ categories

The EN16798-1:2029 standard describes a classification system for IEQ. One aspect is based on perceived air quality and expressed as limit values for CO_2 above the outdoor air concentration. We used the suggested design ΔCO_2 concentration in Table B.12 of the EN16798-1:2029 to define the limits of the IEQ-classes in our analysis. Since the CO_2

dataloggers self-calibrate to 400ppm as outdoor air concentration the limit values can be expressed as absolute measured values, an overview in Table 2-5.

Figure 5-13 shows the distribution of CO_2 as a function of outdoor temperature for the dining room and bedroom of case Occ_C. The top half of the contour of the plot is most interesting to look at in this case as this will represent a situation that will occur at least 5% of the time and the spaces will be occupied at this time. Good IAQ management will be able to keep this value below the design criteria. The two plots are the two worst examples of all results and still we see that the 97.5th percentiles do not go above the Cat II limit which would be the typical target level for residential units. Interestingly, no clear relationship between CO_2 concentration and outdoor temperature seems to be present while we might expect a reverse correlation with outdoor temperature. Furthermore, it should be noted that high CO_2 levels in the winter period are quite frequent due to a decrease in window openings because outside temperatures are low.



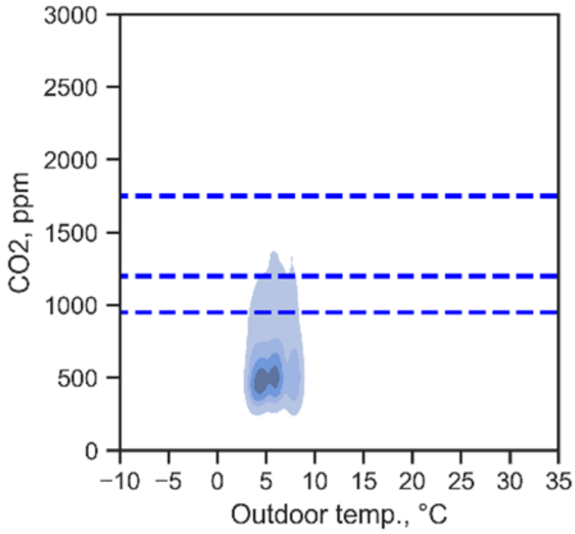


Figure 5-13 Distribution of the measured CO_2 as a function of the exponentially weighted outdoor temperature (density plot for the 2.5th-97.5th percentile data) for the dining room (left) and bedroom (right) of the Italian case Occ_C. The dotted reference lines are the limits of the IEQ categories.

The IEQ-classes analysis was done for Occ_C (which is the only occupied case study). Each day in the dataset was assigned a category based on its 95th percentile CO_2 concentration value. The percentage of time when data collected falls within a specific category is shown in the table below.

Table 5-5 CO_2 based IEQ categorisation for the dining room and bedroom of the case Occ_C (From November 26, 2024 to February 11, 2025).

% of days in Cat. #	Dining room	Bedroom
Days in dataset	77 days	
Start-End data	Nov 26, 2024 to Feb 11, 2025	
Category I	82%	83%
Category II	9%	7%
Category III	7%	7%
Category IV	2%	3%

The results shows that almost all data points lie in category I, with no particular differences between the dining room and bedroom. Only 2-3% of the data lie in the worst category level. Such result underscores the good indoor air quality inside the building, most likely the result of the large amount of air infiltration from existing windows and doors and the natural ventilation employed through window openings.

5.2.7 Relative humidity variability

The relative humidity of a space has an influence on perceived comfort of the occupant. Both, too low or high RH values with respect to the ideal (around 50% with margins of 10-20%) are considered unfavourable for the hygrothermal comfort of the occupants.

Figure 5-14 illustrates the diurnal profiles of relative humidity across three rooms (dining room, bedroom, and kitchen) for the three cases (Occ_A, Occ_B, and Occ_C), during both summer and winter periods. The shaded areas represent the distribution of relative humidity over a 24-hour period, with blue and red zones corresponding to winter and summer data, respectively. Dashed horizontal lines indicate recommended comfort thresholds.

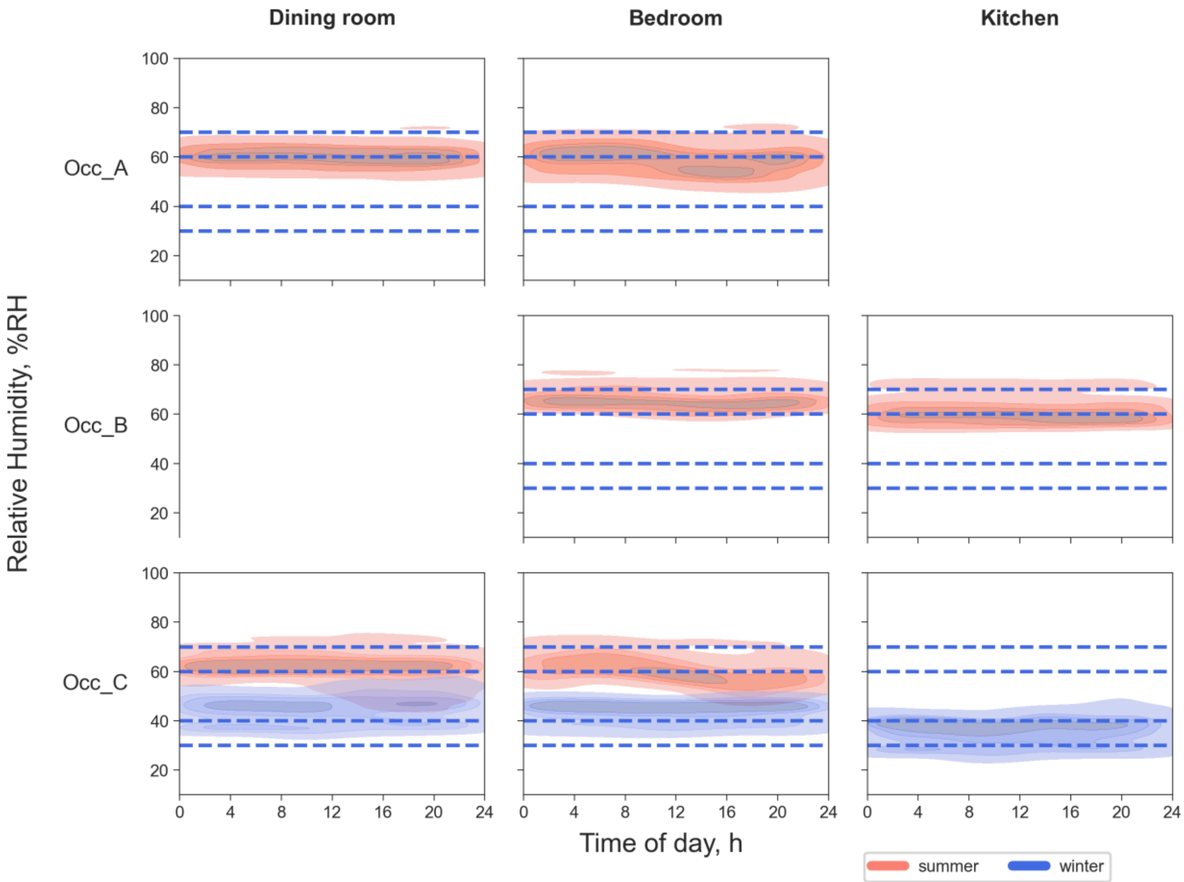


Figure 5-14 Relative humidity distribution (density plot for the 5th-95th percentile) as a function of the time of day for the Italian cases. Display of summer (Jun-Jul-Aug) and winter (Dec-Jan-Feb) in three spaces: dining room, bedroom and kitchen. Empty slots mean no data was available. The blue dotted reference lines at 30-40% and 60-70% indicate typically used intervals considered to be perceived as comfortable by people.

In the unconditioned buildings (Occ_A and Occ_B), relative humidity values during summer predominantly remain between 55% and 70%, with minor diurnal variation. Limited data availability is evident in Occ_B for the dining room and in Occ_A for the kitchen.

In contrast, the air-conditioned *and occupied case* (Occ_C) demonstrates distinct seasonal differences. In summer, RH values tend to be higher, particularly in the bedroom and dining room, occasionally exceeding the upper comfort threshold (60%). In winter, RH levels are significantly lower, often falling below 40%, especially during daytime hours, indicating potential dryness due to *the* heating *system*.

5.2.8 Internal humidity classes

The Internal humidity classes methods described in EN ISO 13788:2013 can be used to classify the internal humidity load of a space from class 1 (low internal humidity load) to class 5 (high internal humidity load). This is an important boundary condition for mould growth on a thermal bridge. According to the standard dwellings, usually lie within class II.

Table 5-6 Internal humidity classification of the dining room, main bedroom and kitchen for the Italian case Occ_C.

	Dining room	**Bedroom**	**Kitchen**
Occ_C	Class 3	Class 1	Class 2

Figure 5-15 illustrates the relationship between outdoor temperature (°C) and indoor air moisture excess (g/m³) in three different rooms: dining room (left), bedroom (centre), and kitchen (right). The shaded blue areas represent the empirical density of observations, while the dashed blue lines indicate threshold values corresponding to increasing humidity classes, from low (bottom) to high (top).

A general negative trend is observed across all rooms, with indoor moisture excess decreasing as outdoor temperature rises. The dining room and bedroom exhibit broader distributions, suggesting greater variability in indoor moisture levels, whereas the kitchen shows a narrower range, indicating more stable or better-controlled humidity conditions.

The dashed lines provide a basis for classifying data into five humidity classes, facilitating comparative analysis of hygrothermal conditions across rooms and supporting assessments of condensation or mold growth risk.

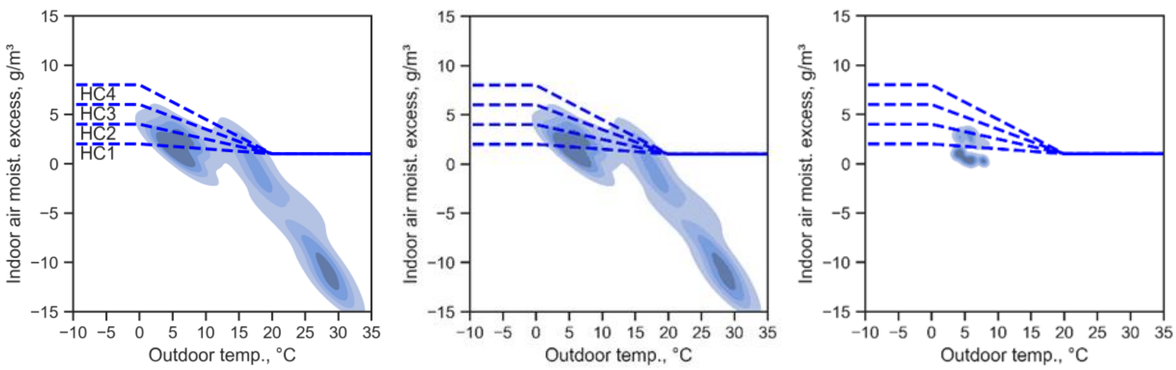


Figure 5-15 Weekly average indoor air moisture excess distribution as a function of the exponentially weighted outdoor temperature (density plot for the 5th-95th percentile data) for the dining room, bedroom and kitchen of the Italian case Occ_C. The dotted reference lines represent the threshold values defined by the internal humidity classes as described in the EN ISO 13788:2013 standard.

5.2.9 Insights

The analysis of the indoor environmental conditions across the three case studies (Occ_A, Occ_B, and Occ_C) attributes a significant role of air conditioning and ventilation systems in ensuring thermal comfort and acceptable air quality. In the unconditioned cases (Occ_A and Occ_B), particularly during the summer period, indoor temperatures frequently exceed the recommended setpoint of 26°C, with limited diurnal variation. This suggests inadequate thermal control and a potential discomfort for occupants. Relative humidity levels in these cases remain relatively stable but often close to or slightly above the upper comfort limit, further indicating the need for active intervention. Although CO_2 data were not available for these scenarios, it is reasonable to assume that, in the absence of mechanical ventilation, indoor air quality may degrade significantly during periods of high occupancy.

In contrast, the air-conditioned building (Occ_C) shows improved thermal conditions, with temperatures maintained closer to comfort standards and reduced variability. The CO_2 concentrations in this case are generally lower and more stable, especially during winter, although some peaks occur in specific rooms and times of day, reflecting typical patterns of use. However, during the winter period, relative humidity levels often fall below recommended thresholds, particularly in the bedroom and kitchen, which may lead to discomfort due to excessive dry air probably caused by the heating system.

Based on the analyses carried out, a general positive condition for comfort in summer can be noted in rooms situated on the ground floor (according to the adaptive model) thanks to the thermal mass that characterize such buildings. However, there may be some rooms, based on location, orientation, proximity to the roof, amount of glazed area and presence of shading, which may have non-optimal conditions for comfort. This is mostly observed in unconditioned cases.

Therefore, expecting more challenging summer outdoor conditions in the context climate change, to improve overall indoor comfort conditions, unconditioned spaces would benefit from the introduction of active climate control, along with effective natural or mechanical ventilation to control both temperature and CO_2 levels.

In conditioned environments, while thermal and air quality conditions are generally satisfactory, there is a potential need to address the issue of low humidity during the heating season. Introducing humidification control or adjusting HVAC settings could for example help restore balance and enhance occupant well-being. In all cases, tailoring system operation to occupancy patterns and time of day appears essential for maintaining optimal indoor environmental quality throughout the year and improve the energy efficiency of these buildings.

5.3 Space conditioning and IAQ management

For the three cases where long time measurements were carried out, a detailed inventory of the space conditioning systems present in those dwellings was carried out. In Table 5-7, the focus is on the distribution and emission systems (with the corresponding control system), alongside with the ventilation systems. The overview of the energy systems can be found in 'D4.1 R²ES-Based Energy Supply Concepts for Heritage Buildings in Historical Neighbourhoods'.

Table 5-7 Overview of space conditioning installations for Montanara, Romano and Leonardo

Building code			**Montanara**	**Romano**	**Leonardo**
Heated area (int. dim.), m²			413	366	350
Archetype			Palazzetto	Gothic lot	Extended
Distribution	Heating	Central/local	local	local	central
		Transport medium	hydronic	hydronic	hydronic
		Type of distribution	pipes	pipes	pipes
	Cooling	Central/local	n/a	n/a	local
		Transport medium	n/a	n/a	R-410A
		Type of distribution	n/a	n/a	pipes
Emission	Heating	Main type	radiators	radiators	radiators
		total installed power, W	n/a	n/a	n/a
	Cooling	Main type	n/a	n/a	split units
		total installed power, W	n/a	n/a	n/a
Ventilation		Central ventilation system	natural	natural	natural
		Bathroom extraction, m³/h	n/a	n/a	n/a
		Toilet extraction, m³/h	n/a	n/a	n/a
		Vented range hood, m³/h	n/a	n/a	n/a
Temperature control		Control type	zonal thermostat	zonal thermostat	zonal thermostat
		Night setback, °C	n/a	n/a	n/a
		Day setback, °C	n/a	n/a	n/a

5.4 Defining space conditioning pre-renovation baselines and renovation baselines

5.4.1 Pre-renovation baseline

In all Italian archetypes, no particular difference is revealed.

For pre-renovation baseline, in all Italian the archetypes the heating system relies on a central hydronic distribution network, which supplies high-temperature radiators. The indoor environment is regulated through a central thermostat in combination with thermostatic radiator valves, allowing for basic zone-level temperature control. This configuration reflects a conventional approach typical of older, pre-renovation dwellings, characterized by limited automation and reliance on user-operated components. A cooling system or whole building (mechanical) ventilation system is not present, therefore, to supply fresh air, the only solution is to use the openable windows present in all the rooms. This pre-renovation scenario is very similar to the Belgian pre-renovation space conditioning scenario.

For all the archetypes the setpoint temperature during the heating period is 20°C (from October 15 to April 15) for 14 hours per day. Given the presence of thermostatic valves in the radiators, it is technically possible to change the temperature by a few degrees in each room according to the user's individual needs when the central heating system is activated.

However, to ensure comparability of simulation results across different building archetypes and climatic contexts in the baseline scenario, it is assumed the thermostatic valves stay at their default setting of 20°C throughout the heating season.

Although in practice the use of thermostatic valves or user-controlled systems may allow temperature adjustments in individual rooms, introducing variable setpoints would introduce significant heterogeneity and compromise the comparability of energy performance metrics. Therefore, the assumption of a fixed setpoint represents a standard boundary condition that facilitates uniformity in thermal comfort modelling. This fixed heating setpoint is applied whenever the heating system is active, regardless of the actual presence of room-specific control systems.

While not all buildings are physically equipped with a climatized system, such set point will be applied across all archetypes, including unconditioned spaces, to maintain consistency in evaluating passive and active thermal behaviours under a unified framework. This approach also aligns with standard practice in thermal simulations where a fixed setpoint strategy allow to assess the relative performance of design or retrofit options.

Regarding the summer season, the cooling system can be activated at any time it is needed, normally with a setpoint of 26°C. However, not all rooms are equipped with air conditioning splits. It should be noted that even in unconditioned cases the conditions above described can be considered valid.

In Figure 5-16, an overview of the pre-renovation baseline for all the archetypes is given.

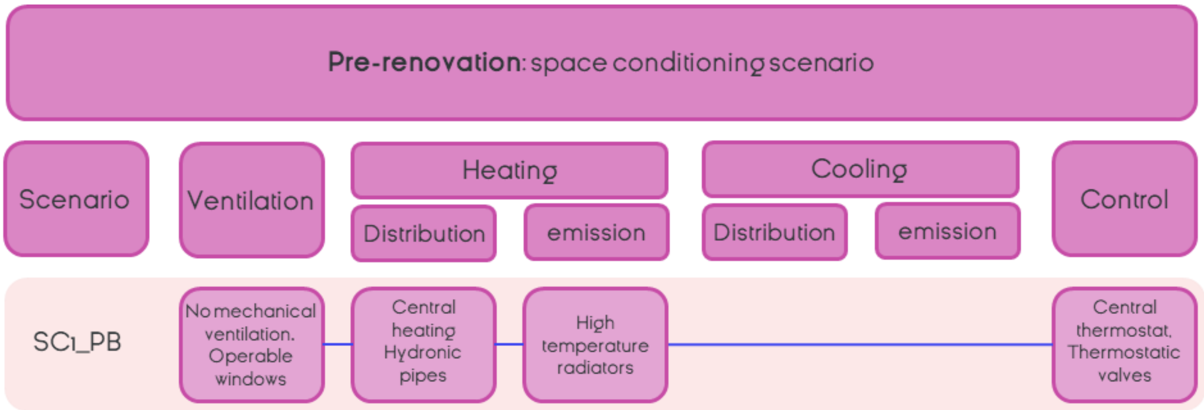


Figure 5-16 Schematic overview of the Pre-renovation Baseline (PB) Space Conditioning (SC) scenario for the Italian archetypes.

5.4.2 Renovation baseline

As the pre-renovation space conditioning baseline in all archetypes are similar, also how these are renovated is similar.

Figure 5-17 illustrates the renovation space conditioning scenarios SC1_RB, SC2_RB and SC3_RB, outlining the modifications implemented in ventilation, heating, cooling, and control systems. In both scenarios SC1_RB and SC2_RB, ventilation remains unchanged from the pre-renovation condition, relying solely on natural ventilation through operable windows, with no mechanical systems installed. Heating continues to be delivered through a central hydronic distribution system. In SC1_RB, the existing high-temperature radiators are retained, while in SC2_RB, they are replaced with new and more efficient high-temperature radiators, indicating an upgrade in the emission system.

The SC3_RB scenario introduces a passive ventilation strategy, that could be applicable in the Montanara and Romano cases where there is a staircase connecting the different floors of the building. Specifically, for this scenario renovation baseline, it is proposed to use the staircase as a wind tower, as there is an opening on the top that enhancing natural air movement through stack effect. This strategy aims to reduce the reliance on mechanical systems, improving energy efficiency while maintaining indoor air quality through architectural means. The heating and cooling system is the same as the scenario SC2_RB.

A cooling system, which was previously absent, is introduced in all three renovation scenarios. It is distributed through local cooling tubes and emitted via a multi-split system, representing a significant enhancement in thermal comfort capabilities. The control strategy is also modernized: the scenarios include a central thermostat with a heating curve and thermostatic valves for regulating heating, while cooling is managed manually. This setup reflects a transitional phase toward more efficient and responsive environmental control, while still maintaining some degree of user interaction.

The temperature setpoints during winter and summer are the same as in the pre-renovation baseline, to make a fair comparison possible.

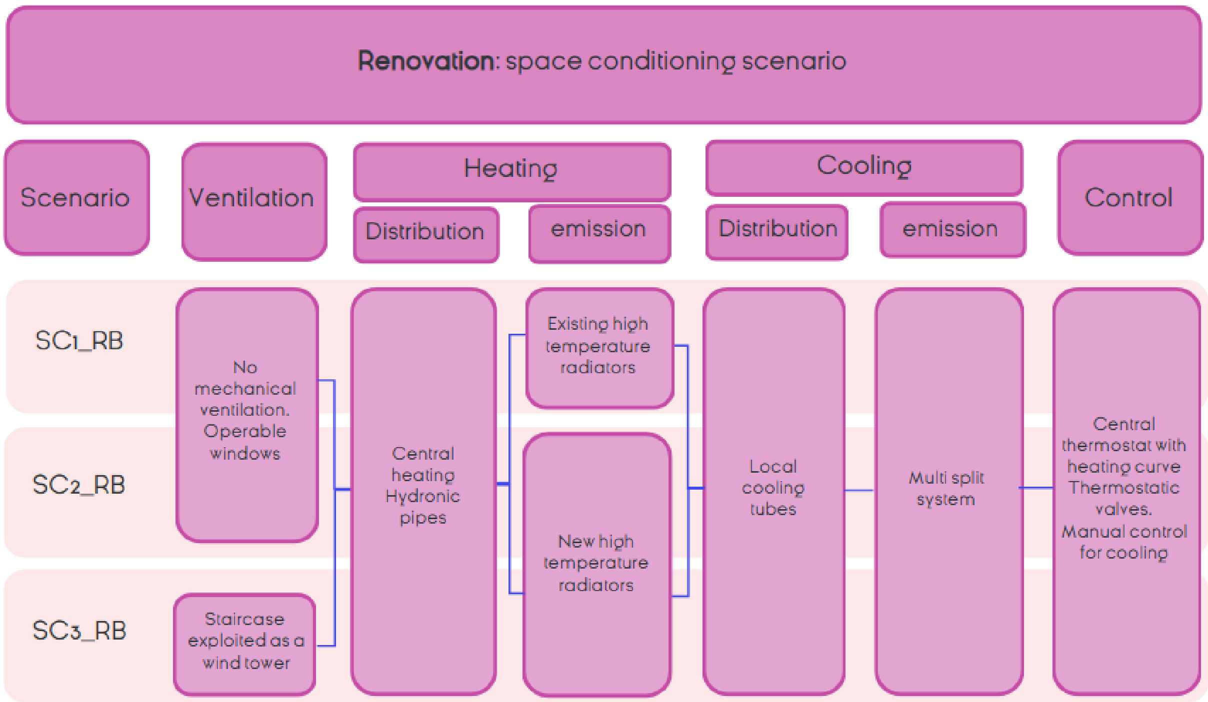


Figure 5-17 Schematic overview of the Renovation Baseline (RB) Space Conditioning (SC) scenarios for the Italian archetypes.

6 Conclusion

This deliverable represents a foundational step in the HeriTACE project's broader ambition to develop energy-efficient HVAC strategies that enhance indoor environmental quality (IEQ) in heritage townhouses across Europe. Through extensive measurement campaigns across Belgium, Norway, Estonia, and Italy, this work examined the current comfort conditions, space conditioning systems, and indoor air quality (IAQ) within the representative townhouse archetypes selected in in each country (D5.1). The findings presented here not only offer vital empirical evidence to inform subsequent modelling and renovation strategies but also shed light on the lived experience of heritage building occupants under varying climatic conditions.

6.1 General Observations

Across the four nations involved in the study, certain consistent themes emerged.

First, indoor temperatures observed during the heating season were different from the regulatory assumptions set out by EPBD. This finding challenges the relevance of standard assumptions in the energy performance calculation frameworks when applied to heritage housing.

Second, measured IEQ levels—particularly for CO_2—were better than anticipated in most dwellings, with a substantial number of rooms qualifying in IEQ category I or II as per EN 16798. This suggests that traditional ventilation practices, including natural infiltration and airing (window opening) by the occupants, still play a decisive role in maintaining acceptable indoor conditions even in buildings lacking advanced mechanical systems. This also indicates that a 'High' to 'Medium' level of IEQ is expected by occupants and that renovation measures that focus on energy saving should be accompanied by an adequate IEQ management strategy.

Third, thermal comfort as evaluated through the adaptive comfort model (EN 16798) generally fell within acceptable boundaries. However, the data also reveal a spatial heterogeneity in thermal comfort performance, certainly throughout the different climate zones.

6.2 Country-Specific Reflections

6.2.1 Belgium

A key finding in Belgian homes was the role of high thermal mass in moderating diurnal temperature swings, enabling acceptable summer conditions without active cooling in large parts of the dwelling. While winter indoor temperatures often dipped below standard comfort thresholds, this was not due to system limitations, but rather deliberate occupant behaviour aimed at energy sufficiency. Bathrooms were often unheated or selectively heated, and bedrooms showed low CO_2 levels—likely due to regular window opening and/or natural infiltration.

6.2.2 Norway

Despite a cold climate and the limited use of mechanical space conditioning systems, Norwegian homes maintained remarkably stable indoor temperatures with narrow seasonal variability. Heating was typically maintained throughout the year, resulting in winter temperatures that often-exceeded EPBD assumptions and fall at the upper-end of the adaptive comfort boundaries. Natural ventilation prevailed, with window airing sufficiently maintaining CO_2 within acceptable ranges in most cases. However, humidity spikes in bathrooms indicated the need for improved exhaust systems to mitigate mould risk.

6.2.3 Estonia

Estonian cases demonstrated the challenges posed by airtight envelopes and long heating seasons. Moisture management was a particularly salient issue, with evidence of high internal humidity classes in several monitored rooms. At the same time, the widespread use of natural ventilation combined with well-managed heating practices helped maintain thermal comfort within EN Class II for most occupied periods. High indoor air temperature requirements set by the occupants result in temperatures often-exceeded EPBD assumptions. The Estonian cases emphasized the sensitivity of IAQ and comfort to both envelope interventions and user routines.

6.2.4 Italy

The Italian cases revealed the critical role of HVAC systems in maintaining thermal comfort and air quality. Unconditioned buildings (Occ_A and Occ_B) experience frequent overheating in summer (above 26°C) with poor temperature control and likely CO_2 buildup, given the lack of mechanical ventilation. In contrast, the air-conditioned home (Occ_C) maintains better temperature and CO_2 levels, though wintertime dryness is a concern due to low relative humidity.

Ground-floor rooms perform quite good in summer due to proximity to the ground and passive shading from surrounding buildings without active cooling, but discomfort is very likely in upper floors or poorly shaded areas. To prepare for hotter summers under climate change, unconditioned homes would benefit from active cooling and improved ventilation. In conditioned spaces, occupancy-based system management are recommended to optimize comfort and energy efficiency year-round.

6.3 Key take-aways and Recommendations

Deliverable D3.2 offers robust empirical support for a nuanced approach to heritage townhouse renovation. Rather than pursuing maximum technical intervention, it argues for systems and strategies that align with building characteristics, occupant behaviours, and climatic context. The insights and baselines derived from this work now serve as a critical foundation for the simulations and renovations that follow in WP3 and beyond. As climate targets tighten and energy expectations rise, such grounded, context-sensitive understanding will be essential for making Europe's architectural heritage both resilient and future-ready.

Key Cross-region take-aways are:

Occupant Behaviour and Sufficiency:

The data clearly indicate that users apply sufficiency-based strategies—e.g., partial heating, night-time window opening, or unheated rooms—without significant detriment to comfort. This validates the HeriTACE project’s hypothesis that non-uniform, time-and-space-dependent HVAC strategies are not only feasible to enhance energy efficiency but already in practice to some extend.

Construction type and overheating risk:

Across all regions, the non-wooden heritage townhouses benefited from their thermal mass to buffer against high temperature extremes. The wooden townhouse types have a higher overheating risk but are only found in the colder climatic region.

HVAC System Characteristics:

Most buildings featured traditional hydronic heating systems, often controlled by a central thermostat with additional thermostatic valves, or direct electric heaters. Only in the colder regions, woodstoves are still in use but of secondary nature. Few included mechanical ventilation, and even fewer had mechanical cooling.

Risk of Moisture Damage:

While relative humidity was generally within acceptable comfort ranges, localised conditions (e.g., bathrooms, below-grade living spaces) posed mould and condensation risks. Moreover, building upgrades—especially those that enhance airtightness—could exacerbate these issues if not paired with effective ventilation strategies.

The following **recommendations** can inform building designers, policy makers, and heritage conservationists:

- Leverage existing occupant behaviour: New HVAC systems should be designed to support and optimize prevalent sufficiency-based behaviours rather than override them.
- Account for spatial variability: Renovation strategies should consider intra-building variation—particularly the thermal challenges posed by different functions in different locations (annexes, attics, cellars, …).
- Targeted mechanical upgrades: Rather than overhauling entire HVAC systems, targeted lower-impact enhancements can potentially yield significant gains.
- Monitor airtightness effects: Any intervention aimed at improving airtightness should be complemented with a ventilation design that considers the sensitivity of the intervention to internal moisture accumulation.
- Use adaptive comfort models: Regulations and renovation targets should integrate adaptive comfort frameworks, which better reflect occupant experience in heritage buildings than static setpoint-based metrics.

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