Title: Indoor environmental conditions in vernacular dwellings in Alentejo, Portugal

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Acknowledgements

A special thank you to all the inhabitants for allowing data collection at their homes and participating in the surveys.

Funding

This work was supported by the Foundation for Science and Technology (FCT) from the Portuguese Ministry for Science, Technology and Higher Education, under Grant No: SFRH/BD/95911/2013, and its financing programme POPH/FSE.

Disclosure statement

The authors report that there are no competing interests to declare.

Biographical Note

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Indoor environmental conditions in vernacular dwellings in Alentejo, Portugal

Understanding the indoor environmental conditions of livable architectural heritage such as vernacular dwellings is a key step towards its conservation. Yet, there is a lack of large-sample studies that assess indoor conditions using long-term quantitative and qualitative data complying with monitoring standards. This paper addresses this gap in Portuguese vernacular dwellings using long-term mixed methods, by analyzing the thermal performance, indoor air quality, and illuminance of 22 case studies. Key findings highlight the role of thermal mass in damping the outdoor thermal wave and providing thermal stability, night ventilation, and lack of windows. Summer thermal performance bettered that of winter, but occupant control strategies negatively impacted thermal stability and overheating. In winter, the most prevalent heating system, electric, performed less efficiently than radiant heating, leaving occupants exposed to thermal discomfort and health risks from cold, mold, and toxins from wood-burning and cooking. Important discrepancies were found between the illuminance monitored and survey data, indicating the significance of cultural practices in indoor environment acceptability and expectations.

[1]

Abbreviations: CIE: International Commission on Illumination; DBT: Dry-bulb temperature; DF: Daylight factor; D_T: Target daylight factor; D_{TM}: Minimum target daylight factor; GA: Genetic Algorithm; IAQ: Indoor Air Quality; OHI: Outdoor Horizontal Illuminance; RH: Relative Humidity; SVV: São Vicente e Ventosa; T_a: Air temperature; T_{aMAX}: Maximum temperature; T_{aMIN}: Minimum temperature; T_{MRT}: Mean Radiant Temperature; V_a: Air velocity; WWR: Window-To-Wall Ratio.

1. Introduction

The conservation of livable architectural heritage such as vernacular dwellings largely depends on the understanding of their indoor environmental and living conditions [1,2]. In recent years, research on the indoor conditions of vernacular dwellings has focused on thermal performance in humid climate locations, such as the following research: [3–25]. This is then followed at a distance by Portuguese [26–28], and Iranian studies [29–31]. The combination of *in situ* monitoring and occupant surveying stands out as a popular methodological approach, added to, most recently, the coupling of monitoring with dynamic simulation. Even though it has been suggested that thermally-unrelated indoor environmental quality factors such as illuminance [32] and indoor air quality [33] affect indoor thermal comfort perception, these are seldom addressed.

Portuguese vernacular architecture has been reviewed from a predominantly heritage perspective. There is a lack of mixed-methods, i.e. combining qualitative and quantitative data collection, large-sample studies on indoor conditions. In Alentejo, while a few qualitative historical, ethnological, and construction studies have been undertaken since the 1930s [34–38], quantitative research entailing monitoring is scarcer [27,28,39,40] and long-term large-sample studies are non-existent. Previous research focused on identifying passive strategies and reporting thermal performance based on short-term monitoring in single case studies, which may lead to extrapolation bias. Only one previous study used data triangulation to assess the indoor comfort of a rammed-earth vernacular dwelling in Alentejo [26] and compare it to a northern building [27,28]. Furthermore, to the best of the authors' knowledge, no comprehensive research looking at thermal performance, indoor air quality, and daylight illuminance has been conducted in vernacular dwellings in this region.

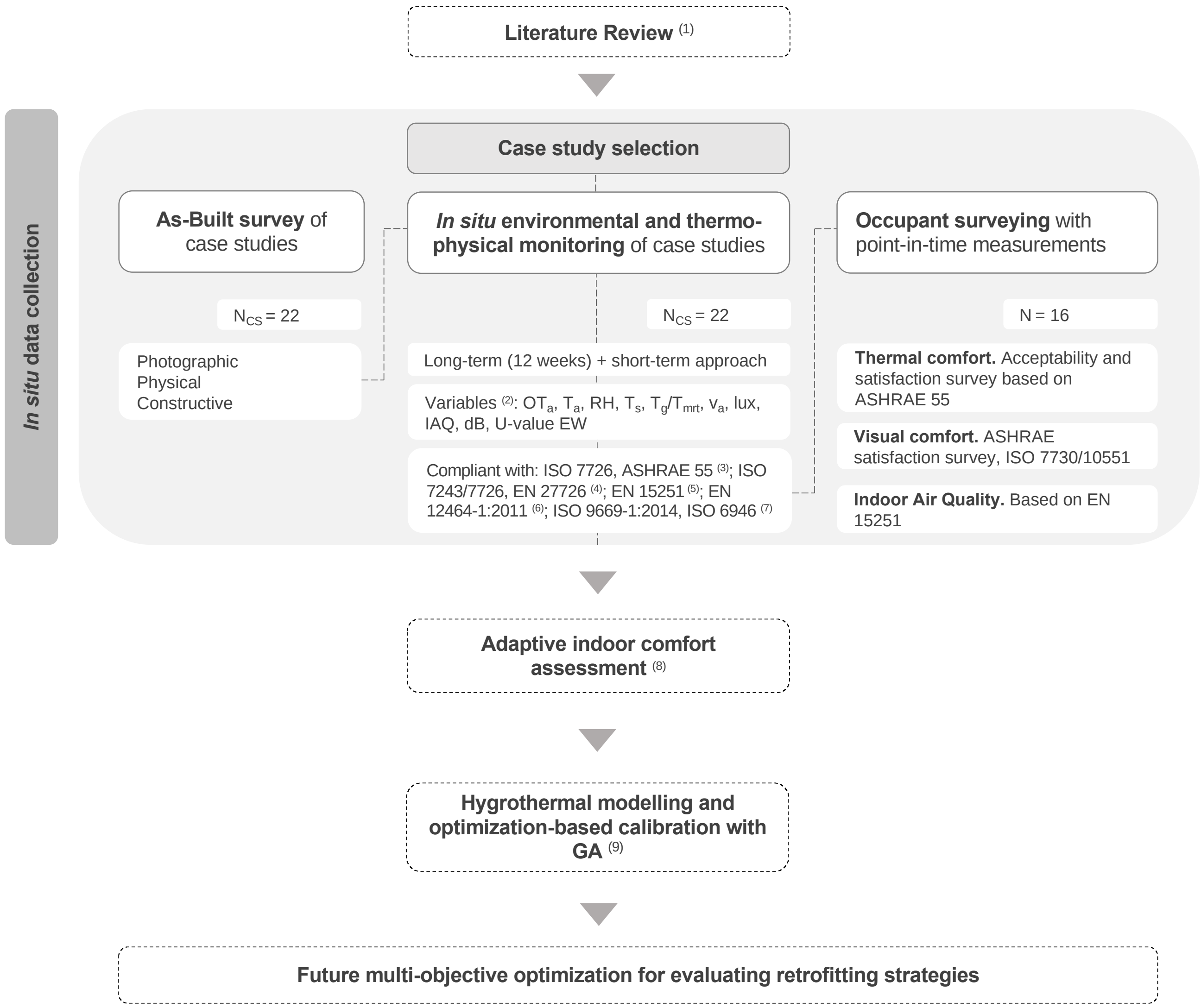
The undertaking of large-sample and long-term studies is essential for obtaining robust and transferable conclusions on vernacular dwellings' indoor behavior. Moreover, it is crucial that this research analyses unresearched vernacular typologies to maintain their livability and encourage their conservation [1,2].

2. Aim

This paper addresses this gap by analyzing a large sample of an unexplored typology of vernacular dwellings in São Vicente e Ventosa (SVV), Alentejo, Portugal, and aiming to determine their indoor environmental performance, i.e. thermal performance, indoor air quality, and illuminance, and living conditions, based on long-term *in situ* data collection in summer and winter.

3. Materials and methods

The mixed-methods approach adopted encompasses quantitative and qualitative data collection to carry out an informed assessment of the case studies' indoor conditions. This is the second step of a four-stage global methodology, entailing literature review, *in situ* data collection, thermal comfort assessment, and optimization-based modelling (see infographic in Fig. 1). Its overarching aim was to develop a Genetic Algorithm (GA)-based multi-objective optimization methodological framework applicable to the hygrothermal modelling of vernacular heritage models to ultimately contribute to fostering adequate retrofit strategies for enhancing thermal comfort in heritage buildings worldwide. For the published outcome of the first, third, and fourth stages the interested reader may refer to [41–43]. The methods employed for the second stage, i.e. monitoring and surveying, which informs the adaptive comfort assessment and modelling stages of the research, are outlined in the ensuing section.



(1) Stage 1 of the research published in [42].

(2) OT_a: Outdoor Air Temperature; T_a: Indoor Air Temperature; RH: Relative Humidity; T_s: Surface Temperature; T_g: Globe Temperature; T_{mrt}: Mean Radiant Temperature; V_a: Air Velocity; Lux: Natural illuminance; IAQ: Indoor Air Quality; dB: Sound level; U-value EW: Thermal Transmittance of the external walls; (3) T_a, RH, and V_a; (4) T_{mrt}; (5) IAQ, Lux, dB; (6) Lux; (7) U-value;

(8) Stage 3 of the research published in [41].

(9) Stage 4 of the research published in [43].

Figure 1. Infographic of the research sequence developed.

3.1. Case studies selection and description

3.1.1. Case studies selection

The selected case studies are based in the rural settlement of SVV (38.57’14’’N 7.12’46’’W) and their passive strategies and environmental and socioeconomic conditions are considered typical of the region, permitting a broader impact of findings.

Their selection was conducted according to the following criteria: i. representativeness of regional vernacular dwellings and their bioclimatic strategies; ii. preservation of traditional building elements, including the façade's integrity; iii. residential occupancy; iv. physical condition. To this end, a photographic survey of the façades of the entire settlement was carried out, resulting in 75 preliminary options, which decreased to 22 final ones due to additional considerations, i.e. access denied by occupants, abandonment or construction work; absence of occupants; modified indoor space and construction systems.

Figure 2. Location and street views of the selected case studies. Location Plan: Own elaboration based on cartography from the Portuguese Geographic Institute.

3.1.2. Case studies description

The case studies' layout and occupancy profile are deeply rooted in the primary regional economic activity, i.e. agriculture [40], originally providing shelter for rural workers. The case studies technical sheet can be found in the Appendix A, with their respective labelling (D01-D22). Three main typologies were identified; the predominant one (70 % of cases) is illustrated in Figure 3, its typical features, based on the *in situ* data collection and the traditional technical literature, are outlined in Table 1 and Table 2, and its respective constructive details (D01-D03) are presented in the Appendix B. Amongst these, their significantly-sized fireplace and chimney play a predominant role in the case studies and their lack of windows in all walls (with only built-in wickets on front and rear doors) are amongst their key bioclimatic features. The current heating and cooling systems contrasted with the traditional techniques are equally provided in Appendix C according to the four categories identified for summer and winter within occupied dwellings, based on the survey conducted. Moreover, the typical occupancy and behavioral profile are outlined in Table 3.

Contrary to the regional traditional building technique, i.e. rammed earth [34,44–47], the case studies combined the locally available limestone with earth from surrounding fields. The local limestone availability has been acknowledged in the literature [34], and the soils geological constitution corroborates its use in the dwellings, with the latter sitting on a limestone and dolomite patch of Cambrian soil [48].

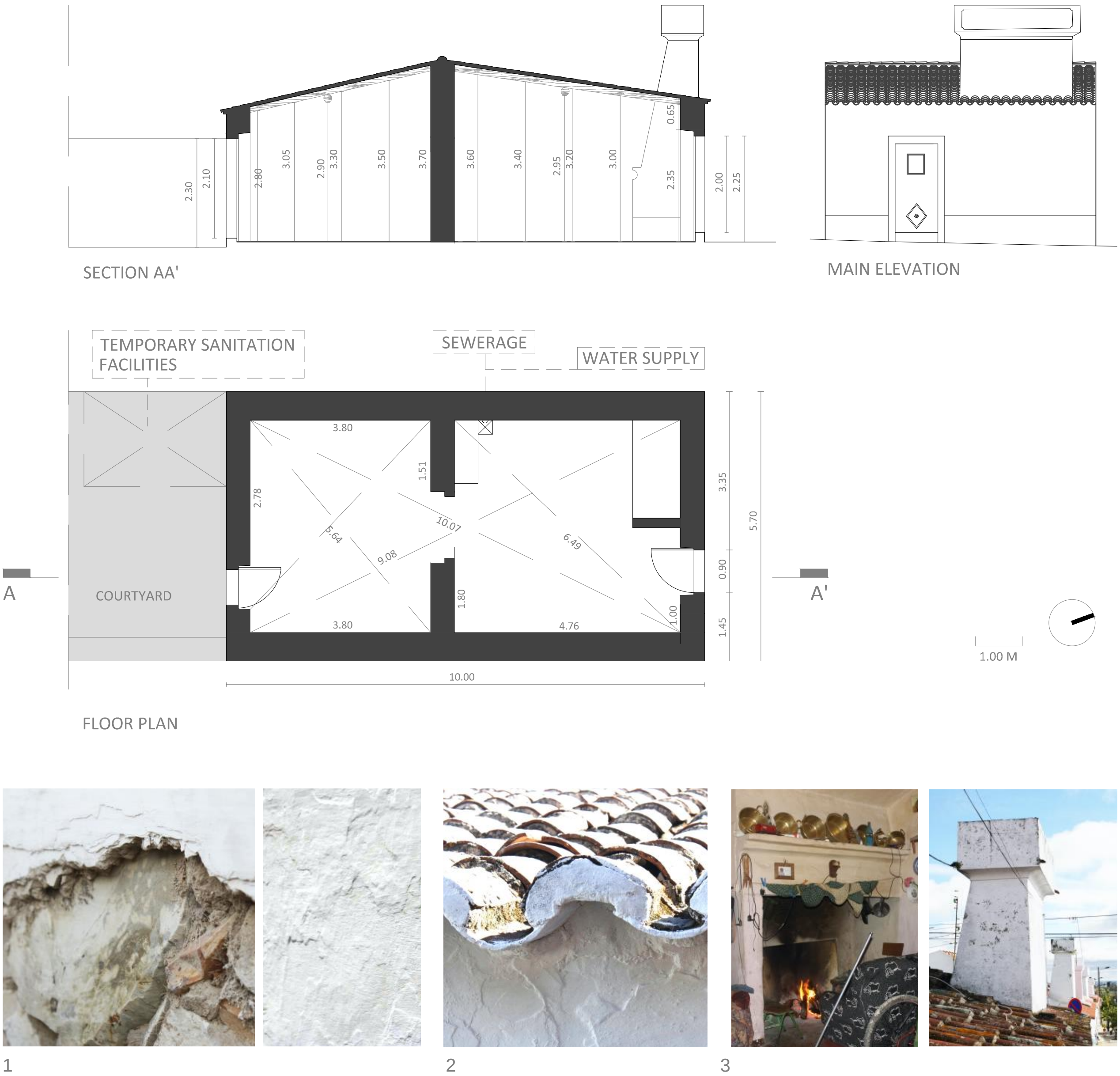


Figure 3. Typical case study layout: Floor plan, section, and elevation. Views: 1 - Limestone and earth masonry, lime wash; 2 – Roof with Arabic tiles; 3 - Chimney-Fireplace.

Table 1. General description and dwelling typology features of a typical vernacular dwelling in SVV

General description	
Construction date	1800s
Orientation	NE-SW; SE-NW; E-W
Heritage protection	Yes. Façade
Dwelling Typology	
Number of storeys	1
Average plan dimensions	6.00 m x 10.00 m
Number of rooms	2: living area + sleeping area

Outdoor space	Rear courtyard + front entrance steps (if existent)
Fireplace indoor space	1.50 - 2.00 m x 1.00 m
Ceiling height range	2.80 m (average lowest) - 3.60 m (av. highest) [(1)]
Openings	0.15 m^2: Built-in wicket on front and rear doors
	Window-to-Wall Ratio (WWR): < 1 % [(2)]

[(1)] The case studies who have installed an expanded polystyrene false ceiling were excluded from the calculation for the average lowest and highest points displayed in the table.

[(2)] The WWR was computed with reference to the in-built-wicket area.

Table 2. Construction features of a typical vernacular dwelling in SVV.

Dwelling Construction	**Thickness**	**U-value**	**Decrement delay** [(4)]
External and internal walls			
Lime render + limestone and earth masonry + lime plaster + lime wash	0.60 m + 0.025 m	1.32 $W/m^2.K$ [(2)] (EW) 1.17 $W/m^2.K$ [(2)] (IW)	18 (h)
Roof			
Wooden joists + single hollow clay bricks + lime mortar + Arabic tile	0.30 x 0.15 x 0.03 m + 0.012 m + 0.19 x 0.40 x 0.07 m	3.13 $W/m^2.K$ [(3)]	-
Ground			
Ceramic floor tiles + lime mortar + earth	0.03 m + 0.010 m	1.53 $W/m^2.K$ [(2)]	-
Fireplace walls			
Baked brick + lime mortar + lime wash	0.20 m + 0.013 m	1.73 - 1.50 $W/m^2.K$ [(1, 2)]	-

[(1)] The fireplace has both exterior and interior walls, so the U-value was calculated according to the respective Rse and Rsi values.

[(2)] [49].

[(3)] [50].

[(4)] The decrement delay was computed based on the following formula given in [51]:

$$D_d = 0.53 * \frac{t}{2} * \sqrt{\frac{\rho * c_p}{\pi * \lambda * t}} * d \qquad (1)$$

Where, t is 24 hours, ρ is the density, c_p is the specific heat, λ is the thermal conductivity and d is the thickness of the layer.

3.1.3. Climate

SVV is characterized by a hot dry-summer Mediterranean climate, i.e. Csa according to the Köppen Climate Classification [52]. The dry and lengthy summer period averages 25 ºC and peaks around 40 ºC in August [52]. Significant annual thermal amplitudes average 11 ºC, peaking in summer (15 ºC)

[40]. The average winter temperature is 10 ºC, while the minimum ranges from 6 ºC to 8 ºC. Spring and Autumn have little presence. The annual average rainfall is scarce, below 500 mm. The average wind speed is 8 km/h, with prevailing Northwest and Southwest directions [53]. Finally, the region is extremely sunny, with 3000 hours of annual sunshine [54].

Thus, regional vernacular dwellings developed climate-responsive strategies centered on passive cooling, solar radiation shielding, and minimizing summer heat gains [26–28,39,40,55]. The dwellings' key passive strategies are discussed in 4.4..

Table 3. Occupancy and behavioral profile.

		Living room	Bedroom	Courtyard
	Activity and metabolic rate	Miscellaneous (cooking, house cleaning): 2.0 met/115 W/m^2 Seated, quiet/watching TV: 1.0 met/60 W/m^2)/sewing: 1.0 met/55	Sleeping: 0.7 met/40 W/m^2	Standing, relaxed (1.2 met/70 W/m^2)
Summer	Occupancy profile	07:30-23:00	23:00-07:00	Occasional occupancy (use of sanitation facilities and specific activities) during the day
	Strategies and equipment	Wicket and door closed until the evening (around 22:00) Cross ventilation 07h00-09h00/22:00-23:00 Mechanical ventilation (ventilation fans) throughout the day, starting around 12:00, in 70 % of case studies No shading mechanisms apart from the door wicket	Wicket and door closed until the evening Cross ventilation 07h00-09h00/22:00-23:00 No shading mechanisms apart from the door	-
	Thermal insulation (Clo) (2)	0.54-0.57 clo	0.54-0.57 clo	-
Winter	Occupancy profile	07:30-23:00	23:00-07:00	Occasional occupancy throughout the day
	Strategies and equipment	Heating from 07:30 to 23:00/ twice-daily from 07:30-09:30 and 23h00. No heating systems in 23 % of the case studies	Usually no heating system	-
	Thermal insulation (Clo)	1.30 clo	1.50 clo	-

(1) According to the metabolic rates for typical tasks in ASHRAE 55-2020.

(2) According to the thermal insulation data in ASHRAE 55-2020.

3.2. Quantitative methods: in situ monitoring

The authors requested monitoring permission through a preliminary meeting with the city and parish council, where the research scope, its main goals and duration were delivered. These then established the liaison with the inhabitants, which were briefed and asked to provide permission.

3.2.1. As-built survey

Due to the lack of previous surveys and graphic documentation related to SVV's vernacular dwellings, the authors conducted an as-built survey within the *in situ* data collection phase, encompassing photographic records, floor plans, sections, elevations, and constructive systems, before monitoring.

3.2.2. Environmental monitoring

To quantitively assess the case studies' indoor environment, the outdoor and indoor air temperature, relative humidity, globe and surface temperature, air velocity, illuminance, air quality, and sound level were measured. The monitoring ran from July 5th to August 16th and from January 16th until February 27th, in 2015. A long-term *in situ* monitoring approach, as per ASHRAE [56], was adopted for outdoor and indoor temperature and relative humidity, in combination with short-term monitoring for the remaining parameters. The thermal measurements complied with ISO 7726 [57] and ASHRAE 55 [56]. Table 4 details the measurements conducted and Table 5 lists the equipment specifications.

Table 4. Details of the measurements conducted.

	Parameter	Measurement length LT [(1)]	ST [(2)]	PIT [(3)]	Location of measurement	Standard complied with	Specifics
Thermal comfort	Air temperature	■			Living room, bedroom, outdoors	ISO 7726 [57] ASHRAE 55 [58]	Outdoor temp.: dataloggers shielded from direct solar radiation or rainfall Indoor temp.: a centered single measuring point per space (air temperature difference homogeneous per the ISO 7726 criteria) at 1.0 m from the walls Temp. and RH: sensors at the ISO 7726-recommended sitting height and ASHRAE waist level (0.60 m), shielded from neighboring heat sources and radiation, at 15 minute-measuring intervals
	Relative humidity	■			Living room, bedroom, outdoors	ISO 7726, ASHRAE 55	
	Mean radiant temperature		■		Living room	ISO 7243, ISO 7726, EN 27726	Two-week time spans at a time, in three case studies
	Surface temperature		■		Living room/bedroom	-	Southwest-facing external walls, for 72 hours in the summer in three case studies
	Airspeed (va)			■	Living room	ASHRAE 55, ISO 7726	Repeated single-point indoor summer measurements, in three case studies with sealed and unsealed chimneys. at 3-minute intervals spanning two hours from 07:00 to 09:00, at the 0.1, 0.6, and 1.1 m levels, as recommended in ASHRAE 55 and ISO 7726 for seated occupants [59,60]. Dwellings kept in free-running mode
Other environmental parameters	Indoor air quality			■	Living room	EN 15251 [65]	CO2 (%), CO (ppm), VOCs (ppm). Average seated breathing height, in winter conditions
	Illuminance			■	Living room, outdoors	EN 15251 EN 12464-1:2011 [66]	Indoor daylight: consecutive centered measurements in the living room at 0.80 m high Average daylight factor (DF): measurements under unobstructed overcast sky and excluding direct sunlight (CIE standard general sky [67]) Outdoor average daylight illuminance: 10-point measurements, 0.5 m from the façade, horizontal plane on the ground, in unobstructed CIE standard overcast (winter) and clear sky (summer) (duly protected from direct solar radiation)
	Noise level			■	Living room, outdoors	EN 15251	Indoor and outdoor levels: at 15-min intervals

[(1)] Long-term; [(2)] Short-term; [(3)] Point-in-time.

Table 5. Monitoring equipment technical specifications.

	Equipment	Parameter	Measurement range	Accuracy	Measurement range and accuracy required in ISO 7726 and ASHRAE 55-2013
Thermal comfort parameters	Datalogger PCE-HT 71N	Air temperature	-40 °C to +70 °C	± 1 °C with 0.1 °C resolution	Range: 10 °C to 40 °C | accuracy: ± 0.5/ 0.2 °C
	Datalogger PCE-HT 71N	Relative humidity	0 to 100 % RH	± 3 % RH with 0.1 % resolution	Range: 25 % to 95 % RH | accuracy: ± 5 % RH
	Testo 635 Globe Thermometer, thermocouple type K, Ø 150 mm	Indirect mean radiant temperature	0 to + 120 °C	Class 1 [1]	Range: 10 °C to 40 °C | accuracy: ± 1 °C/ 2 °C
	Multifunction Testo 435-2 Temperature probe with triple sensor system	Surface temperature	-20 to +70 °C	± 0.1 °C + 0.2 % of measured value	Range: 0 °C to 50 °C | accuracy: ± 1 °C
	Multifunction Testo 435-2 hot wire anemometer	Airspeed (v_a)	0 to +20 m/s	± 0.03 m/s + 5 % of measured value	0.05 m/s to 1 m/s/ 2 m/s and ±(0.05 + 0.05 va) m/s
Other environmental parameters	OLDHAM MX21 multi-risk gas detector	Indoor air quality	CO 1000 ppm / CO_2 5 %	1 ppm, <30 sec. Response time at 90 % of final value / 0.1	[2]
	LI-COR Photometer LI-189	Natural illuminance	0 to 1999 lux (lm/m^2)	±0.4 % of reading ± 3 digits on the least significant digit displayed (all ranges). Highest accuracy class L according to DIN 5032 and CIE 69	[3]
	Bruel & Kjaer 2260 Investigator sound level analyzer	Noise level	80-130 dB in 10 dB steps	-26 dB ± 1.5 dB re1 1 V/Pa	[4]

(1) According to standard EN 60584-2, the accuracy of Class 1 refers to -40 to +1000 °C (Type K), Class 2 to -40 to +1200 °C (Type K), Class 3 to -200 to +40 °C (Type K).

(2) Complies with the requirements of the following European standards: EN 50014, EN 50018, EN 50020, EN 50284, EN 50303, EN 50270 and EN 50270.

(3) Complies with the requirements given in DIN 5032 and CIE Nº69.

(4) Conforms with: IEC 60651 (1979) plus Amendment 1 (1993-02) and Amendment 2 (200-10), Type 1; IEC 60804 (2000-10) Type 1; IEC 61672-1 (2002-05) Class 1; DIN 45657 (1997-07); IEC 61260 (1995-07) plus Amendment 1 (2001-09), Octave and 1/3-octave Bands, Class 0; ANSI S1.4-1983 (R 1997) plus ANSI S1.4A-1985 Amendment; ANSI S1.43-1997 Type 1; ANSI S1.11-1986 (R 1993), Octave and 1/3-octave Bands, Order 3, Type 0-C, Optional Range.

3.3. Qualitative methods: occupant surveying

The occupant survey analyzed in the present paper focused on indoor air quality (IAQ) and visual comfort. The point-in-time measurements were paired with a tolerance inquiry measured on a seven-point scale for short-term evaluation (from “perfectly bearable” (+3) to “unbearable” (-3)) and a mixed-mode satisfaction and preference questionnaire was administered to complete the assessment with long-term perception (see the Survey Template in Appendix G.1). It was based on the ASHRAE satisfaction survey [56], ISO 7730 [58] and ISO 10551 [59] and built around visual satisfaction, preference, and tolerance. For the statistical data process and analysis, a linear regression was then undertaken to investigate the relationship between the occupants’ tolerance and the point-in-time monitored data. This is illustrated in the scatter plot in Fig. 11 and the summary table characterizing the relationship between the illuminance tolerance votes and the monitored lux, with the determination coefficient (R^2), Pearson’s Chi-Squared value (p-value), and the Standard Error of Estimate (Se) in the Appendix G.2.

Prior to conducting the survey, the respondents had been sitting for more than 15 min and confirmed how long they had been living in the dwelling to ensure the reliability of the perception results. Electricity consumption data from the previous year was requested on an optional basis.

To assess the occupants’ IAQ perception, the authors adapted the methodology for subjective evaluations presented in the Annex H of EN 15251 and applied it during the winter monitoring. The results presented in this paper focus on the perception of IAQ based on a four-option scale and explored the occupants’ perception of leading sources of discomfort or IAQ decline and odors.

The thermal comfort section of the occupant survey was examined in depth in [41]. The strategy combined short-term evaluation with environmental and long-term comfort perception, measured on seven-point thermal sensation and satisfaction scales. Additional sections focused on occupant adaptive behavior and identifying the source and time of discomfort. The present paper touches, only tangentially, on this point at the end of the thermal performance analysis.

The statistical package for social sciences, SPSS, was used for data processing and the significance level was set at 0.05 (confidence intervals at 95 %).

4. Results and discussion

The case studies' environmental performance is analyzed according to four main sections: i. summer and winter thermal performance in the living area; ii. IAQ results; iii. visual comfort; iv. impact of passive strategies. The thermal performance of the dwellings was explored according to the main categories of conditioning strategies employed by users and identified during the research's surveying stage, i.e. five summer categories (unoccupied, stand-alone natural ventilation, natural ventilation with mechanical ventilation, nighttime natural ventilation with mechanical ventilation, and stand-alone mechanical ventilation) and winter categories (unoccupied, electric heating, wood-based heating, gas heating, and heating off). The noise level data exploitation was excluded from the analysis in this paper due to the preliminary results suggesting a favorable acoustic behavior and no adverse effects on the occupants' well-being [60].

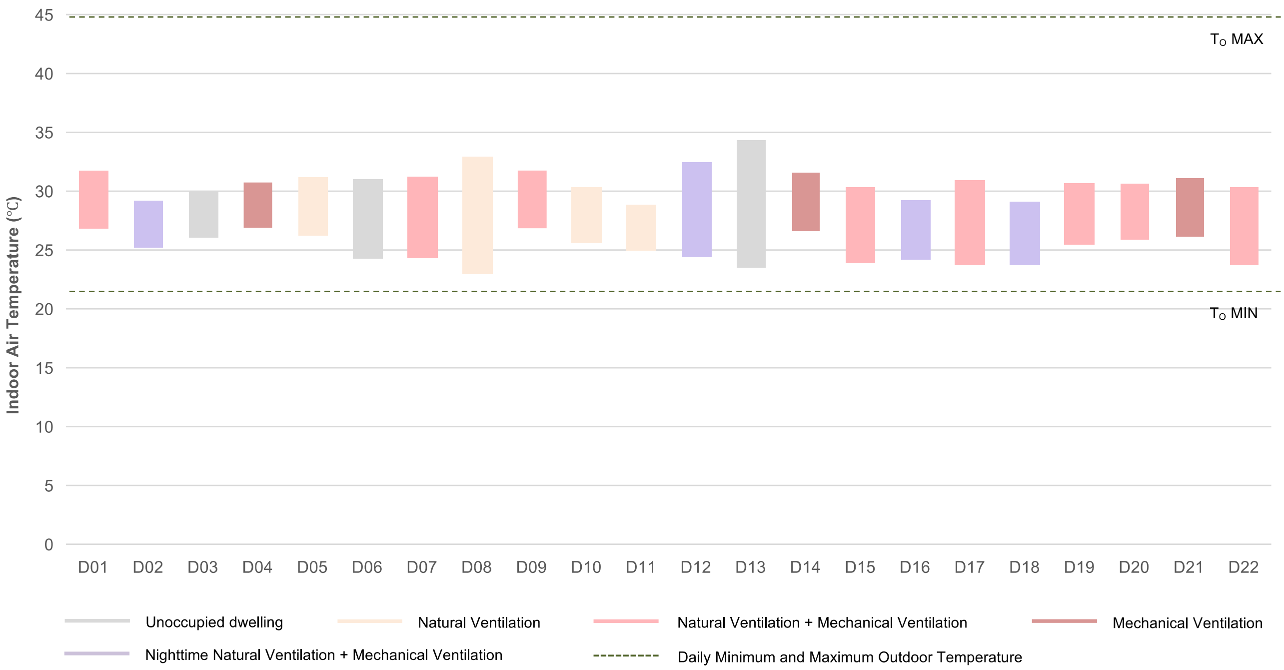
4.1. Thermal performance

4.1.1. Summer in situ monitoring

4.1.1.1. Average indoor air temperature and relative humidity. The outdoor dry-bulb temperature (DBT) ranged from 44.6 ºC (peaking around 17:00-18:00 in August) to 18.1 ºC (05:00-07:00). The average maximum and minimum were 35.1 ºC and 21.1 ºC, respectively. Relative humidity (RH) fluctuated between 9.7 % and 84.1 %. The full summer monitoring data can be found in the Appendix D.1.

To contrast the case studies' thermal performance, the free-floating indoor air temperature (T_a) in each monitored dwelling on the most extreme day, August 6th, is benchmarked. On this day, the outdoor temperatures ranged from 22.3 ºC to 44.8 ºC, as the continuum of a fairly homogeneous week temperature-wise.

Specifically, Figure 4 illustrates their thermal behavior, per five categories: unoccupied dwellings (14 %), stand-alone natural ventilation (18 %), natural ventilation with mechanical ventilation (40 %), nighttime natural ventilation with mechanical ventilation (14 %), and stand-alone mechanical ventilation (14 %). Additionally, please find the superimposed summer single-day temperature oscillation of representative case studies per each of the categories identified in the Appendix E.1., to better examine the divergent performances resulting from the different strategies adopted.



(1) The interested reader may refer to the schedule of the strategies in Table 3.

Figure 4. Daily temperature oscillation in the living room of each monitored dwelling (D01-D22) according to their category, on August 6th 2015. Solar orientations: NE-SW axis: D01, D03, D08, D09, D10, D17, D16, D02, D04, D07, D21, D12; SE-NW axis: D22, D20, D14, D05, D06; E-W axis: D11, D15, D13, D19, D18.

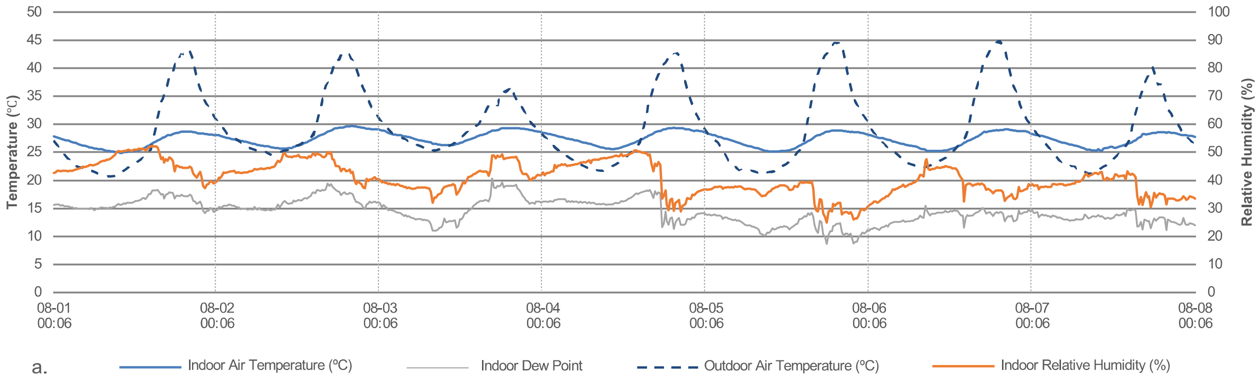
All dwellings displayed a common T_a belt (25 ºC-30 ºC), with nearly 80 % of cases exhibiting maximum temperatures (T_{aMAX}) above that threshold. Large indoor thermal amplitudes were observed, between 8 ºC and 10.6 ºC. Performance discrepancies were observed between dwellings adopting different but also equivalent regulating strategies.

- **Approaches for regulating indoor Ta and bioclimatic strategies**

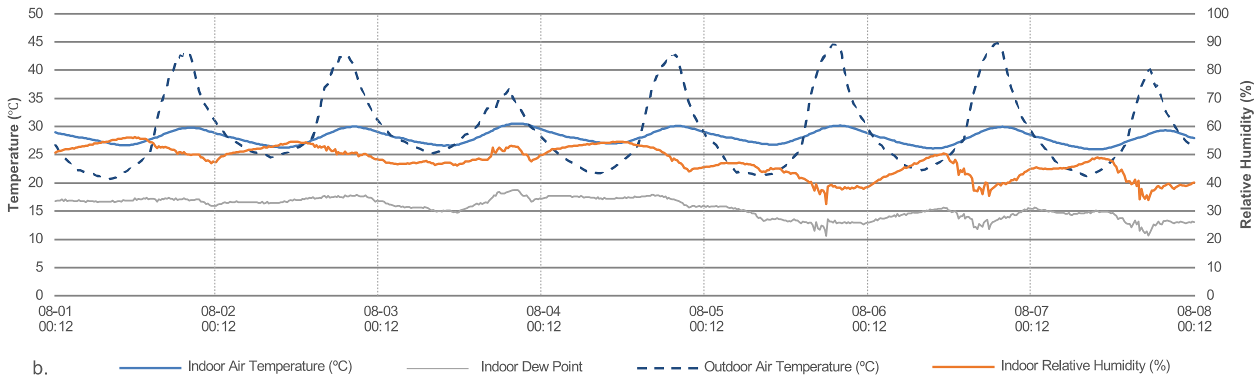
The most common summer strategy lies in combining daytime natural and mechanical ventilation. Yet, the preliminary overview points to nighttime ventilation compounded by daytime mechanical ventilation displaying a superior thermal performance, with shorter amplitudes and enhanced stability, which can clearly be observed in the Appendix E.1. D12, however, presents the peculiarity of having an unauthorized window and when compared to other dwellings in their category with identical solar orientation (NE-SW) and occupancy, it is suggestive of poorer behavior under extreme heat (peaking at 32.4 º C) and lower thermal stability. This highlights the relevance of the lack of windows as a bioclimatic strategy for reducing solar gains and overheating.

Although natural ventilation was traditionally applied during nighttime, it has reduced progressively due to insecurity. Currently, only four case studies still practice it, with the remaining dwellings using natural ventilation in the early morning and, or evening. It is plausible that this adaptation may be hindering the dwellings' thermal performance and contributing to overheating. Despite the in-depth occupant survey, uncertainty remains linked to adaptive behavior, which may account for divergencies within categories. This emphasizes the criticality of pinpointing occupancy to the best extent possible.

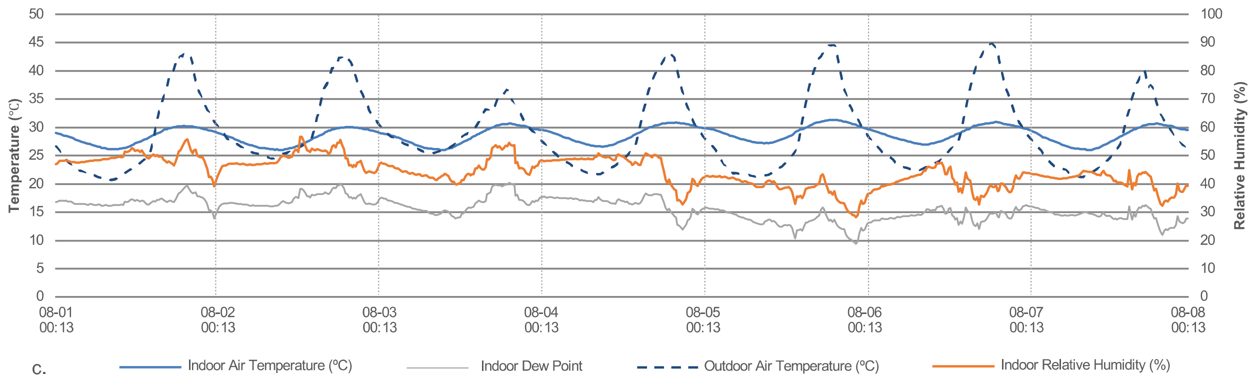
- **Representative week of indoor thermal fluctuation**


Temperature (°C)
Relative Humidity (%)
08-01 00:06
08-02 00:06
08-03 00:06
08-04 00:06
08-05 00:06
08-06 00:06
08-07 00:06
08-08 00:06
Indoor Air Temperature (°C)
Indoor Dew Point
Outdoor Air Temperature (°C)
Indoor Relative Humidity (%)

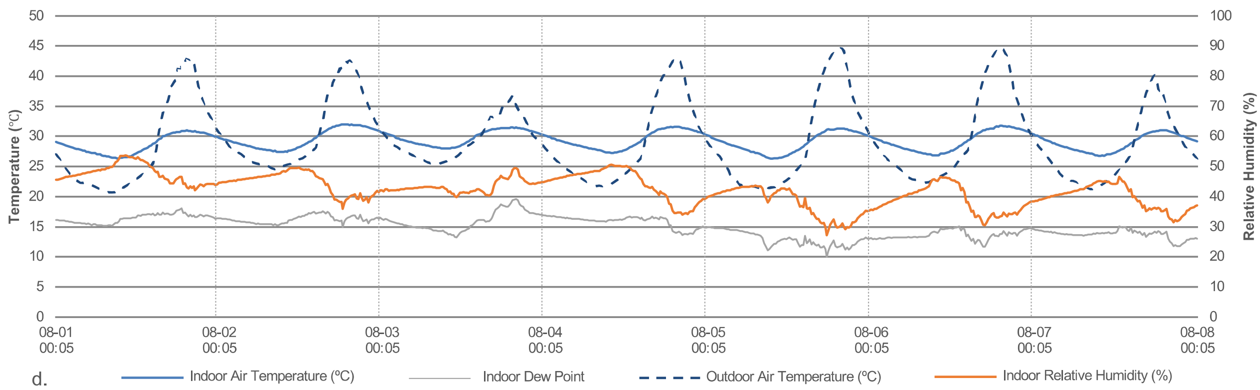
a.


Temperature (°C)
Relative Humidity (%)
08-01 00:12
08-02 00:12
08-03 00:12
08-04 00:12
08-05 00:12
08-06 00:12
08-07 00:12
08-08 00:12
Indoor Air Temperature (°C)
Indoor Dew Point
Outdoor Air Temperature (°C)
Indoor Relative Humidity (%)

b.


Temperature (°C)
Relative Humidity (%)
08-01 00:13
08-02 00:13
08-03 00:13
08-04 00:13
08-05 00:13
08-06 00:13
08-07 00:13
08-08 00:13
Indoor Air Temperature (°C)
Indoor Dew Point
Outdoor Air Temperature (°C)
Indoor Relative Humidity (%)

c.


Temperature (°C)
Relative Humidity (%)
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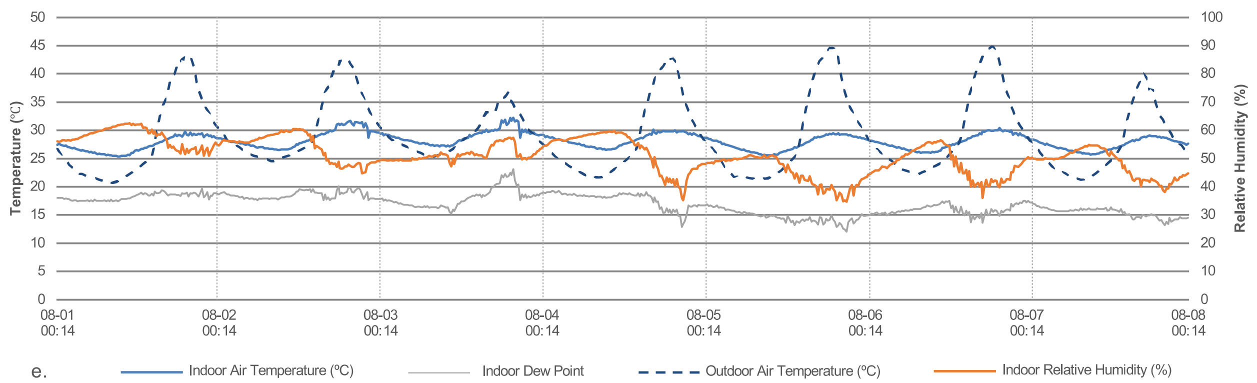
08-02 00:05
08-03 00:05
08-04 00:05
08-05 00:05
08-06 00:05
08-07 00:05
08-08 00:05
Indoor Air Temperature (°C)
Indoor Dew Point
Outdoor Air Temperature (°C)
Indoor Relative Humidity (%)

d.


Temperature (°C)
Relative Humidity (%)
08-01 00:14
08-02 00:14
08-03 00:14
08-04 00:14
08-05 00:14
08-06 00:14
08-07 00:14
08-08 00:14
Indoor Air Temperature (°C)
Indoor Dew Point
Outdoor Air Temperature (°C)
Indoor Relative Humidity (%)

e.

Figure 5. One-week extract from the summer monitoring, displaying T_a and RH, where: a. D02, nighttime natural and mechanical ventilation (NE-SW); b. D03, unoccupied dwelling (NE-SW); c. D04, mechanical ventilation (NE-SW); d. D09, natural and mechanical ventilation (NE-SW); e. D11, natural ventilation (E-W).

Figure 5 provides a closer look at the hottest week of the monitoring (1st-8th of August). The indoor T_{as} fluctuated between 32 ºC (18:30-20:00) and 24.4 ºC (09:00) and followed the overall pattern of the outdoor T_{as} with a time lag.

The average T_{aMAX} was well-nigh 31 ºC, between 18:30 and 20:00, followed by thermal stability well into 22:00, an hour after the outdoor peak. Still, the indoor-outdoor thermal jump is quite sharp (14 ºC) considering the indoor and outdoor T_{aMAX}.

Throughout the morning, the thermal environment of the case studies remains very stable, which is substantiated in the Appendix E.1. Before stepping into the different strategies used in the dwellings, the results regarding the thermal stability of D03, an unoccupied dwelling, were outstanding: the thermal stability coefficients or decrement factors, i.e. relating the amplitude of the indoor temperature to the amplitude of the outdoor temperature as an indicator of whether the building is prone to temperature changes, and calculated based on [51], averaged 0.11, suggesting sky-high thermal stability and an 11 % impact regarding outdoor variations approximately [51,61]. The unoccupied category as a whole scored the average decrement factor of 0.22 for entire monitoring period (see Appendix F for the decrement factors for the entire monitoring period and average depression values of the maximum temperatures Table).

Furthermore, if we take D02, adopting nighttime and mechanical ventilation, the temperature at 14:30 was around 26.7 ºC early in the week and it displayed a 2 ºC increment until reaching 28.7 ºC at 19:30; in the meantime, the outdoor DBT rose by more than 16 ºC, i.e. 10 times the indoor increment. The thermal wave damping effect of thermal mass can be observed across all categories, delaying outdoor-indoor heat transfer and avoiding excessive peaks. For the analyzed week, the decrement factors averaged 0.30, suggesting high thermal stability and a 30 % impact regarding outdoor variations approximately. In this regard, the strategy combining nighttime natural and mechanical ventilation seems to provide the best thermal stability overall, with an excellent average decrement factor of 0.19 when taking the entirety of the summer monitoring into account. On the other hand, the natural and mechanical ventilation category exhibited the least favorable performance, despite being the most used strategy, closely followed by mechanical ventilation alone (see Appendix E.1). A possible explanation could lie in the fact that the DBT between 22:00 and 23:00, a self-reported ventilation window, is still too high (35 ºC) to provide cooling comfort from natural ventilation and may exacerbate the dwellings' daily thermal load. Nonetheless, the decrement factors for both categories for the entire summer monitoring, i.e. 0.30 and 0.29 for natural and mechanical ventilation combined and stand-alone mechanical ventilation, respectively, are still indicators of very high thermal stability, with only a small percentage of the outdoor thermal fluctuation being reflected indoors (see Appendix E.1).

Moreover, in graph (e) of Figure 5, i.e. the case study using stand-alone natural ventilation, on days 2 and 3 the temperature rises sharply in the early evening (also please refer to Appendix E.1). This could be attributable to a combination of factors: firstly, opening the wickets around 19:00, when outdoor DBTs stand around 40 ºC-42 ºC, which can be corroborated by the lowering of the RH observed throughout the week, with the exception of day 3, where this adaptive behavior possibly didn't take place. The second one would be linked to cooking activities, being that cooking loads without proper ventilation may contribute to overheating and additional humidity. Nonetheless, cooking takes place on a daily basis and the fluctuation in question occurs in the first three days, which could suggest that we are observing a combination of both phenomena.

Comparing the indoor thermal environments of dwellings adopting natural and mechanical ventilation combined and nighttime natural with mechanical ventilation (see Appendix E.1., and diagrams (d) and (a), respectively, in Figure 5), suggested that the latter could contribute to lowering T_{aMIN} and T_{aMAX} on average by more than 1.5 ºC and 2 ºC, respectively, stressing the convective cooling potential of nighttime natural ventilation. During the representative week in analysis, stand-alone mechanical ventilation provided slightly higher thermal stability than daytime natural and mechanical ventilation (< 4 ºC variations), with average T_{aMIN} and T_{aMAX} around 26.5 ºC and 30.6 ºC, respectively. These overall lower temperatures contradict the preliminary overview (Fig. 3), reinforcing the importance of continuous monitoring. However, when contrasting mechanically-ventilated dwellings with those adopting nighttime natural and mechanical ventilation, the stored heat dissipation by convection seems to optimize the thermal inertia capacity. This is reflected in the offset of outdoor extreme temperatures, by lowering the average temperature by 1.2 ºC (Appendix E.1). On top of seldom nighttime natural ventilation, the inherent lack of insulation, particularly in roofs, might be further aggravating overheating (Appendix C).

On a final note, it is worth emphasizing that in July, the indoor T_{aMAX} average did not exceed 29 ºC. In any case, safely restoring nighttime natural ventilation would be crucial for improving the case studies' thermal performance and IAQ. Furthermore, it is interesting how occupants exhibit a much higher threshold tolerance regarding T_{as} of up to 30 ºC than their winter counterparts.

- **Indoor relative humidity fluctuation**

The indoor RH fluctuated between 24.9 % and 62.1 %, in diametrically opposite fashion to T_{as}. Indoor RH daily variation averages 15 percentage points against 45 of outdoor variation framed by extreme maximums and minimums (9.7 % to 84.1 %). Some days, the indoor RH only oscillated between 25 % and 37 %. This is a low level of airborne moisture but could be typical for dry-hot regions. According to EN 15251 [62], long-term low humidity values have detrimental health impacts, such as irritating mucous membranes and respiratory tract, eye dryness, and enhanced susceptibility to pollutants [63].

4.1.1.2. Average indoor air and inner wall surface temperature. Due to the case studies' size, it was foreseeable that the walls would strongly influence the T_{mrt} [64]. Overall, the inner wall surface temperatures (T_{ws}) incurred the same trend as the T_{as}, with little difference between them. The T_{as} surpassed the T_{ws} from the early afternoon to the following early morning, with a peak difference of 1.5 ºC. From that point onwards, as T_{as} decrease, both temperatures level out, with T_{ws} slightly exceeding T_{as} and the wall losing heat by convection from early to mid-morning. This points to the impact of high thermal mass walls on the modulation of T_{ws}, on top of stabilizing T_{as}. These findings align with previous studies on vernacular dwellings with high thermal mass [22].

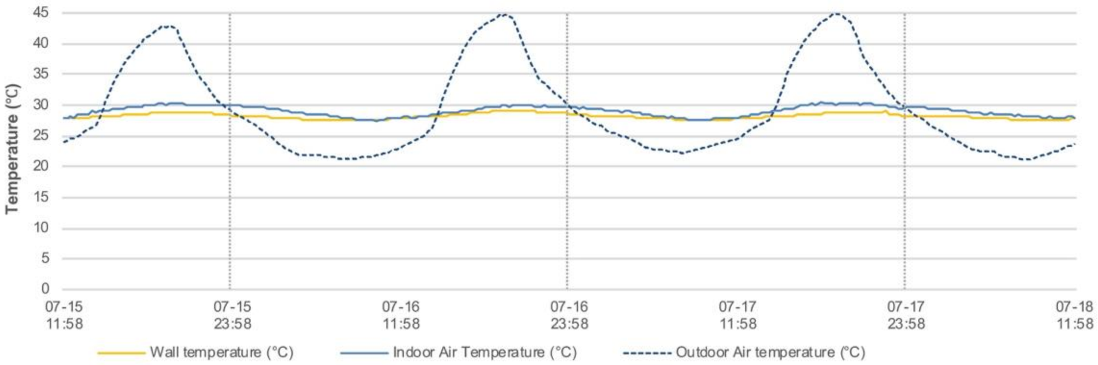


Figure 6. Inner wall surface temperature, indoor air temperature, and outdoor air temperature, 72-hour summer monitoring. D03 (SW-NE).

4.1.1.3. Globe temperature and Mean Radiant Temperature (T_{mrt}). According to [57], the T_{mrt} was derived from the conversion of the black globe temperature measurements, based on the following equation:

$$T_{mrt}=\sqrt{(T_g+273.15)^4+\frac{h_{cg}}{\varepsilon*D^{0.4}}*\left(T_g\text{-}T_a\right)}\ \text{-}273.15 \qquad (2)$$

Where T_g is the black globe temperature (ºC), h_{cg} is the globe's mean convection coefficient ($1.1*10^8*v_a^{0.6}$), v_a is the air velocity (m/s), ε is the emissivity of the sphere (0.95), D is the diameter of the sphere (mm), and T_a is the air temperature.

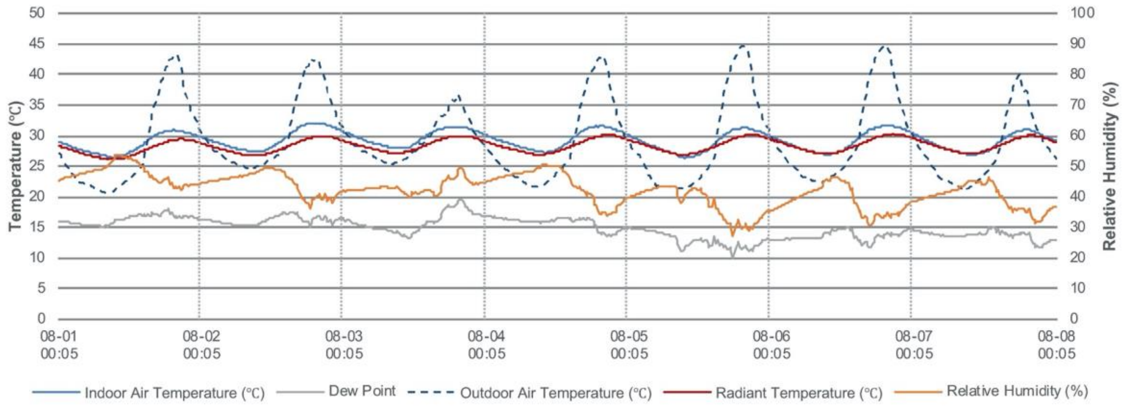


Figure 7. Median radiant temperature (T_{mrt}), indoor air temperature (T_a), and outdoor air temperature. D06 (SE-NW).

Overall, and as illustrated in Fig. 7, the disparities between T_{mrts} and T_{as} under moderate outdoor temperatures are marginal, i.e. only a few decimal degrees, but with rising temperatures from the early afternoon onwards, the gap widens until around 19:00, which is consistent with previous studies [21,65].

An explanation for the narrow difference found might lie in the absence of the main driving factors for these deviations, previously identified as windows' size and exposure as well as the intensity and duration of a room's or surface's direct solar radiation [66]. Additionally, the results obtained reflect earlier studies on traditional dwellings' thermal performance [19,29,64].

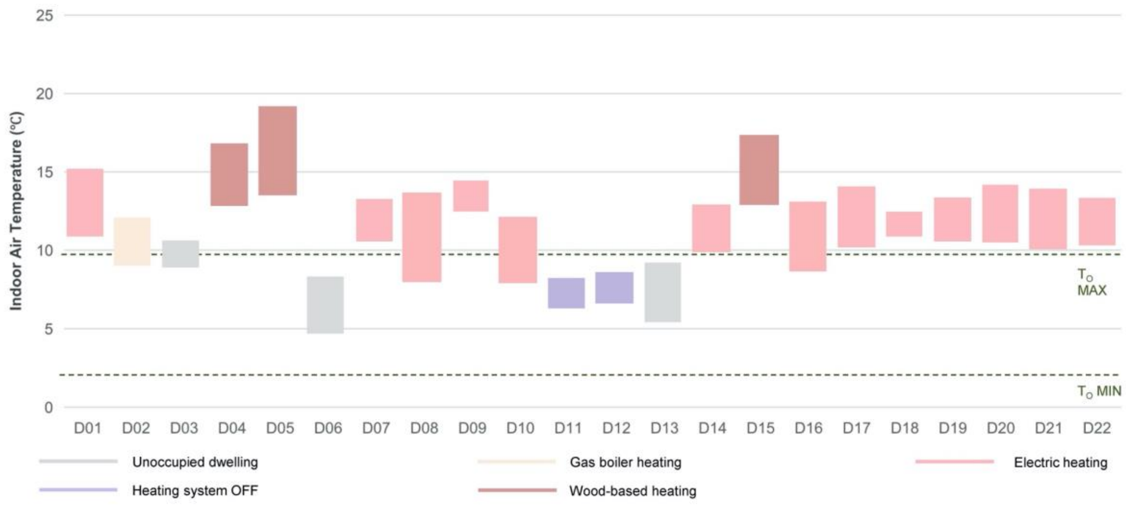
4.1.1.4. Air velocity (V_a). The V_a was found to average 0.15 m/s for unsealed-chimney case studies and 0.05 m/s for sealed ones. These values conform to still air conditions and are within ASHRAE 2013's limits for V_a with occupant control, in which case V_a measurements are not required for indoor thermal comfort assessment [56].

The *ad hoc* chimney sealing scheme compromises the stack effect ventilation, limiting fresh-air intake. Nonetheless, the air leakage rate through the envelope is estimated to be quite high, contributing to dissipating pollutants and moisture, but allowing inward warm air leakage while simultaneously underventilating, possibly playing into overheating episodes. Conversely, the winter air leakage can lead to cold drafts and decreased indoor thermal comfort.

Apart from the lack of nighttime cross-ventilation, a low V_a could augment summer thermal discomfort due to excessive peaks. Moreover, the high adhesion to daytime mechanical ventilation is the only counter-measure to increased T_{as} that occupants control, for natural ventilation is infeasible during the daytime in light of outdoor out-of-scale temperatures.

4.1.2. Winter in situ monitoring

4.1.2.1. Average indoor air temperature and RH. During the entirety of the winter monitoring, the outdoor DBT ranged from 1.6 ºC (around 09:00) to 15.4 ºC (15:00-17:00). The average maximums and minimums were 12.5 ºC and 6 ºC, respectively. The RH fluctuated between 59.1 % and 100 %.



(1) The interested reader may refer to the schedule of the strategies in Table 3.

Figure 8. Daily temperature oscillation in the living room of each monitored dwelling (D01-D22) according to their category, on February 8th 2015. Solar orientations: NE-SW axis: D01, D03, D08, D09, D10, D17, D16, D02, D04, D07, D21, D12; SE-NW axis: D22, D20, D14, D05, D06; E-W axis: D11, D15, D13, D19, D18.

Figure 8 displays the temperature oscillation in each dwelling on the coldest monitored day, when outdoor temperatures ranged from 1.6 ºC to 9.5 ºC, exhibiting a considerable dip in regard to the previous week: while on the preceding day, the 7th, the outdoor DBTs varied between 2 ºC and 9.6 ºC, the previous week had been characterized by minimum temperatures of over 5.5 ºC and maximum values of around 15 ºC. Due to significant performance disparities between categories, i.e. electric heating (59 %), wood-based heating (14 %), gas heating (4.5 %), and heating off (9 %), a cross-category analysis was discarded. Such disparities were also found within the electric category, mainly due to two coexistent heating schedules: 07:30 to 23:00 and 07:30-09:30/17:00-23:00. Furthermore, the superimposed winter single-day temperature oscillation of representative case studies per each of the categories identified is presented in the Appendix E.2., to better examine the divergent performances resulting from the different strategies adopted.

The most common strategy is electric heating from early morning until bedtime at around 23:00 (45 %) versus bi-daily electric heating (14 %), i.e. 07:30 to 09:30/17:00 to 23:00. Within the former, a common T_a belt between 10.5 ºC and 13.7 ºC was identifiable, with the T_{aMIN} being 9.8 ºC. The latter performed worse than all-day electric, and fireplace and wood-burning stove heating schemes, and has a common T_a belt at 8 ºC-12.9 ºC, with the T_{aMIN} being 7.7 ºC. The T_a belt of the wood-heated dwellings is much higher, 13.1 ºC-17.9 ºC, the closest to the lower end of indoor comfort acceptability [67]. The best performing dwelling (D05) pertains to this category and ranged between 13.5 ºC-19.4 ºC (also see D15 in the Appendix E.2).

- **Representative week of indoor thermal fluctuation**

Figure 9 showcases a representative week (16th-23rd of February) for each category. The full winter data can be found in the Appendix D.2. The criteria for selecting the representative week of thermal fluctuation consisted in its inherent depiction of the usual coldest week behavior. In this case, the coldest week coincided with an atypical extreme weather event, entailing average wind gusts of 70 km/h and reaching extremely dangerous speeds of 120 km/h. Thus, the period above mentioned was chosen in its place for its representativeness and presented in the analysis presented in this paper.

The indoor T_{as} fluctuated between 19.3 ºC (18:30-20:00) and 7.9 ºC (08:30-10:00), following the outdoor pattern compounded by substantial time lag averaging nearly five hours. This features the high thermal inertia of the dwellings' envelope and exhibits its strong thermal wave attenuation properties.

- Unoccupied and unheated dwellings

D06 and D11 are an unoccupied dwelling and a dwelling with heating off, respectively. Their free-floating T_{as} variations confirmed that despite behaving similarly, the unoccupied dwelling's thermal amplitudes are steeper, averaging 2.5 ºC between T_{aMAX} and T_{aMIN} (see Appendix E.2). The beneficial thermal stability in both categories is evidenced by average decrement factors of 0.34 and 0.28, respectively, over the course of the whole winter monitoring (Appendix F). Moreover, both dwellings displayed indoor T_{aMAX} consistently below the outdoor DBT. Yet, D11 registered higher temperatures than D06, especially when it came to T_{aMIN} (averagely 1 ºC higher). The lack of thermal loads from miscellaneous sources including, *inter alia*, radiant body heat emission, equipment, and lighting, could hypothetically explain this dissimilarity.

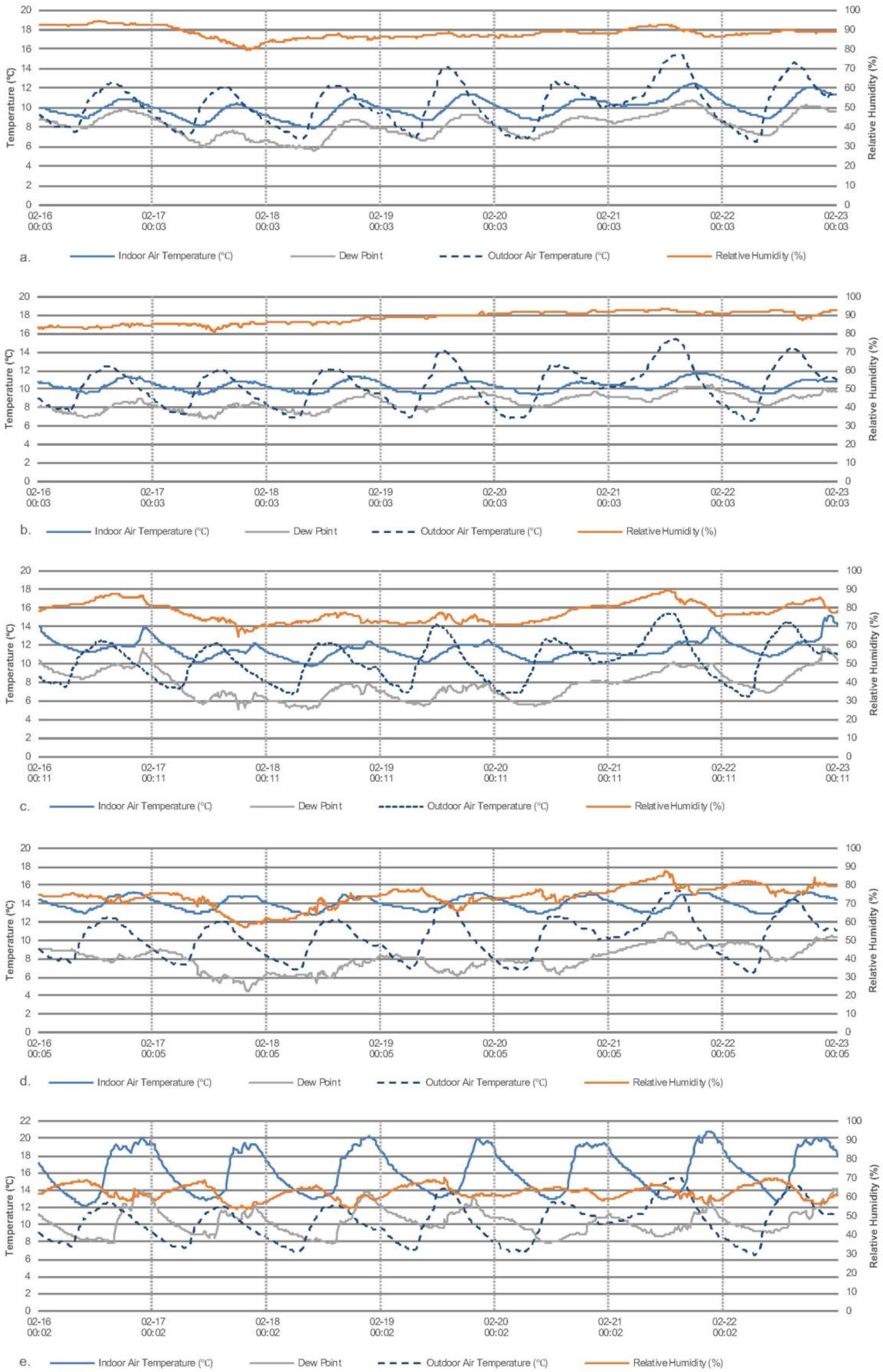


Figure 9. Extract from the winter monitoring, displaying T_a and RH: a. D06, unoccupied dwelling (SE-NW); b. D07, electric heating from 07:30 to 23:00 (NE-SW); c. D11: heating turned off (E-W);

d. D16, electric heating from 07:30-09:30/17:00-23:00 (NE-SW); e. D15, Wood-burning stove heating from 07:30 to 23:00 (E-W).

Furthermore, D11's thermal stability coefficient averages 0.25 computed for the whole winter monitoring (Appendix F), which again indicates very high thermal stability [51]. This reflects the heat storage capacity of the building's envelope, exhibiting a conspicuous delay of the outdoor thermal wave, which is very apparent in the figure in the Appendix E.2 and in the decrement delay presented in Table 2. In fact, the indoor thermal environment remains very stable between 14:00 and the following day, with an average fluctuation of 0.7 ºC. This capacity is especially valuable during the nighttime, adequately responding to the site's sharp thermal amplitudes. All in all, D11 experiences T_{as} far removed from thermal comfort, averaging a daily T_{aMAX} of 11.1 ºC.

- Approaches for regulating Ta and occupancy patterns

The self-reported bi-daily convection heating schedule roughly matches the pattern identified in D16 (see Fig. 9, diagram (d)). While the outdoor temperature starts increasing in the early morning only to peak around 15:00, the T_a then drops until 8:00-08:30, when the electric heating is likely to kick in, as it takes about an hour to fully heat the air, and sustains an increase until 17:00. T_{as} then remain stable until approximately 19:30, in the face of a 3 ºC outdoor dip, which could indicate that heating would be turned on around 18:30. From there on, T_{as} rapidly rise until around 22:00 when it usually reaches its peak. Moreover, between 08:00/09:00 and 16:30/17:30 the T_{as} are lower than the outdoor DBT.

The occupancy patterns are also reflected in the thermal variation of D07, electrically-heated from early morning to late evening. A temperature increase is consistently singled out, from early morning until 15:00-16:00, after which it usually stabilizes until 23:00 while outdoor temperatures drop sharply, and then smoothly descend until 08:00. However, temperature-wise, when we compare it with D15's performance, using a wood-burning stove on an analogous schedule, the latter unmistakably provided higher temperatures, 5 ºC on average, at around 19.9 ºC (see Appendix E.2).

The thermal inertia's impact on the indoor environment was distinctly observed in both categories. Yet, the radiant heat linked to wood-burning stoves keeps T_{as} stable at their peak for up to two hours. The results suggest that radiant heating systems provided more comfortable indoor temperatures, thus contributing more significantly to the thermal comfort of the occupants than convection ones, i.e. electric oil heating. Despite its efficiency, this traditional heating technique was nearly abandoned due to safety and maintenance concerns.

- **Indoor RH fluctuation**

The indoor RH fluctuated between 50.4 % and 94.5 %, against a 59.1 % to 100 % outdoor variation. This high level of airborne moisture leads to extremely saturated air in unheated and unoccupied dwellings, followed by electrically-heated ones (see overlay in Appendix E.2). Without adequate ventilation, moisture condensations and adverse health effects can arise, by causing microbial growth [62] and long-term discomfort [68]. The case studies' winter environment is in an extremely humid and cold spectrum, except for wood-heated dwellings, with RHs under 65 %.

4.1.2.2. Globe temperature and T_{mrt}. In wintertime, the T_{mrts} and T_{as} draw a similar curve with negligible differences, yet, conversely to summertime, the T_{mrts} surpass the T_{as} during the night until midday, denoting anew the thermal mass' stabilizing influence in preventing sharper nighttime thermal drops.

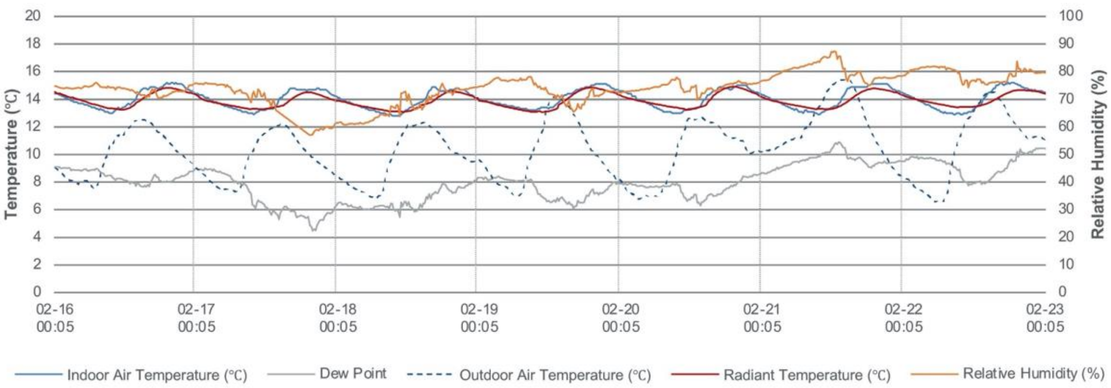


Figure 10. Median radiant temperature (T_{mrt}), indoor air temperature (T_a), and outdoor air temperature. D07 (NE/SW).

- **Thermal comfort perception**

Lastly, it should be mentioned that the subsequent paper of this series delves into the thermal comfort evaluation of the case studies, including the thermal comfort perception based on the occupant survey data and their comfort acceptability and satisfaction levels [41]. The analysis is conducted by means of linear regression to derive the quantitative relationship between the Thermal Sensation Votes and the indoor air temperature, and the indoor operative temperature and outdoor running mean temperature. The high summer thermal acceptability rate of occupants found in that analysis ties in with the discussion put forward in the representative week of indoor thermal fluctuation subsection of the present paper, and would suggest that T_{as} fluctuate within a comfortable range. Yet, the monitoring results indicated otherwise: with an average of 27.7 ºC and T_{aMAX} of 28.9 ºC during the monitoring period, it is safe to say that the indoor temperatures in the case studies exceed comfortable values. The main findings, corroborated by the neutral temperature range yielded in the strong and statistically significant linear relationship between the occupants' thermal sensation votes and the point-in-time monitoring, pointed to the focus group displaying a broader summer comfort range than the average tolerance; more specifically, exceeding the maximum threshold set in the national regulation at 25 ºC [69], as well as the maximum indoor temperature recommended in EN 16798 even for category III buildings, i.e. existing buildings with a moderate level of expectation, which is 27 ºC [62]. These results are in line with previous vernacular dwellings studies [9,10,20,27] and should be framed within the rural vernacular socio-cultural context and thermal expectations of inhabitants, as these bear influence on thermal comfort acceptability [70].

4.2. Indoor air quality conditions

The IAQ monitoring and survey results confirmed cooking and heating emissions as the case studies' main sources of indoor pollution.

In electrically-heated living rooms, when no cooking activities were occurring, average minimal concentrations for CO, CO_2 and VOCs were yielded (0.1-0.2 ppm). During cooking, VOCs emissions increased to 2 ppm and 10 ppm near the stove. Also noteworthy was the cooking CO average concentration, at 3.5 ppm, which could be explained by accumulated cooking emissions due to the lack of adequate ventilation or exhaust system. Moreover, gas stoves, which should be vented, release ultrafine particles, hazardous pollutants, CO, and NO_2 [71]. The occupants' adaptive behavior could help mitigate exposure, however, the former is limited by the dwellings' layout. Additionally, winter adaptive behaviors focus on preventing heat loss, at the expense of healthy IAQ. Nonetheless, the minimal values obtained in electrically-heated living rooms when no cooking is taking place suggest that winter natural ventilation is still occurring, possibly with unsealed chimneys and the envelope's pronounced air infiltration playing an important role in dissipating contaminants.

Over half the occupants customarily leave the heating on all day, which would amount to daily 15-hour exposure periods. Prolonged periods of wood-based heating can be worrisome for occupants' health due to PM2.5, ultra-fine particles and other VOCs, such as benzene and formaldehyde, and hazardous pollutants such as Polycyclic-aromatic hydrocarbons, for which there is no safe exposure level [71,72] and that can lead to respiratory ailments, lung tissue damage, and carcinogenic effects. Even though the current analysis cannot elaborate on the individual levels of the different VOCs, the results confirmed wood-burning heating as a critical source of indoor contaminants, inducing a significant increase in VOCs compared to non-heating baseline values, surpassing 100 ppm, which far exceeds the threshold established in the World Health Organization (WHO) guidelines [71,73] by a thousand fold.

On top of VOCs, CO values occasionally exceeded these guidelines [73,74] by reaching 34 ppm (9ppm threshold), but averaged 8.8 ppm over a 15-hour period. *Per contra*, quite low absolute CO_2 values were found [74] in spite of wood burning, qualifying as high IAQ ($\leq$ 800 ppm) [75] and below 1000 ppm, i.e. the threshold between hygienically harmless and conspicuous ranges, where increased air exchange and improved ventilation behavior would be required.

The questionnaire-based surveys indicated that nearly half the occupants (44 %) perceive their IAQ to be just acceptable in the long-term, against 37.5 % for unacceptable and 19 % for clearly unacceptable (on a scale from clearly unacceptable to clearly acceptable). Over half the interviewees perceived the odor intensity as moderate and only 12.5 % described it as overpowering. The results also indicate that while there is little awareness of IAQ's impact on health, there is an overall acknowledged need of increased ventilation rates for odor and moisture dissipation, especially in winter when thermal comfort is prioritized to the detriment of ventilation. The sealing of chimneys hampers the necessary ventilation in the cooking and heating area.

The survey results were consistent with the monitoring, in that all interviewees identified cooking and heating, and lack of adequate ventilation as the leading sources of IAQ decline. 70 % reported excessive winter RH levels, moisture, and water infiltration as the second leading cause of odors. Hence, the findings suggest that measures focusing on promoting moisture control, increasing natural ventilation rates and reinstating adequate air exchange, along with retrofitting the dwellings' envelope and chimneys, would be pivotal for restoring a healthy IAQ.

4.3. Indoor visual conditions

In this section, the average daylight factor (DF) estimation and its comparison against daylight recommendations for visual comfort, as well as the quality of the view out, i.e. the view outside through the daylight openings [76] are analyzed. Based on the daylight provision calculation method in EN 17037, the target daylight factor (D_T) was computed as follows:

$$D_T = (E_{in}/E_{ext})*100 \qquad (3)$$

Where, D_T is the target daylight factor, E_{in} is the indoor illuminance at a fixed point and E_{ext} is the outdoor horizontal illuminance (OHI) under overcast CIE sky conditions. The value taken for the average indoor illuminance was 20 lux (opened wicket and glass roof tile) and the average OHI measured was 18280 lux. Hence, D_T was estimated to be 0.11 %, which is 15-fold lower than recommended in EN 17037: the D_T and D_{TM} (Minimum Target Daylight Factor) should have been around 1.64 % and 0.55 %, respectively, for the local outdoor illuminance. Moreover, the standard Portuguese reference values, i.e. 1.7 % for D_T and 0.6 % for D_{TM}, suggested that the measured OHI aligned with national values. The results pointed to the weak correlation between indoor illuminance, and outdoor illuminance and sky conditions, as the average indoor illuminance yielded under clear-sky conditions, i.e. 27 lux, did not differ significantly from that found under overcast conditions, i.e. 20 lux, for a fairly higher OHI, i.e. 85900 lux. International sustainability assessment schemes address visual comfort, encompassing daylighting and view out; e.g., BREEAM determines that a 2 % average DF should be attained in living/dining rooms, and kitchens and that the average daylight illuminance should exceed 100 lux for 3450 hours per year [77].

Regarding the quality of the view out, EN 17037 establishes the following criteria: the glazing should provide a clear and neutrally-colored view; openings should have horizontal sight angles higher than 14 º; the distance to the outside view should exceed 0.6 m; for a room depth of 4.0 m, the view opening should be at least 1.0 m x 1.25 m; and at least urban and, or natural landscape should be seen. While the case studies do not meet the distance and dimension criteria, they do provide urban landscape. BREEAM states that all positions within relevant areas should be within 5.0 m of a façade opening with adequate view out that is ≥ 20 % of the surrounding wall area. The case studies' openings account for less than 1 % of the façades, which additionally breaches the minimum ratio glazing area for adequate daylight provision defined in the General Regulation of Urban Buildings [78].

This analysis confirmed that the daylight availability is inadequate for any standard-recommended task or permanence, on top of heterogeneously distributed. The fact that indoor daylight levels stand below minimum recommended thresholds leads to inefficient artificial lighting use throughout the day with its associated costs. This could also explain the rising appearance of illegal façade openings, in spite of the protection of the Municipal Master Plan and the Municipal Regulations for Building and Urbanization (RMUE) [79].

Given this scenario, it would be expected that the occupant surveys reflected the need for increased daylight or the inadequacy of current levels, but a mismatch between quantitative and qualitative findings was yielded. The data were processed according to two main indexes: lighting dissatisfaction (occupants' sensation regarding illuminance levels) [80] and tolerance index [59]; and three categories for assessing artificial light use, occupants' view out satisfaction, and their priorities linked to openings.

The level of satisfaction inferred revealed that over half the interviewees (57 %) are actually slightly satisfied with their daylight availability, while 37 % expressed slight dissatisfaction, and only 6 % reported being highly dissatisfied, mainly in wintertime. Tolerance-wise, 45.5 % of occupants found the daylight availability slightly bearable versus 22.7 % for moderately bearable and 13.6 % for perfectly bearable. Only 4.55 % reported high difficulty in bearing it (fairly difficult to bear, very difficult to bear, and unbearable) and 13.6 % felt neutral (Fig. 11). An extremely weak and non-statistically significant correlation was found between the occupants' illuminance tolerance votes (ITVs) and the point-in-time monitored data. The estimated equation relating the ITVs and the monitored illuminance is as follows:

$$ITV = \underset{(0.023)}{0.009}\, lux + \underset{(0.008)}{1.053}, \quad R^2 = 0.007, \; S_e = 1.18 \qquad (4)$$

Where, R^2 is the determination coefficient, S_e is the Standard Error of Estimate, and the respective error of estimation for each parameter is indicated underneath. The slope of the regression line is 0.009, which means that for each lux, the ITV increased by 0.009 units of scale. The R^2 value inferior to 0.1 implies a very weak positive correlation, which is non-statistically significant (p-value = 0.081, the variable association is significant when p-value is inferior to 0.05). In being a positive correlation, the ITVs are observed to increase proportionally to the lux measured. Yet, as can be seen in Fig. 11, the correlation is marked by strong incoherence and heterogeneity, with the bulk of moderately bearable and perfectly bearable votes being linked to a range between 8.4 and 16.2 lux for the former, and at opposite ends of the illuminance spectrum measured (9.5 and 39.9 lux) for the latter. Given that the DF estimation was based on the monitored data, it would be safe to say that findings also suggest a weak correlation between the tolerance levels and the DF estimated. Additionally, the results of the occupants' long-term perception and satisfaction with poorly-lit spaces surpassed the authors' expectations.

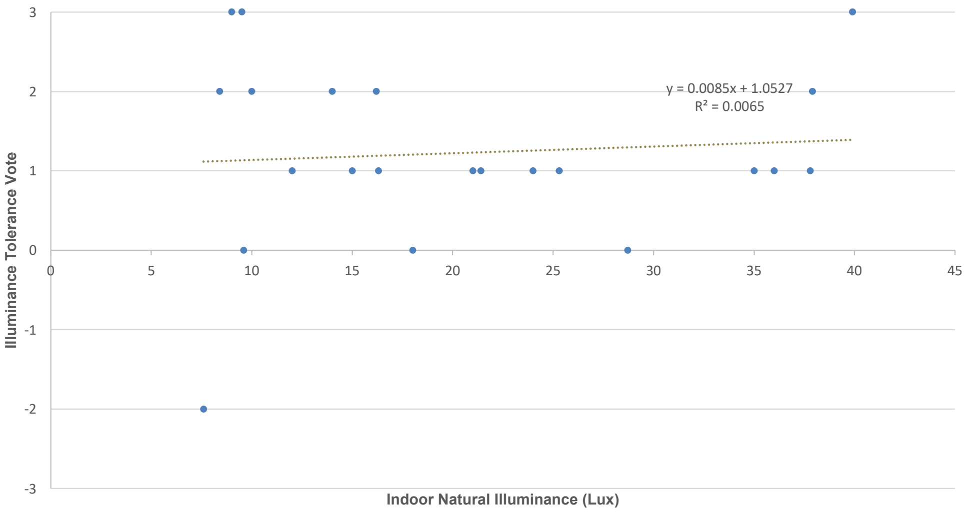


Figure 11. Point-in-time survey data: correlation between the occupants' tolerance votes and the monitored illuminance data.

Though counterintuitive, these findings highlighted the determinant role of cultural backgrounds in daylight acceptability and expectations, on top of the age of the focus group. When requested to elaborate on their satisfaction and tolerance levels, those who had reported slight satisfaction claimed being used to those conditions. In addition, the fact that the occupants spend much time outdoors, in their courtyards or sitting on their front steps or benches, might also contribute to attenuate the impact of living in poorly-lit dwellings.

Nearly 70 % of interviewees disagreed that it is possible to perform tasks relying on daylight only. Those spending under one daily hour of artificial light emphasized the intentional avoidance as a financial strategy. This is important to keep in mind since the quantification of artificial light usage does not reflect actual requirements. The weight of financial constraints dictates the occupancy patterns and adaptive behaviors of these dwellings, rather than the quest for greater comfort or health. This is culturally acquired, deeply rooted in their socioeconomic background and living culture, and should be understood within that context. In fact, when asked to rate fresh air, increased daylight, view out, and reduced electricity consumption, linked to a façade opening or skylight, reduced consumption was ranked the highest (70 %) to the detriment of other parameters. The view out was the overall bottom-end voted (88 %). For increased daylight availability, however, the scoring was quite scattered, with as many top scores as second-to-last scores (37 % respectively), revealing a strong divergence in priorities.

Finally, lighting allows very little room for occupant behavior control, and, in the case studies, it is mainly limited to the use of artificial light or adapting to performing tasks under conditions that fall far from minimum recommendations. Nonetheless, as mentioned above, the traditional pattern of spending long periods outdoors could be considered a coping behavior.

4.4. Impact of passive strategies

The main climate-responsive strategies found in the literature for vernacular dwellings in this region, i.e. passive cooling, solar radiation shielding and minimizing summer heat gains, were mentioned in 3.1.3.. Additionally, this analysis allowed to pinpoint key passive strategies in view of their effect on thermal performance (Table 6).

Table 6. Key passive strategies of a typical vernacular dwelling in SVV.

Bioclimatic strategies	Key features
Settlement pattern	• continuous single row of dwellings along main road • alignment with predominant wind directions for airflow passage • secondary narrow streets to reduce solar incidence and heat gains
Façades without window openings	• reduced summer solar gains and overheating • scarce indoor natural illuminance
Lime-washed walls	• antibacterial and solar radiation protection
High thermal inertia walls	• inhibited outdoor-indoor heat transfer, avoiding excessive temperature peaks and supporting thermal stabilization

	• especially beneficial during the nighttime and for the site's sharp thermal amplitudes
Natural cross-ventilation	• traditionally implemented during the nighttime • performed via built-in wickets and chimney • symbiotic effect with high thermal inertia • removal of diurnal thermal loads for summer cooling
Ceramic floor tiles	• possibility of evaporative cooling due to permeability
Courtyard	• private outdoor space with its own microclimate • shading from vegetation and important for natural ventilation • contrasting the scarce indoor illuminance

Concerning their impact on thermal performance, the following stood out:

- The predominant traditional typology was established as a resourceful bioclimatic adaptation compared to variants lacking a courtyard.
- The role of natural ventilation through the courtyard in enhancing summer thermal behavior and stability. It additionally helps mitigating the effects of poor indoor natural illuminance.
- Nighttime natural and mechanical ventilation was singled out as the best performing strategy, leading to enhanced thermal performance and stability than the most common strategy, i.e. daytime natural and mechanical ventilation.
- The relevance of the lack of windows for reducing summer solar gains and overheating was evidenced through the comparison of two identically solar-oriented dwellings applying the same strategies, where one had an unauthorized window and displayed significantly poorer behavior under extreme outdoor heat.

- The dwellings' high thermal inertia and outdoor thermal wave attenuation properties were highlighted in both seasons, adequately responding to sharp thermal amplitudes.
- The traditional chimney's heating role was backed by its efficiency in providing indoor T_{as} over 18 ºC, despite being dropped to the detriment of underperforming electric heating.

5. Conclusions

Thermal performance and occupancy patterns

Current occupancy patterns are suggested to be hindering the dwellings' thermal performance, evidencing inadequate climate adaptation. Occupants are exposed to winter thermal discomfort and health risks arising from cold temperatures, moldy spaces, and airborne toxins. However, even during the summer hottest periods, occupants exhibited a much higher threshold tolerance than in winter.

Key sources of indoor air pollution

The compounded effect of wood-burning heating and cooking emissions were confirmed to be crucial sources of indoor pollution, aggravated by the lack of adequate ventilation. Incorporating less contaminant sources, and retrofitting the chimney to avoid *ad hoc* sealing schemes and improving ventilation through an adequate exhaust system, could contribute to reducing the occupants' health burden.

The importance of sociocultural background in indoor environment perception and acceptability in heritage dwellings

Sociocultural background plays a determinant role in occupants' indoor environment perception and acceptability in heritage dwellings. This was attested in this research by broader thermal ranges and acceptability of inadequate natural illuminance levels and IAQ. When analyzing the indoor environment of vernacular dwellings, it is imperative to consider how occupancy patterns and behaviors can be dictated by financial constraints, rather than the quest for greater comfort or health.

5.1. Key takeaways for the future conservation of the case studies and analogous typologies

Reversing the decline of vernacular dwellings requires intentional investment in improving their indoor conditions. In the case studies, the priority should be improving cold-related risks through accessible and efficient solutions compatible with its conservation. Moreover, traditional efficient practices were rejected in favor of less efficient measures linked to globalization. While some strategies have lost adherence due to safety issues, there are anthropological variables leading to traditional knowledge dilution and hindering the dwellings' performance. As architects it is our task to consider these issues when suggesting adequate interventions that, not only enhance energy efficiency and thermal comfort but also habitability, adapting the strengths of vernacular strategies for a harmonious relationship between heritage and their occupants. Awareness-raising campaigns could be undertaken, focusing on best practices for the use, maintenance, and conservation of heritage dwellings. Some of the key interventions for future conservation are outlined hereunder:

- Improving the envelope's thermal insulation, as their inherent lack of insulation could aggravate overheating and underheating. The roof solar absorptance could also be addressed. The walls' external insulation would complement the high thermal inertia and contribute to thermal stability and energy savings.
- The above addresses the high airflow leakage rate, but air proofing should be extended to doors.
- Devising a safe nighttime ventilation system to improve summer thermal performance and IAQ by retrofitting the chimney to vent the cooking area, mitigate humidity and water infiltrations, but also incorporating a skylight, to restore healthy airflow and illuminance levels.
- Devising an efficient and renewable heating system that does not compromise the occupants' health, restoring the possibility for clean radiant heating, which was shown to overperform electric heating.
- Considering solar water heating for improving hot water access.

- Replacing the courtyards' unauthorized settlements with annexed sanitation facilities connected to the water supply network.

5.2. Limitations of the study and suggestions for future work

The dataloggers' accuracy was slightly out of range per the ISO 7726 and ASHRAE-55 2013 criteria (Table 5). Nonetheless, dataloggers with analogous ranges have been successfully employed in the thermal assessment of vernacular dwellings in the same region [26,27,81]. Additionally, the calibration time of the dataloggers was longer than expected (ISO 7726). Hence, the initial 10 hours of measured data were discarded, with no impact on the long-term analysis.

Furthermore, had it been available, with a surface probe of thermocouple type K for long-term monitoring the ceilings' surface temperature measurements could have been conducted to further understand its role in the indoor thermal environment and radiant temperature asymmetry.

The three-months monitoring period chosen encompassed the hottest and coldest annual weeks, and the analysis was developed based on worst-case scenario weeks, following the methodology of previous research in the same climate [26–28,82,83].

Given the occupants' advanced age, it would be interesting that future work considers the impact of occupant switching. Newcomers would have different socioeconomic backgrounds and thermal expectations, and may occupy the dwellings differently, which may lead to performance discrepancies.

Finally, the lack of long-term studies on vernacular dwellings' indoor conditions stems from the challenge of finding large samples, accessibility issues, occupants' availability and willingness, elderly and illiterate focus groups, managing cultural specificity, sensitive information, survey bias, and the inherent uncertainty linked vernacular architecture. The present research strove to contribute with a long-term study of a larger sample than the bulk of previous work. Future research dedicated to expanding a systematic, long-term, and large-scale approach to vernacular dwellings' indoor conditions is warranted, as their preservation and legacy depend on it.

Acknowledgements

Disclosure statement

The authors report that there are no competing interests to declare.

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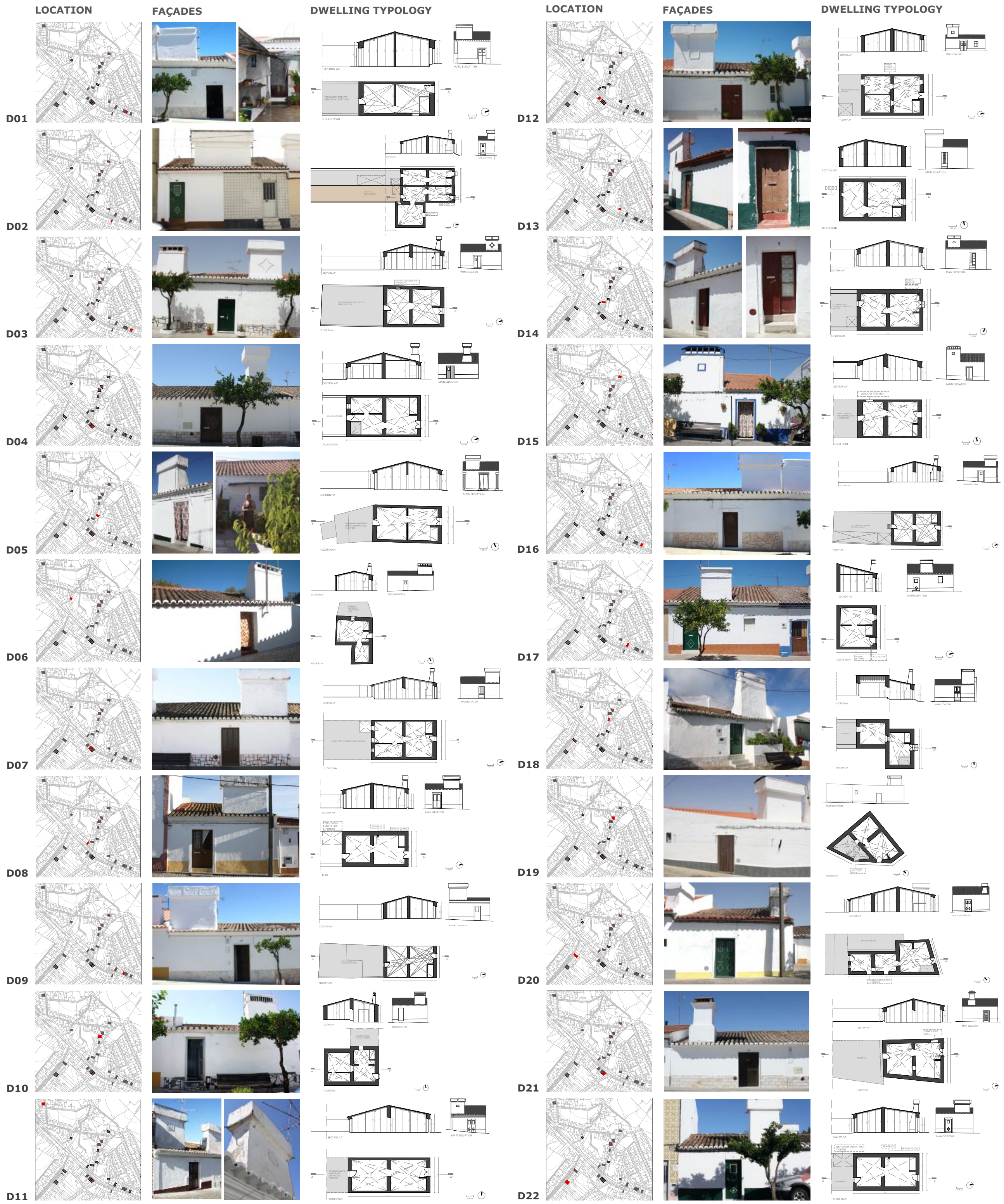
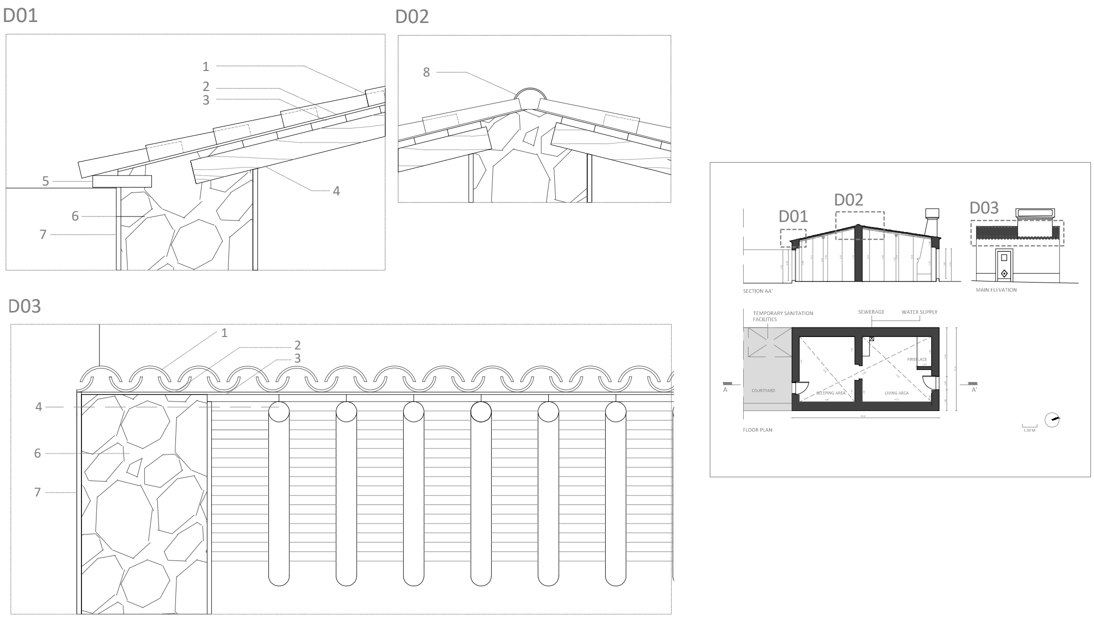
Appendix

Appendix A. Summary of case studies sheet (D01-D22)



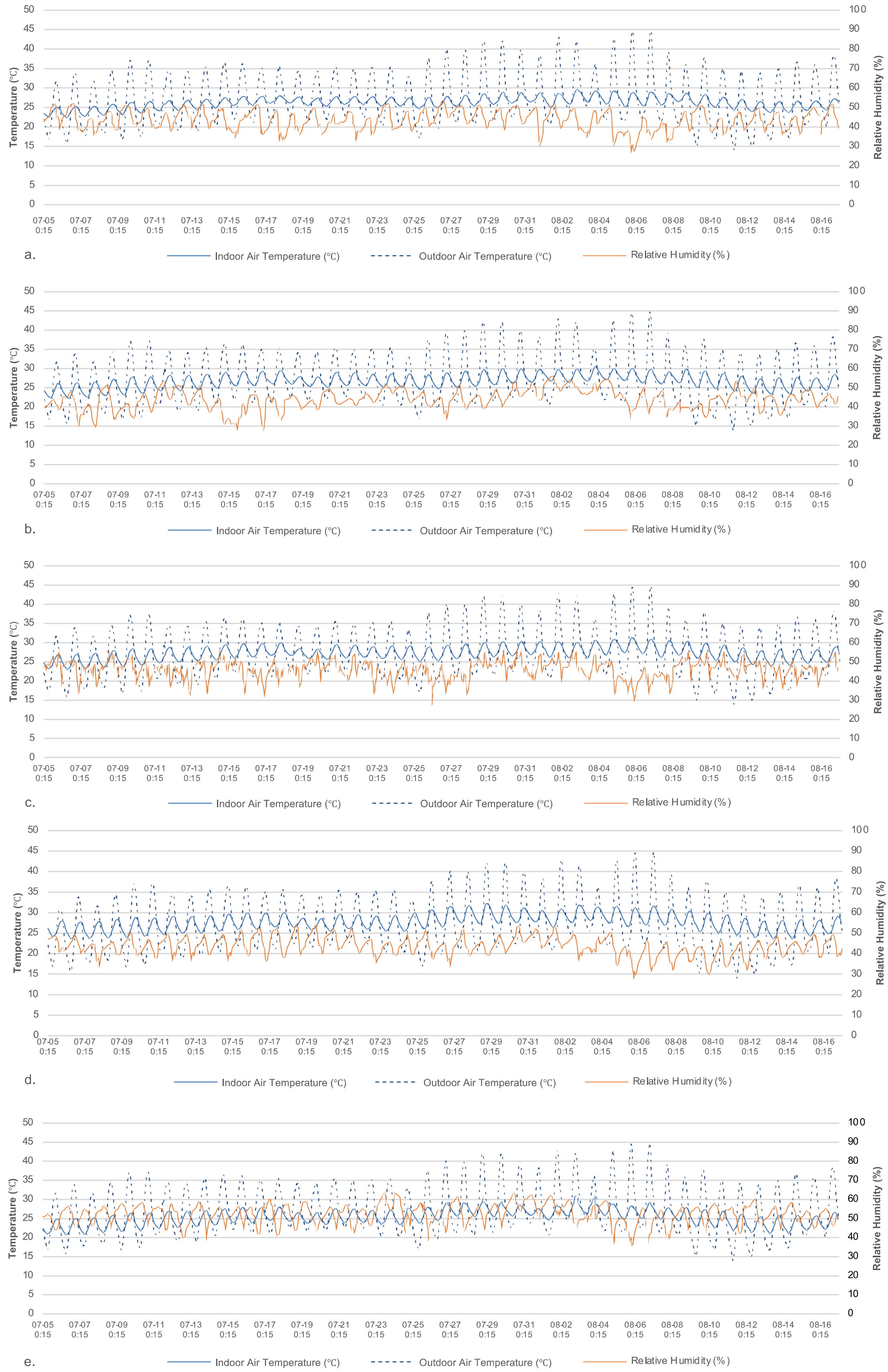
Appendix B. Constructive details D01, D02, D03. 1 – Traditional Arabic tile; 2 – Lime mortar; 3 – Single hollow clay bricks; 4 - Wooden joists; 5 – Roof eaves with brick overhang; 6 – Limestone and earth masonry; 7 – Lime plaster and lime wash; 8 – Ceramic ridge tile.



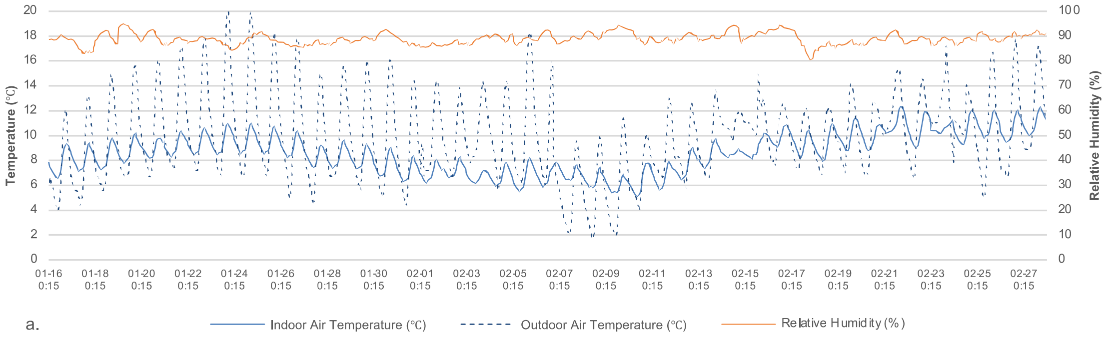
Appendix C. Infrastructure and systems of a typical vernacular dwelling in SVV.

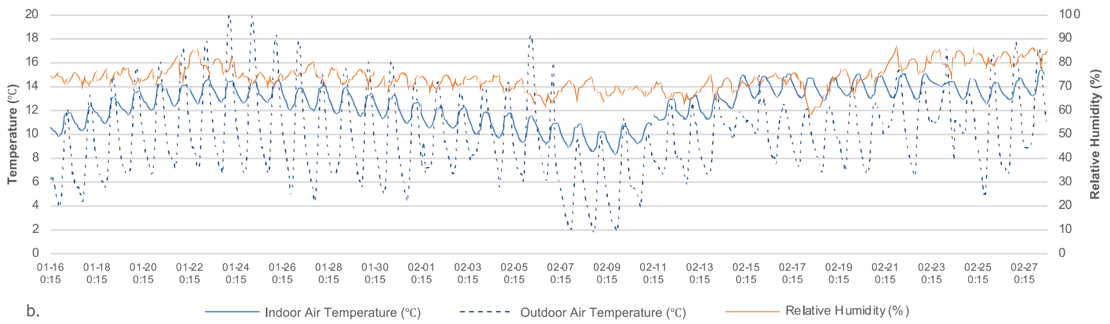
	Traditionally	**Currently**
Infrastructure and sanitation		
Sanitation facilities (SF)	Non-existent	50 % of case studies (CS) do not have access to basic SF, with unauthorized settlements. SF non-existent in 10 % of CS
Kitchen facilities (KF)	Non-existent. Fireplace cooking	25 % of CS have built KF in annex. 70 % of CS use a gas oven in the fireplace indoor space with no access to water supply
Sewerage system (SS)	Non-existent	Installed in the 1970s, connected to the public SS
Water supply network	Non-existent	Installed in the 1970s. To this day, 35 % of CS do not have water access in their sanitation facilities
Systems		
Heating system	Wood-burning fireplace	59 % are electric, only 5 % rely on a fireplace and 9 % on wood-burning Stoves (wood-based heating 14 %), 4 % are gas heating and 9 % do not use any heating system (14 % unoccupied)
Cooling system	Natural ventilation	Stand-alone natural ventilation (18 %), natural ventilation with mechanical ventilation (40 %), nighttime nat. ventilation with mechanical ventilation (14 %) and stand-alone mechanical via pedestal fans (14 %) (14 % unoccupied)
Hot water system	Non-existent	70 % of CS now have 1 hot-water access point

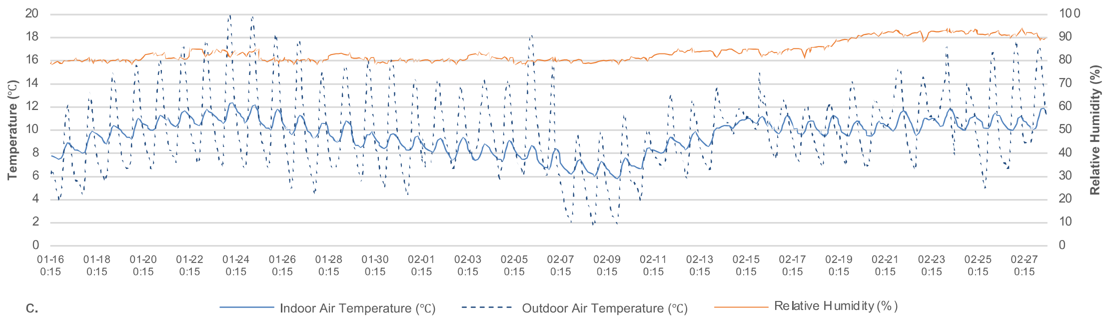
Appendix D.1. Summer monitored data (July 5th – August 16th, D02 (a), D03 (b), D04 (c), D09 (d), D11 (e)

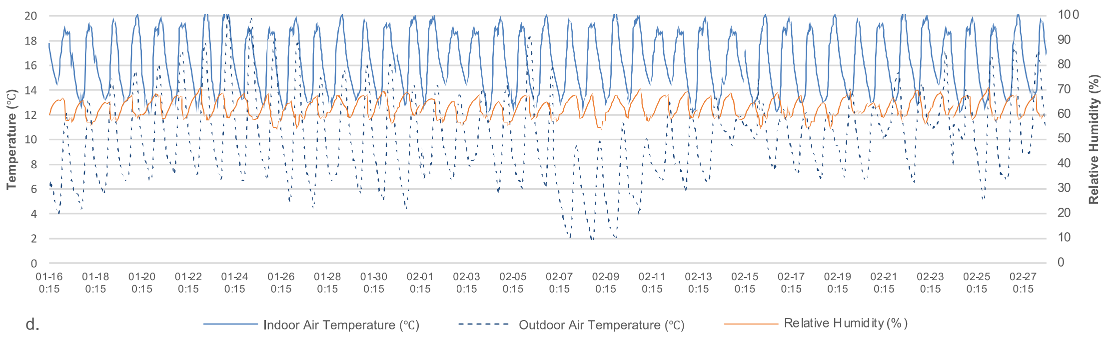


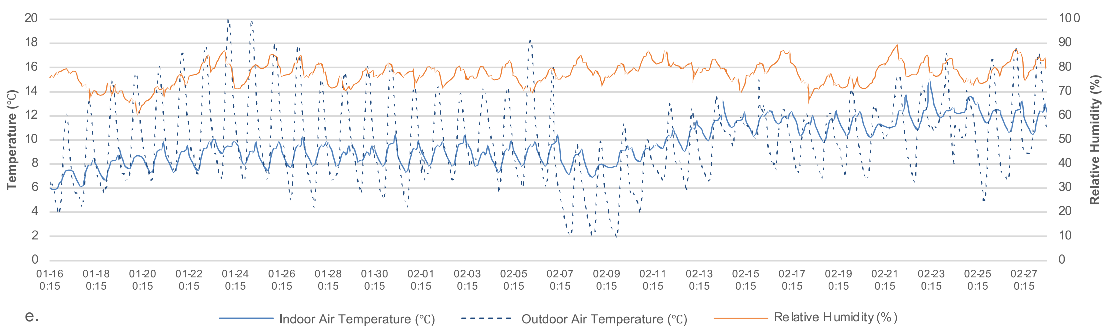
Appendix D.2. Winter monitoring (January 16th – February 27th, D06 (a), D11 (b), D16 (c), D07 (d), D15 (e)



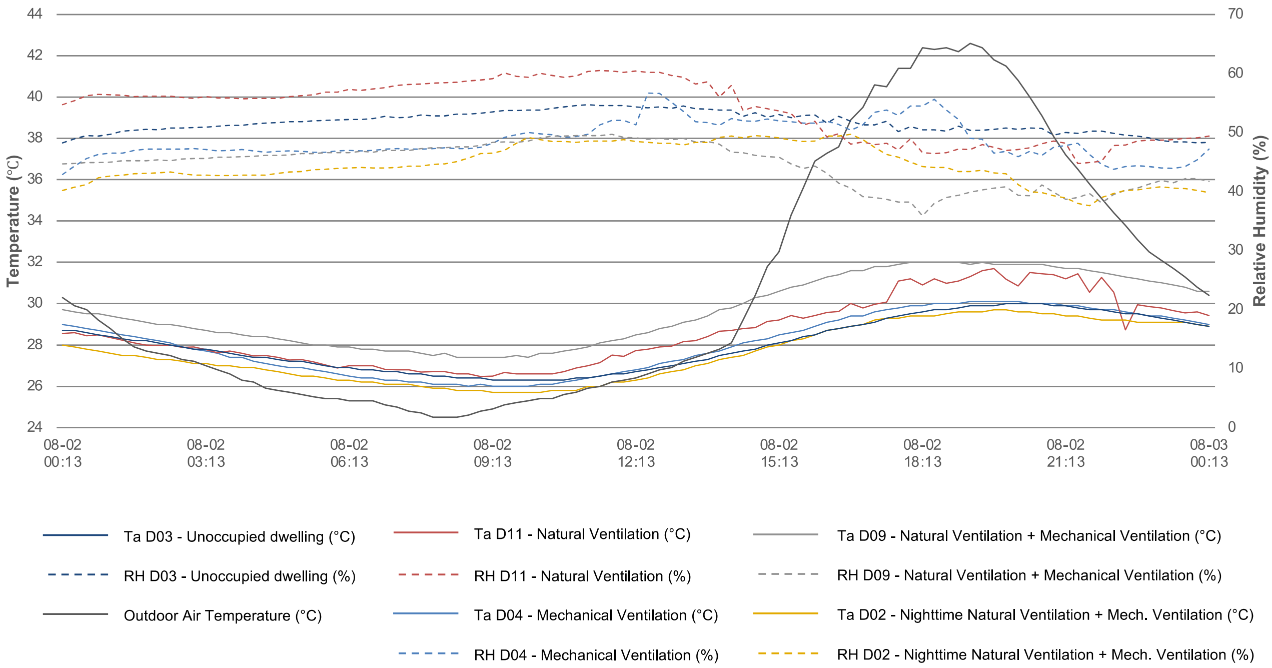




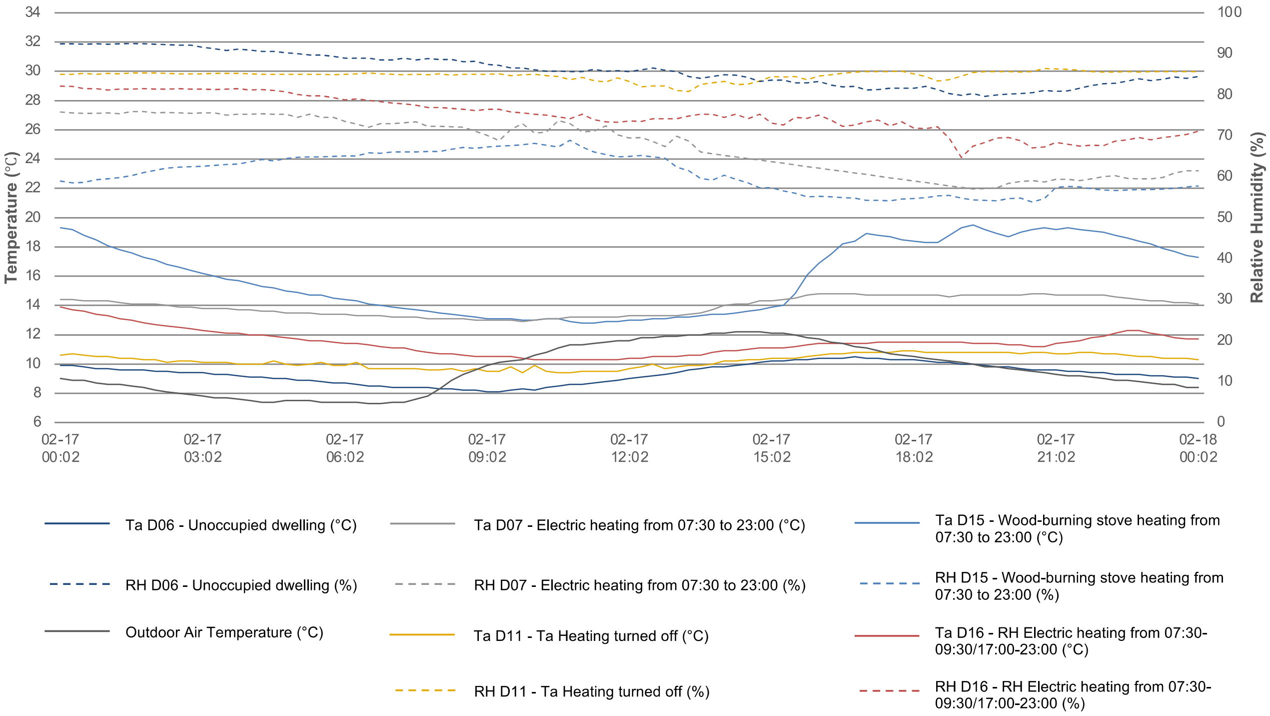




Appendix E.1. Overlay of summer single-day temperature oscillation of the different categories of case studies identified.



Appendix E.2. Overlay of winter single-day temperature oscillation of the different categories of case studies identified.



Appendix F. Average decrement factors/coefficients of stability and absolute depression values of the maximum temperatures for the summer and winter monitoring.

SEASON	CATEGORY	CASE STUDY	AVERAGE DECREMENT FACTOR [(1)]	AVERAGE T_a MAX DEPRESSION (ºC)
SUMMER				
	Unoccupied dwellings	**D03**	**0.11**	**12.27**
		D06	0.34	4.84
		D13	0.21	11.43
		$\bar{x}$	**0.22**	**9.51**
	Natural Ventilation	D05	0.3	5.71
		D08	0.45	3.32
		D10	0.07	9.06
		D11	**0.18**	**7.08**
		$\bar{x}$	**0.25**	**6.29**
	Natural Ventilation + Mechanical Ventilation	D01	0.33	3.14
		D07	0.55	3.88
		D09	**0.23**	**9.69**
		D15	0.23	5.41
		D17	0.22	11.88
		D19	0.24	9.62
		D20	0.20	9.98
		D22	0.38	2.68
		$\bar{x}$	**0.30**	**7.04**
	Nighttime Natural Ventilation + Mechanical Ventilation	**D02**	**0.19**	**10.06**
		D12	0.21	9.98

		D16	0.16	10.86
		D18	0.18	10.94
		x̄	**0.19**	**10.46**
	Mechanical Ventilation	**D04**	**0.33**	**3.92**
		D14	0.27	4.42
		D21	0.26	5.35
		x̄	**0.29**	**4.56**
WINTER				
	Unoccupied dwelling	D03	0.17	1.34
		D06	**0.41**	**2.11**
		D13	0.44	1.33
		x̄	**0.34**	**1.59**
	Electric heating	D01	0.47	0.81
		D07	**0.15**	**2.34**
		D08	0.34	0.66
		D09	0.31	0.58
		D10	0.49	1.06
		D14	0.30	1.23
		D16	**0.28**	**0.61**
		D17	0.29	1.34
		D18	0.37	1.33
		D19	0.40	1.24
		D20	0.33	1.99
		D21	0.28	1.96
		D22	0.47	3.83

	x̄	**0.35**	**1.46**
Wood-based heating	D04	1.03	8.31
	D05	2.11	16.30
	D15	**0.67**	**3.96**
	x̄	**1.27**	**9.52**
Gas heating	D02	0.31	0.55
Heating system OFF	**D11**	**0.25**	**1.90**
	D12	0.31	1.53
	x̄	**0.28**	**1.71**

(1) The decrement factor or coefficient stability was computed based on the following formula given in [51] and for the entirety of each monitoring period:

$$d_f = \frac{Ti_{MAX} - Ti_{MIN}}{Te_{MAX} - Te_{MIN}} \quad (5)$$

Where, Ti_{MAX} is the maximum indoor temperature, Ti_{MIN} is the minimum indoor temperature, Te_{MAX} is the maximum outdoor temperature, and Te_{MIN} is the minimum outdoor temperature.

Appendix G.1. Survey template with the thermal, visual, and indoor air quality sections.

Name:
Date of birth:
Marital status:

Date and time:
Outdoor temperature:
Weather conditions:

Employment status:

Occupation:

Income bracket:
- ☐ Below minimum wage bracket
- ☐ 650 - 1000 euros bracket

Occupants per household:

Educational attainment:
- ☐ No education
- ☐ Primary education. Literacy
- ☐ Primary ed. Functional illiteracy
- ☐ Lower secondary education

Occupant location during survey. Is the occupant near an external wall/opening?

Indoor thermal temperature and RH:

Thermal comfort

1. Please check each item of clothing that you are wearing.

- ☐ Short-sleeve shirt
- ☐ Long-sleeve shirt
- ☐ T-shirt
- ☐ Long-sleeve sweatshirt
- ☐ Sweater
- ☐ Vest
- ☐ Jacket
- ☐ Knee-length skirt
- ☐ Ankle- length skirt
- ☐ Dress
- ☐ Shorts
- ☐ Athletic sweatpants
- ☐ Trousers
- ☐ Undershirt
- ☐ Long underwear bottoms
- ☐ Long sleeve coveralls
- ☐ Overalls
- ☐ Slip
- ☐ Nylons
- ☐ Socks
- ☐ Shoes
- ☐ Sandals
- ☐ Other
- ☐ No reply

2. What is your activity level right now?

- ☐ Reclining
- ☐ Seated
- ☐ Standing relaxed
- ☐ Light activity standing
- ☐ Medium activity standing
- ☐ High activity

3. What is your general thermal sensation?

- ☐ Hot (3)
- ☐ Warm (2)
- ☐ Slightly warm (1)
- ☐ Neutral (0)
- ☐ Slightly cool (-1)
- ☐ Cool (-2)
- ☐ Cold (-3)
- ☐ No reply

4. Which of the following do you personally adjust or control in your space?

- ☐ Opening/closing wicket
- ☐ Opening/closing door
- ☐ Mechanical ventilation/Portable fan
- ☐ Natural ventilation
- ☐ Heating (if so, which type)
- ☐ Clothing and bed clothing
- ☐ Other
- ☐ No reply

☐ Much more daylight
☐ More daylight
☐ No change
☐ Less daylight
☐ Much less daylight
☐ No reply

3. Personal tolerance (painfulness index according to the ISO 10551). Is it:

☐ Perfectly bearable
☐ Moderately bearable
☐ Slightly bearable
☐ Neutral
☐ Fairly difficult to bear
☐ Very difficult to bear
☐ Unbearable
☐ No reply

4. When is this most often a problem?

☐ Morning (before 11am)
☐ Midday (11am-2pm)
☐ Afternoon (2pm-5pm)
☐ Evening (after 5pm)
☐ No particular time
☐ Always

☐ Winter
☐ Spring
☐ Summer
☐ Autumn
☐ Always

5. To what extent do you disagree with the statement: "It is possible to perform indoor tasks during the day by relying on daylight availability alone"?

☐ Strongly agree
☐ Agree
☐ Neither agree nor disagree
☐ Disagree
☐ Strongly disagree
☐ No reply

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6. How many daily hours on average do you use artificial light?

- [ ] > 10 hours
- [ ] > 7 hours
- [ ] > 3 hours
- [ ] > 1 hour
- [ ] < 1 hour
- [ ] No reply

7. How satisfied are you with the view out from the wicket?

- [ ] Very satisfied (3)
- [ ] Moderately satisfied (2)
- [ ] Slightly satisfied (1)
- [ ] Neutral (0)
- [ ] Slightly dissatisfied (-1)
- [ ] Moderately dissatisfied (-2)
- [ ] Very dissatisfied (-3)
- [ ] No reply

8. How would you score the following as a result of introducing a façade opening/skylight? from 0 to 5, where 0 is the bottom classification and 5 the top one.

- [ ] Fresh air
- [ ] Increased daylight
- [ ] View out
- [ ] Electricity consumption reduction

Indoor Air quality

1. Do you perceive the air quality to be:

- [ ] Clearly acceptable
- [ ] Just acceptable
- [ ] Just unacceptable
- [ ] Clearly unacceptable

2. Do you perceive the odour intensity to be:

- [ ] Non-existent
- [ ] Weak
- [ ] Moderate
- [ ] Strong
- [ ] Very strong
- [ ] Overpowering

3. How would you best describe the source of this discomfort?

Appendix G.2. Summary Table of the linear regression study between the survey's illuminance tolerance votes and the monitored data.

ITV = A. Lux + b		**R^2**	**p-value**	**S_e**
A	b			
0.009	1.053	0.007	0.081	1.176

A: coefficient of Lux, the slope of the regression line, how much ITV changes for each change in Lux; p-value: Pearson's chi-squared; b: constant, equals the value of ITV when the value of Lux = 0; R^2: Coefficient of determination; S_e: Standard error of estimate; Lux: Indoor Natural Illuminance; ITV: Illuminance Tolerance Vote.