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

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Indoor environmental conditions in vernacular dwellings in Alentejo, Portugal

Understanding the indoor environmental conditions of liveable 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 analysing 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, mould, 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.

Keywords: indoor environmental performance; vernacular dwellings; *in situ* monitoring; hot-dry climate; occupant survey

[1]

1. Introduction

The conservation of liveable architectural heritage such as vernacular dwellings largely depends on the understanding of their indoor environmental and living conditions (Fabbri, Pretelli, and Bonora 2019; Fabbri and Bonora 2021). In recent years, research on the indoor conditions of vernacular dwellings has strongly focused on thermal performance in humid climate locations (Du, Bokel, and

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[A]bbreviations: CIE: International Commission on Illumination; DBT: Dry-bulb temperature; DF: Daylight factor; D_T: Target daylight factor; D_{TM}: Minimum target daylight factor; 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.

van den Dobbelsteen 2014; Kubota, Toe, and Ossen 2014; Djamila, Chu, and Kumaresan 2015; Hermawan, Prianto, and Setyowati 2015; Sarkar and Bose 2015; Singh, Mahapatra, and Teller 2015; Toe and Kubota 2015; L. Huang et al. 2016; Shastry, Mani, and Tenorio 2016; Yan et al. 2016; Gupta et al. 2017; Z. Huang et al. 2017; Kubota et al. 2017; S. Liu et al. 2018; Xu et al. 2018; Zhang, Zhang, and Jin 2018; Zhu et al. 2019; Tsovoodavaa and Kistelegdi 2019; Yang et al. 2020; Zhao et al. 2020; Henna, Saifudeen, and Mani 2021; Rijal 2021; Bassoud et al. 2021). This is then followed at a distance by Portuguese (Jorge Fernandes et al. 2019; Jorge Fernandes, Pimenta, et al. 2015; Jorge Fernandes, Mateus, et al. 2015), and Iranian studies (Shaeri et al. 2018; Shaeri, Yaghoubi, and Habibi 2018; Foruzanmehr 2016). 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 for comfort assessment. Even though it has been suggested that thermally-unrelated indoor environmental quality factors such as illuminance (Michael et al. 2017) and indoor air quality (Zhu et al. 2020) 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 large-sample studies on indoor conditions following a mixed-methods approach. In Alentejo, while a few qualitative studies undertaken since the 1930s (SNA 1961; Moutinho 1979; JM Fernandes 1997; Veiga de Oliveira and Galhano 2003; Lima Basto, Faria e Silva, and Silva 2013) gathered data on historical, construction, and ethnological features, quantitative research entailing monitoring is scarcer (Costa Carrapiço and Neila González 2014; Jorge Fernandes, Pimenta, et al. 2015; Jorge Fernandes, Mateus, et al. 2015; Costa Carrapiço 2016) 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 (Jorge Fernandes et al. 2019) and compare it to a northern building (Jorge Fernandes, Mateus, et al. 2015; Jorge Fernandes, Pimenta, et al. 2015). 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 therefore essential for obtaining robust and transferable conclusions on the indoor behaviour of liveable architectural heritage such as vernacular dwellings. Moreover, it is crucial that this research analyses unresearched vernacular typologies and construction systems, to maintain the liveability of these dwellings and encourage their conservation (Fabbri, Pretelli, and Bonora 2019; Fabbri and Bonora 2021).

2. Aim

This paper addresses the identified gap by analysing 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

This research uses a mixed-methods approach encompassing quantitative and qualitative data collection to carry out an informed assessment of the case studies' indoor conditions. The methods and materials employed for the monitoring and surveying are outlined in the ensuing section.

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 extrapolation of results and a broader impact of findings.

Their selection was conducted according to the following set of criteria: i. representativeness of regional vernacular dwellings, and their bioclimatic strategies; ii. preservation of traditional building elements and the integrity of the façade; iii. preservation of 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 the occupants, abandonment or construction work; absence of the occupants; modified indoor space and construction systems.

Figure 1. 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 layout and occupancy profile of the case studies are deeply rooted in the primary regional economic activity, i.e. agriculture (Costa Carrapiço 2016), originally providing shelter for rural workers. The technical sheet for all 22 case studies can be found in the Appendix A. Three main typologies were identified; the predominant one (70%) is illustrated in Figure 2, and its typical features are outlined in Table 1.

Contrary to the regional traditional building technique, i.e. rammed earth (M. Fernandes and Mariana Correia 2005; SNA 1961; Inês Fonseca 2007; Mariana Correia 2007; VV.AA. 2005), the case studies combined the locally available limestone with earth from surrounding fields. The local limestone availability has been acknowledged in the literature (SNA 1961), and the geological constitution of the soils corroborates its use in the dwellings, with the latter sitting on a large patch of

Cambrian soil consisting of limestone and dolomite (Direcção-Geral de Minas e Serviços Geológicos, Ministério da Economia 1972).

Figure 2. 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. Features of a typical vernacular dwelling in SVV.

General description			
Construction date	1800s		
Orientation	NE-SW; SE-NW		
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		
Dwelling Construction		**Thickness**	**U-value**
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.ºC (3) (EW) 1.17 W/m^2.ºC (3) (IW)

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.ºC (4)
Ground	Ceramic floor tiles + lime mortar + earth	0.03 m + 0.010 m	1.53 W/m^2.ºC (3)
Fireplace walls	Baked brick + lime mortar + lime wash	0.20 m + 0.013 m	1.73 - 1.50 W/m^2.ºC (2, 3)
Infrastructure and sanitation	**Traditionally**	**Currently**	
Sanitation facilities (SF)	Non-existent	50% of case studies (CS) do not have access to basic SF, with unauthorised settlements. SF non-existent in 10% of CS	
Kitchen facilities (KF)	Non-existent. Fireplace cooking	25% of CS have built KF in annexe. 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 access to water supply in their sanitation facilities	
Systems			
Heating system	Wood-burning fireplace	Only 5% rely on a fireplace: 60% are electric, 9% are wood-burning stoves, 5% are gas heating and 9% do not use any heating system	
Cooling system	Natural ventilation	Natural and mechanical via pedestal ventilation fans	
Hot water system	Non-existent	70% of CS now have 1 hot-water access point	

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

(3) (Pina dos Santos and Rodrigues 2017).

(4) (Pina dos Santos and Luís Matias 2018).

3.1.3. Climate

SVV is characterised by a hot dry-summer Mediterranean climate, i.e. Csa according to the Köppen Climate Classification (AEMET and IM 2011). The dry and lengthy summer period averages 25 ºC and peaks around 40 ºC in August (AEMET and IM 2011). There is a significant annual thermal amplitude, averaging 11 ºC and peaking in summer (15 ºC) (Costa Carrapiço 2016). 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 (Miranda, Abreu, and Salgado 1995). Finally, the region is extremely sunny, with 3000 hours of annual sunshine ("IPMA" 2016).

Thus, regional vernacular dwellings developed climate-responsive strategies centred on passive cooling, solar radiation shielding, and minimising summer heat gains (Costa-Carrapiço 2013; Costa Carrapiço 2016; Costa Carrapiço and Neila González 2014; Jorge Fernandes, Mateus, et al. 2015; Jorge Fernandes, Pimenta, et al. 2015; Jorge Fernandes et al. 2019; Correia 2002; Pereira 2014). The key passive strategies of the dwellings and their impact are discussed in section 4.5..

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 access 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 the monitoring stage.

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 (ANSI/ASHRAE Standard 55 2013), 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 (Environment 1998) and ASHRAE 55 (ANSI/ASHRAE Standard 55 2013). Table 2 details the measurements conducted and Table 3 lists the equipment technical specifications.

Table 2. Details of the measurements conducted.

	Parameter	Measurement length			Location of measurement	Standard complied with	Specifics
		LT [(1)]	ST [(2)]	PIT [(3)]			
Thermal comfort	Air temperature	■			Living room, bedroom, outdoors	ISO 7726 (Environment 1998) ASHRAE 55 [58]	Outdoor temp.: dataloggers shielded from direct solar radiation or rainfall Indoor temp.: a centred 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 neighbouring 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
	Natural illuminance			■	Living room, outdoors	EN 15251 EN 12464-1:2011 [66]	Indoor daylight: consecutive centred 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 3. 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 analyser	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 focused on indoor air quality (IAQ) and visual comfort. To avoid the skewing of visual comfort results from point-in-time conditions, a mixed-mode satisfaction and preference questionnaire was administered during winter and summer, specifying that it evaluated long-term perception. It was based on the ASHRAE satisfaction survey (ANSI/ASHRAE Standard 55 2013), ISO 7730 (ISO 7730 2005) and ISO 10551 (Standardization 1995) and was built around visual satisfaction, preference, and tolerance.

To evaluate the occupants' IAQ perception, the authors adapted the subjective evaluation in EN 15251. Electricity consumption data from the previous 12 months was requested on an optional basis. The statistical package for social sciences, SPSS, was used for data processing.

4. Results and discussion

The case studies' environmental performance is analysed according to five main sections. The first one investigates summer and winter thermal performance in the main living area. The second one discusses IAQ results, while the third one analyses visual comfort, and a fourth one looks at the noise level. Finally, the impact of the passive strategies is considered.

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 B.1.

To contrast the thermal performance of all 22 case studies, the benchmarking of the free-floating indoor air temperature (T_a) in the living room of each monitored dwelling on the most extreme monitored day is presented. Specifically, Figure 3 illustrates their thermal behaviour on the hottest day, according to 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%).

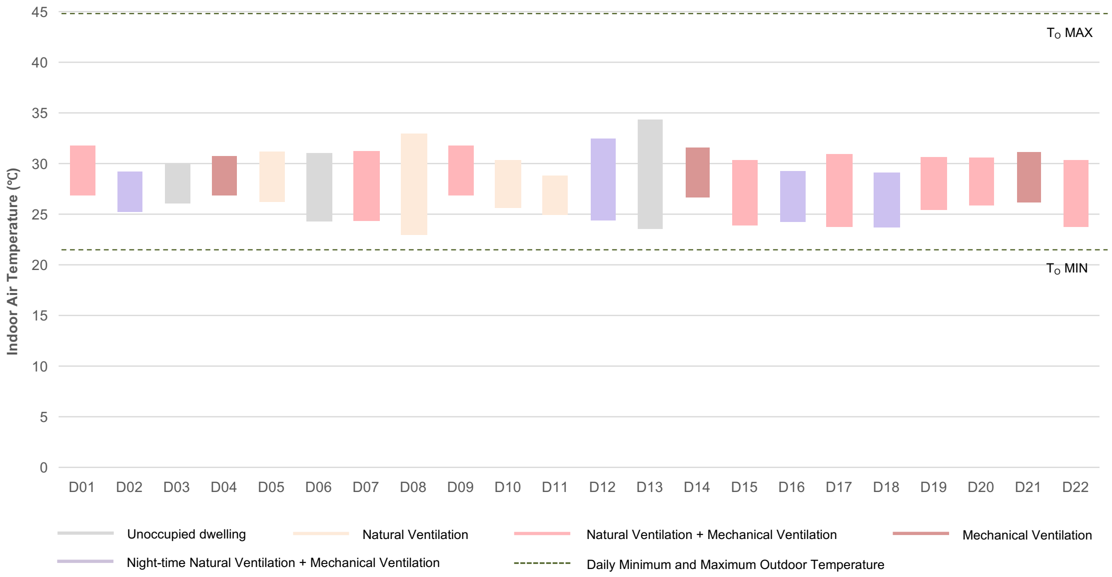

Figure 3. Daily temperature oscillation in the living room of each monitored dwelling (D01-D22) according to their category, on August 6th 2015.

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

- **Approaches for regulating indoor T_a 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 thermal amplitudes and enhanced thermal stability. However, D12 appears to be an exception. It presents the peculiarity of having an unauthorised window on the façade and when compared to other dwellings within the same category and identical solar orientation (NE-SW) and occupancy, it is suggestive of a significantly poorer behaviour under extreme heat, with lower thermal stability and peaking at 32.4 º C. This is noteworthy because it suggests the relevance of the lack of windows as a summer bioclimatic strategy for reducing solar gains and overheating.

Although natural ventilation was traditionally applied during nighttime, it has been progressively reducing 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, a degree of uncertainty linked to adaptive behaviour remains, which may account for divergencies within categories and challenges in identifying clear patterns. This emphasises the criticality of pinpointing daily schedules to the best extent possible.

- **Representative week of indoor thermal fluctuation**

Figure 4 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.

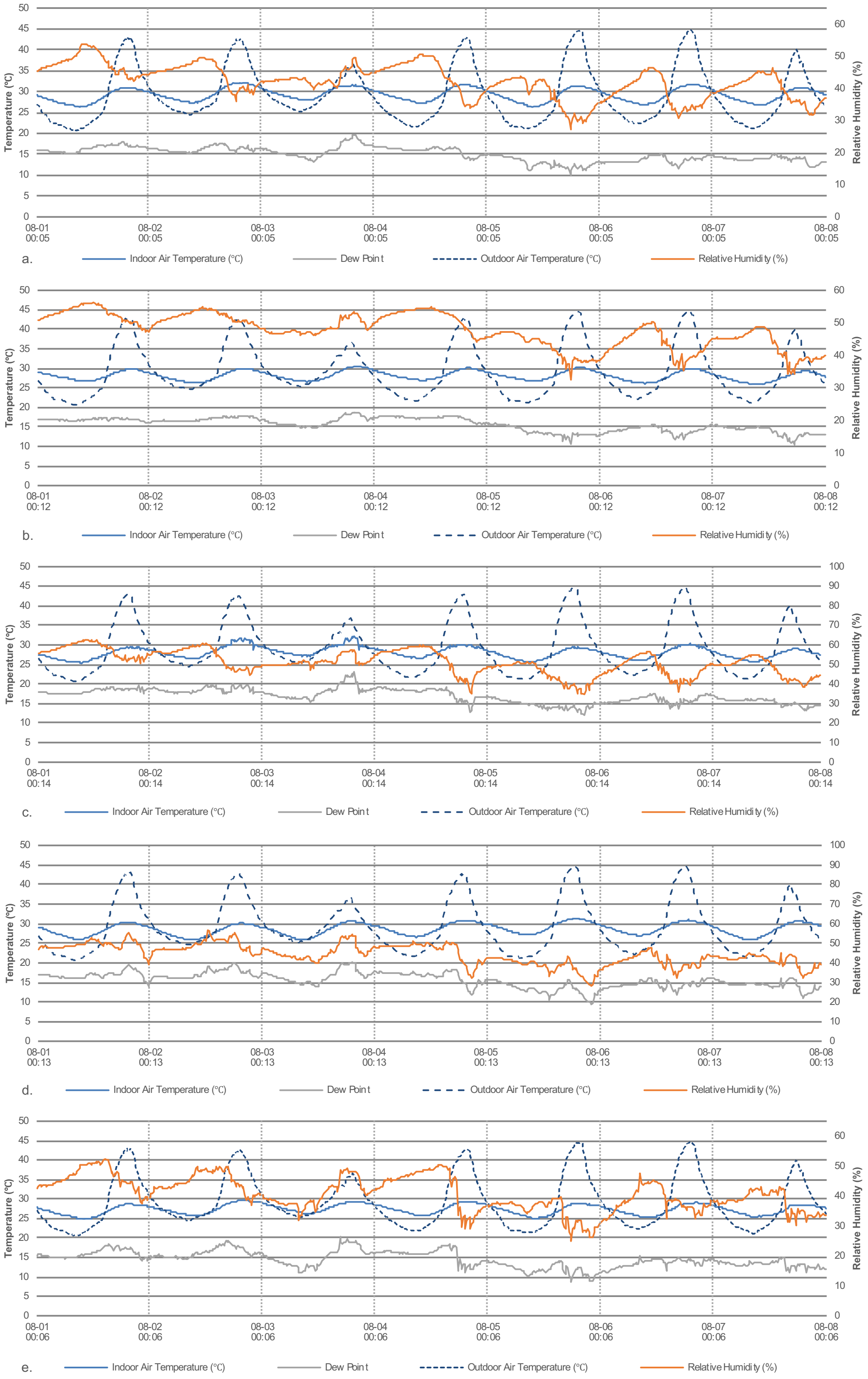

Figure 4. One-week extract from the summer monitoring, displaying T_a and RH, where: a. D09, natural and mechanical ventilation; b. D03, unoccupied dwelling; c. D11, natural ventilation; d. D04, mechanical ventilation; e. D02, nighttime natural and mechanical ventilation.

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 remains very stable and within reasonably comfortable ranges. If we take D02, adopting nighttime and mechanical ventilation, the temperature recorded for 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 the outdoor-indoor heat transfer, and avoiding excessive peaks. For the analysed week, the thermal stability coefficients, calculated based on (Bedoya Frutos and Neila González 2001), average 0.30, suggesting high thermal stability and an impact of approximately 30% regarding outdoor variations (Costa-Carrapiço et al. 2014; Bedoya Frutos and Neila González 2001). In this regard, the strategy combining nighttime natural and mechanical ventilation seems to provide the best thermal stability overall, while short-term early-morning or evening natural and mechanical ventilation performs the least favourably, albeit being the most used strategy, followed by natural ventilation alone. A possible explanation could lie in the fact that the DBT between 22:00 and 23:00, a self-reported ventilation window, are still too high (35 ºC) to provide cooling comfort from natural ventilation and may exacerbate the dwellings' daily thermal load. In fact, in graph (c), i.e. the case study using stand-alone natural ventilation, on days 2 and 3 there is a sharp temperature rise in the early evening. This could be attributable to opening the wickets around 19:00, outside the typical ventilation window, when outdoor DBTs stand around 40 ºC-42 ºC. The initial hypothesis that this was linked to cooking activities was discarded, as their thermal load would likely translate into a higher T_{aMAX}, and not an abrupt temperature fluctuation, on top of being an occasional occurrence, and hence, incompatible with cooking. However, it is likely that cooking loads without proper ventilation may contribute to overheating issues.

A comparison of the indoor thermal environments of dwellings adopting natural and mechanical ventilation combined (a) and nighttime natural ventilation with mechanical ventilation (e), 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, disclosing the convective cooling potential of nighttime natural ventilation. 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 comparing dwellings using mechanical ventilation with those adopting nighttime natural and mechanical ventilation, the dissipation of stored heat by convection seems to optimise their thermal inertia capacity. This is reflected in the offset of outdoor extreme temperatures, by lowering the average temperature by 1.2 ºC. On top of seldom nighttime natural ventilation, the inherent lack of insulation might be further aggravating the dwellings' overheating, in particular regarding the roofs (Table 1).

On a final note, it is worth emphasising 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 the 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 a 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 (European Standard 2007), long-term low humidity values have detrimental health impacts, such as irritating mucus membranes and respiratory tract, eye dryness, and enhanced susceptibility to air pollutants (Wolkoff 2018). Nonetheless, there are no established low-humidity limits for thermal comfort, as occurs with upper humidity (ANSI/ASHRAE Standard 55 2013).

4.1.1.2. Average indoor air and wall temperature

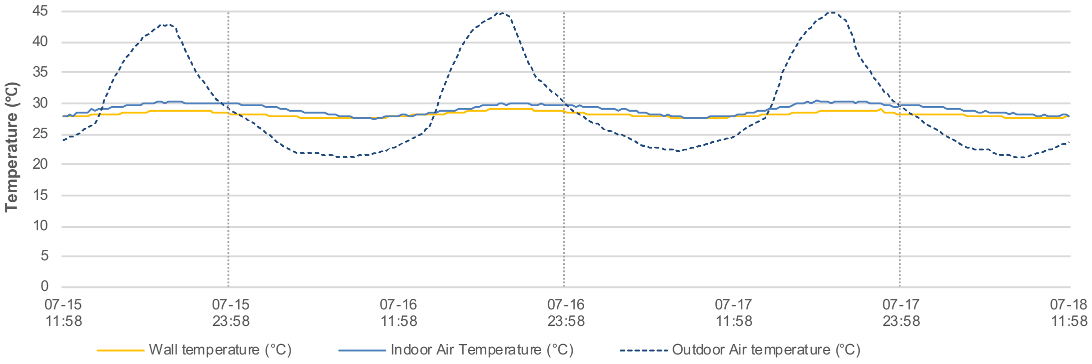

Figure 5. Wall temperature, indoor air temperature, and outdoor air temperature, 72-hour summer monitoring.

Due to the size of the case studies, it was foreseeable that the walls would strongly influence the T_{mrt} (Leo Samuel et al. 2017). 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 in the early to mid-morning. This points to the impact of high thermal mass walls on the modulation of T_{ws}, on top of their stabilising influence on T_{as}. These findings align with previous studies on vernacular dwellings with high thermal mass (Toe and Kubota 2015).

4.1.1.3. Globe temperature and Mean Radiant Temperature (T_{mrt})

According to (Environment 1998), the T_{mrt} was derived from the conversion of the black globe temperature measurements (Walikewitz et al. 2015; Thorsson et al. 2007; Feriadi and Wong 2004; Yan et al. 2016), based on the following equation:

$$T_{mrt}=\sqrt{(T_g+273.15)^4+\frac{h_{cg}}{\varepsilon * D^{0.4}}*\left(T_g-T_a\right)}\ -273.15 \qquad (1)$$

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.

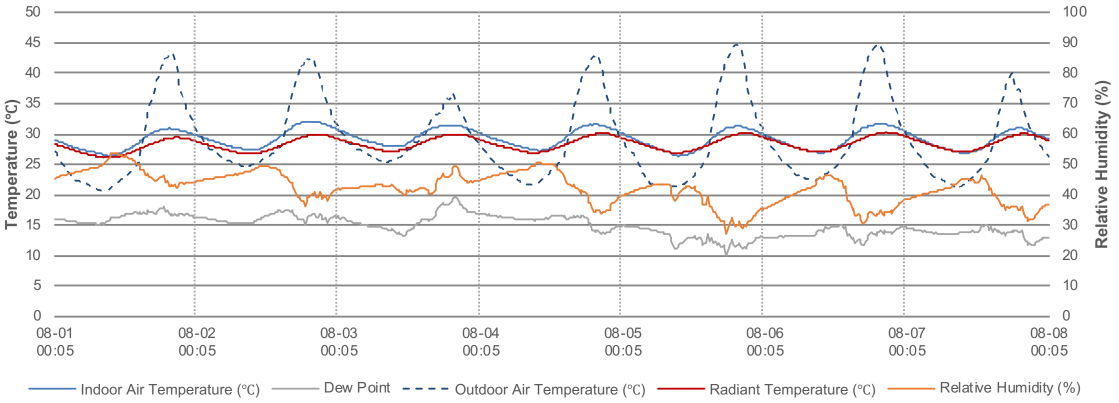

Figure 6. Median radiant temperature (T_{mrt}), indoor air temperature (T_a), and outdoor air temperature.

Overall, 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 (Walikewitz et al. 2015; Dear and G.S. Brager 2002; Singh, Mahapatra, and Teller 2015; Singh, Mahapatra, and Atreya 2010; Langner, Scherber, and Endlicher 2013; Matzarakis and Amelung 2008).

An explanation for the narrow difference found might lie in the absence of the main driving factors for these deviations, previously identified as the size and exposure of the windows as well as the intensity and duration of a room's or surface's direct solar radiation (Walikewitz et al. 2015). Additionally, the results obtained reflect earlier studies on the thermal performance of traditional dwellings (Shaeri et al. 2018; Hermawan, Prianto, and Setyowati 2015; Leo Samuel et al. 2017).

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 (ANSI/ASHRAE Standard 55 2013).

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 warm air to leak into the dwellings while under-ventilating them and 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 the 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 can control, for natural ventilation is infeasible during the daytime in light of the outdoor out-of-scale temperatures. Yet, mechanical ventilation also underperformed in the case studies, conceivably because in a scenario with high T_{as} and lower T_{mrt}, elevated airspeed is less effective at increasing heat loss (ASHRAE 2017).

4.1.2. Winter in situ monitoring

4.1.2.1. Average indoor air temperature and RH

During 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%.

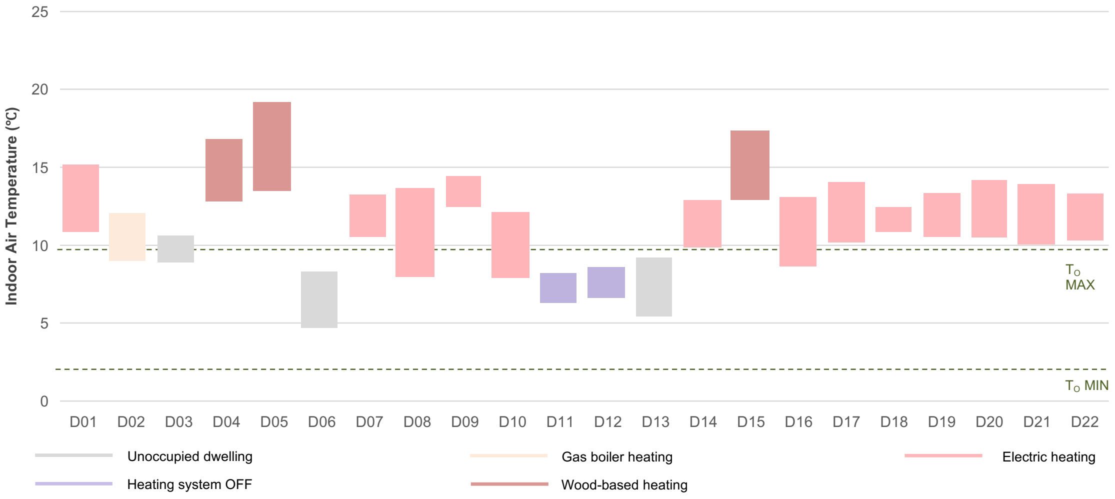

Figure 7. Daily temperature oscillation in the living room of each monitored dwelling (D01-D22) according to their category, on February 8th 2015.

Figure 7 displays the temperature oscillation in the living room of each dwelling on the coldest monitored day. 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 the coexistence of two heating schedules: 07:30 to 23:00 and 07:30-09:30/17:00-23:00.

The most common strategy is electric heating from early morning until bedtime at around 23:00 (45%) versus bi-daily electric heating (14%), from 07:30 to 09:30 and 17:00 to 23:00. Within the first subgroup, a common Ta belt between 10.5 ºC and 13.7 ºC was identifiable, with the T_{aMIN} being 9.8 ºC. The second subgroup performed worse than all-day electric, and fireplace and wood-burning stove heating schemes, and has a common Ta belt at 8 ºC-12.9 ºC, with the T_{aMIN} being 7.7 ºC. The Ta belt of the wood-based heated case studies is much higher, 13.1 ºC-17.9 ºC, the closest to the lower end of indoor comfort acceptability (EN16798-1 2019). The best performing dwelling (D05) pertains to this category and ranged between 13.5 ºC-19.4 ºC.

- **Representative week of indoor thermal fluctuation**

Figure 8 showcases a representative week (16th-23rd of February) of each of the categories. The full winter data can be found in the Appendix B.2. This period was chosen over the coldest week due to an atypical weather event.

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 of nearly five hours on average. This features the high thermal inertia of the dwellings' envelope and exhibits its strong outdoor 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 thermal amplitudes of the unoccupied dwelling are steeper, averaging a 2.5 ºC between the T_{aMAX} and T_{aMIN}. Both dwellings displayed indoor T_{aMAX} below the outdoor DBT at all times. Yet, D11 consistently showed higher temperatures than D06, especially when it came to T_{aMIN} (averagely 1 ºC higher). A possible hypothesis is that the lack of thermal

Figure 8. Extract from the winter monitoring, displaying T_a and RH: a. D06, unoccupied dwelling; b. heating turned off; c. D16, electric heating from 07:30-09:30/17:00-23:00; d. D07, electric heating from 07:30 to 23:00; e. D15, Wood-burning stove heating from 07:30 to 23:00.

loads from miscellaneous sources including, *inter alia*, radiant body heat emission, equipment, and lighting, could explain this dissimilarity. Furthermore, the thermal stability coefficient of D11 averages 0.29, which betters its summer counterpart and indicates very high thermal stability (Bedoya Frutos and Neila González 2001). This reflects the heat storage capacity of the building's envelope, exhibiting a conspicuous delay of the outdoor thermal wave. 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, allowing for an adequate response 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 T_a and occupancy patterns

The self-reported bi-daily convection heating schedule roughly matches the heating pattern identified in D16, with some deviation. While the outdoor temperature starts increasing around 5:30 only to peak around 14:00, the T_a keeps dropping 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 steep temperature increase is consistently singled out, from early morning until 15:00-16:00, after which it usually stabilises until 23:00 while the outdoor temperature drops sharply, and then smoothly descends 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.

The thermal inertia's impact on the indoor environment was distinctly observed in both categories. Yet, with the wood-burning stove, the radiant heat lingering effect keeps T_{as} stable at their peak for up to two hours. The results suggest that the radiant heating systems' performance in the case studies is more beneficial than convection ones, i.e. electric oil heating. Despite its efficiency and traditionally predominant role, this heating technique was 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. Without adequate ventilation, it can lead to moisture condensations and adverse health effects by causing microbial growth (European Standard 2007) and long-term discomfort (ASHRAE 2017). The case studies' winter environment is in an extremely humid and cold spectrum, except for the wood-heated dwellings, with RHs under 65 %.

4.1.2.2. Globe temperature and T_{mrt}

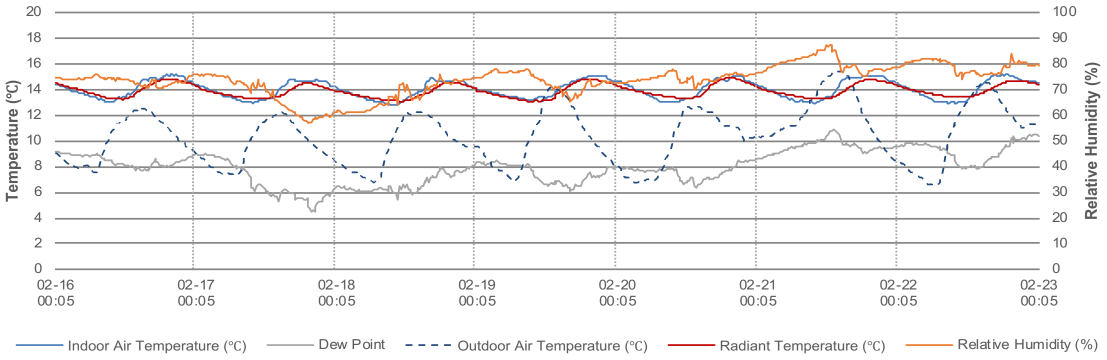

Figure 9. Median radiant temperature (T_{mrt}), indoor air temperature (T_a), and outdoor air temperature.

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' stabilising influence in preventing sharper nighttime thermal drops.

4.2. Indoor air quality conditions

The IAQ results confirmed cooking and heating emissions as the main sources of air pollution in the case studies. 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 in the living room and 10 ppm near the stove. Also noteworthy was the cooking CO average concentration, at 3.5 ppm. This could be explained by the accumulation of cooking emissions due to the lack of adequate ventilation or exhaust system to minimise fumes. Moreover, the use of gas stoves, which should be vented, releases ultrafine particles, hazardous air pollutants, CO, and NO_2 (Organization 2014). The occupants' adaptive behaviour could help mitigate exposure, however the dwellings' layout does not leave much room for other than naturally ventilating through the wickets. During winter, however, this is seldom done, as the adaptive behaviours 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 the unsealed chimneys and the envelope's pronounced air infiltration playing an important role in dissipating contaminants.

During the heating season over half of the occupants customarily leave the heating on all day, which would amount to daily 15-hour exposure periods. Wood-based heating for prolonged periods 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 level of exposure (Salthammer et al. 2014; Organization 2014) 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 air 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 Organisation (WHO) guidelines (Organization 2014; 2010 2010) by a thousand fold.

On top of VOCs, CO values occasionally exceeded these guidelines (2010 2010; 62-2001 2003) 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 (62-2001 2003) in spite of wood burning, qualifying as high IAQ (≤ 800 ppm) (CEN-European Committee for Standardization 2004) and below 1000 ppm, i.e. the threshold between the hygienically harmless and conspicuous ranges, where increased air exchange and improved ventilation behaviour would be required.

The questionnaire-based surveys indicated that nearly half of the occupants (44%) perceive their IAQ to be just acceptable, against 37.5% for unacceptable and 19% for clearly unacceptable. Over half of the interviewees perceived the odour intensity as moderate and only 12.5% described it as very strong or overpowering. The results also indicate that while there is little awareness of the impact of IAQ on health and risk of exposure to harmful emissions, there is an overall acknowledged need of increased ventilation rates for odour and moisture dissipation, especially in winter when thermal comfort is prioritised to the detriment of ventilation. On top of the lack of exhausting system, the sealing of chimneys hampers the necessary ventilation in the cooking and heating area.

A strong correlation between the survey and the monitoring results was found in that all interviewees identified cooking and heating, and lack of adequate natural ventilation as the leading sources of IAQ decline. 70% reported excessive winter RH levels, moisture, and water infiltration as the second leading cause of odours. Hence, measures focusing on promoting moisture control, increasing natural ventilation rates and reinstating adequate air exchange, along with retrofitting the building envelope and chimneys, would be pivotal for restoring a healthy indoor air environment.

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 (CEN-European Committee for Standardization 2019) are analysed. Based on the daylight provision calculation method in EN 17037, the target daylight factor (D_T) was computed as follows:

$$D_T = (E_{in}/E_{ext})*100 \qquad (2)$$

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 the recommended values 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 the 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 also address visual comfort, with daylighting and view out amongst the criteria; 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 (BREEAM 2020).

Regarding the quality of the view out, the following criteria should be met according to EN 17037: the glazing should provide a clear and neutrally coloured view; the opening should have a horizontal sight angle 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 (RGEU 1951).

This analysis confirmed that the daylight availability is inadequate for any standard-recommended task or permanence, on top of heterogeneously distributed. The fact that the 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 Urbanisation (RMUE) (RMUE).

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: dissatisfaction with lighting (occupants' sensation regarding illuminance levels) (Barbara Gherri 2015) and tolerance index (Standardization 1995); and three categories for assessing artificial light use, occupants' view out satisfaction, and their priorities concerning a set of parameters linked to façade or roof openings.

The level of satisfaction inferred revealed that over half of the interviewees (57%) are actually slightly satisfied with their daylight availability, while 37% expressed slight dissatisfaction, and only 6% reported being very dissatisfied, mainly in wintertime. Tolerance-wise, 37.5% of occupants found the daylight availability slightly difficult to bear, versus 25% for moderately bearable and 19% for perfectly bearable. Only 6.25% reported high difficulty in bearing it and 12.5% felt neutral. These findings suggest a weak correlation between the level of dissatisfaction and the previous DF estimation, as the perception and satisfaction with poorly-lit spaces highly surpassed the authors' expectations. Though counterintuitive, these results highlighted the determinant role of cultural backgrounds in daylight acceptability and expectations, on top of the age of the population sample. 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, may that be 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 emphasised 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 behaviours of the 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 behaviour 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 additionally be considered an adaptive coping behaviour.

4.4. Noise level

A favourable acoustic behaviour was found, providing sufficient sound insulation from external noise pollution (over 65 dB). The indoor daytime maximum decibel was 55 dB and the lowest 38 dB, with median outdoor-indoor sound level differences of 10 dB. A more in-depth analysis using ISO-noise indicators was beyond the purview of this research and no further data exploitation was carried out since the preliminary results suggested no adverse effects on the occupant's comfort and well-being (Europe 2018).

4.5. Impact of passive strategies

The main climate-responsive strategies found in the literature on vernacular dwellings in this region, i.e. passive cooling, solar radiation shielding and minimising summer heat gains, were mentioned in 3.1.3.. Additionally, the analysis conducted allowed to pinpoint the key passive strategies in view of their effect on thermal performance (Table 4).

Table 4. 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 stabilisation • 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 behaviour and stability. It additionally helps mitigating the effects of poor indoor natural illuminance.
- Nighttime natural ventilation with mechanical ventilation was singled out as the best performing strategy, leading to enhanced thermal performance and stability, and shorter thermal amplitudes than the most common strategy, i.e. daytime natural and mechanical ventilation. The implementation of nighttime ventilation abated due to safety reasons, which could be hindering thermal performance, especially through overheating.
- The relevance of the lack of windows for reducing summer solar gains and overheating was evidenced through the comparison of two dwellings with

identical solar orientation and strategies, where one had an unauthorised window and displayed significantly poorer behaviour under extreme outdoor heat.

- The dwellings' high thermal inertia and outdoor thermal wave attenuation properties were highlighted in both seasons, especially valuable during the nighttime by providing an adequate response to sharp thermal amplitudes.
- The traditional chimney's heating role was backed by its efficiency in providing indoor T_{as} over 18 ºC, even though it was dropped due to safety and maintenance 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 an inadequate climate adaptation. The occupants were exposed to winter thermal discomfort and health risks arising from cold temperatures, mouldy spaces, and airborne toxins. However, in summer even during the hottest periods, the 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 air 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

The impact of sociocultural background plays a determinant role in occupants' indoor environment perception and acceptability in heritage dwellings. This was attested in this research by their broader thermal range and acceptability of inadequate natural illuminance levels and IAQ. When analysing the indoor environment of heritage dwellings it is imperative to consider how occupancy patterns and behaviours 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 occupants experience significant winter underheating and the priority should be improving cold-related risks through accessible and efficient solutions compatible with its conservation. Moreover, a rejection of traditional efficient practices was detected in favour of less efficient measures linked to globalisation. 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' unauthorised settlements with annexed sanitation facilities connected to the water supply network.

5.2. Limitations of the study and suggestions for future work

The accuracy of the air temperature dataloggers was slightly out of range per the ISO 7726 and ASHRAE-55 2013 criteria (Table 3). Nonetheless, dataloggers with analogous ranges have been successfully employed in the thermal assessment of vernacular dwellings in the same region (Jorge Fernandes et al. 2019; Jorge Fernandes et al. 2020; Jorge Fernandes, Pimenta, et al. 2015) Additionally, the calibration time of the dataloggers was longer than expected (ISO 7726), and hence, the authors discarded the initial 10 hours of measured data, with no impact on the long-term analysis.

Furthermore, had it been available, a surface probe of thermocouple type K for long-term monitoring could have extended the surface temperature measurements to all the surfaces, especially the ceiling, in both seasons, to further the understanding of its role in the indoor thermal environment and radiant temperature asymmetry.

The three-months monitoring period chosen encompassed the hottest and coldest weeks of the year, and the analysis was developed based on worst-case scenario weeks, following the methodology of previous research in the same climate (Jorge Fernandes, Pimenta, et al. 2015; Jorge Fernandes, Mateus, et al. 2015; Jorge Fernandes et al. 2019; Rubio-Bellido, Pulido-Arcas, and Cabeza-Lainez 2016; Montalbán Pozas and Neila González 2016).

Given the occupants' advanced age, it would be interesting that future work considers the impact of inevitable 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 the indoor conditions of vernacular dwellings 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.

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Competing interests

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

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