Title: Understanding thermal comfort in vernacular dwellings in Alentejo, Portugal: a mixed-methods adaptive comfort approach

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Abstract

While a significant body of literature has been published on thermal comfort in dwellings, the particular challenge presented by vernacular dwellings in striking a balance between improving thermal comfort, energy savings, and heritage conservation has not been adequately investigated. The occupants' way of life, embodying regional cultural practices and traditional adaptive behaviours, and their unique thermal expectations, impact thermal comfort perception but are largely ignored in current comfort standards. This paper addresses this gap by evaluating the thermal comfort of vernacular dwellings in Alentejo, Portugal, based on *the Portuguese context-adapted thermal comfort model* (PTC). The work also attempts to assess the suitability of thermal comfort adaptive and steady-state methods by undertaking a comparative analysis with the PTC model results. Key findings include the broad summer thermal acceptability in the vernacular dwellings, exceeding that of regular dwellings and thermal comfort standards, and the significant winter underheating, which highlights that priority should be given to improve cold-related risks. The PTC model was found to accurately represent summer thermal comfort conditions in naturally-conditioned vernacular dwellings in Alentejo, albeit underestimating underheated hours and requiring nighttime and boundaries adjustments to improve its accuracy. Methods detailed under EN 16798 and REH (*Regulamento dos Edifícios de Habitação*/Regulation of Energy Performance of Residential Buildings) are deemed unfit to evaluate thermal comfort in vernacular dwellings, especially in summer.

Keywords: Indoor thermal comfort, vernacular dwellings, adaptive comfort evaluation, *in situ* monitoring, qualitative survey, hot-dry climate.

[1]

1. Introduction

According to the definition established by Oliver [1,2], vernacular dwellings are buildings that are linked to their environmental context and available resources, and built to meet specific needs using traditional technologies while accommodating the values, economies, and ways of life of the cultures that produce them. Due to their inherent nature, they present a specific challenge in striking a balance between improving thermal comfort conditions, energy savings, and heritage conservation [3,4]. However, specificities of these buildings, i.e. their living parameters, the occupants' way of life embodying local collective wisdom and traditional strategies, and their unique thermal expectations, affect thermal comfort perception but are largely overlooked in comfort standards [4].

While recent research has started to evaluate thermal comfort in vernacular dwellings, the bulk of this work is linked to their sustainability strategies [5,6]. A meta-analysis of 40 vernacular dwelling studies [7] highlighted the adaptive thermal comfort approach was the main method used for assessing these buildings, with the ASHRAE 55 model being the most popular (both stand-alone or combined with EN 15251). No studies adopting the updated EN 16798 were found. Furthermore, analysis findings suggested that *context-adapted thermal comfort models,* term put forth by the authors for models whose features were specifically tailored to their context (e.g. local environmental parameters, socio-cultural settings, behavioural actions, and clothing patterns) were becoming more prevalent and may potentially be better suited to studying vernacular buildings compared to existing standard models which overestimate neutral temperature.

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[1] **Abbreviations:** ANCOVA: covariance analysis; ANOVA: analysis of variance; Clo: Clothing insulation unit; df: Degree of freedom; F: F statistic; Met: Metabolic Equivalent of Task; PTC model: Portuguese context-adapted thermal comfort model; p-value: Pearson's chi-squared test; REH: Regulation of Energy Performance of Residential Buildings; R^2: Determination coefficient; RH: Relative Humidity; S_e: standard error of estimate; SVV: São Vicente e Ventosa; T_a: Air Temperature; T_{erm}: Outdoor Running Mean Temperature; T_{MRT}: Mean Radiant Temperature; T_o: Operative Temperature; Tukey HSD test: Tukey's Honest Significant Difference (HSD) test; TSV: Thermal sensation vote; V_a: Air velocity.

As such, further research incorporating field studies covering occupants' thermal comfort and behaviours along with *in situ* quantitative monitoring is therefore required to comprehensively assess thermal comfort within vernacular dwellings and verify whether current standards adequately apply to them.

1.1 Aim, objectives, and structure

The overarching aims of the present research are twofold. Firstly the study will evaluate thermal comfort in vernacular dwellings in São Vicente e Ventosa (SVV), Alentejo, Portugal, under summer and winter conditions, based on the Portuguese *context-adapted thermal comfort model* (PTC). Secondly, the study will assess the suitability of thermal comfort standard adaptive and steady-state methods, i.e. EN 16798 and REH respectively, for evaluating thermal comfort within the context of vernacular dwellings by undertaking a comparative analysis with the PTC model results.

In achieving the aforementioned aims, the objectives are therefore to:

i. examine the case studies' thermal performance based on environmental monitoring;
ii. gain insight on occupants' satisfaction and acceptability of indoor comfort conditions, and whether strategic adaptive actions are adopted to mitigate any discomfort, through occupant surveying;
iii. assess the case studies' thermal comfort based on a *context-adapted approach*;
iv. perform a comparative analysis of underheated and overheated time in reference to EN 16798 and the national Regulation of Energy Performance of Residential Buildings (REH).

2. Background

Building thermal comfort studies [8–10] mainly employ the heat balance/steady-state approach [11] or the adaptive approach [12]. **The heat balance/steady-state approach** is based on the steady-state heat transfer theory for indoor air-conditioned environments and estimates subjects' mean thermal sensation and environment dissatisfaction based on the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) indexes [11]. Various field studies [13–18] to assess the validity of the steady-state approach yielded a consensus on the discrepancy between field study results and the model's thermal comfort predictions mainly due to occupants' adaptation. Further limitations identified were linked to subjects' clothing resistance, metabolic rate and activity, the dynamic character of thermal conditions, and occupant expectations and ability to acclimatise, all of which impact comfort perception [12,19,20].

The adaptive approach, builds on the premise that occupants actively relate to their thermal environment [12,21,22], and is reflected in ASHRAE-55 [23] and EN15251 standards [24]. Even though field assessments of the adaptive approach primarily focused on office environments, studies undertaken in dwellings reported their higher thermal tolerance [8,18,25]. Furthermore, the difference in the stochastic occupancy behaviour, i.e. human-building interaction related to thermal adaptation mechanisms, was emphasised due to greater adaptive opportunities and control over dwellings' environment [26,27], and even more so in naturally-ventilated buildings. As such, the adaptive approach has been considered to be the model of choice for thermal comfort assessment of naturally ventilated-buildings [8], which encompass vernacular dwellings [4,6,26,28].

2.1 Overview of the European Standard and Portuguese thermal comfort models

A number of models have been used within the Portuguese context for thermal comfort assessment. Listed hereunder are their brief features:

- **European adaptive thermal comfort model - EN 16798:** This standard [29] replaced EN 15251:2007 and focuses on thermal environment, IAQ, lighting, and acoustics based on four categories of expectation: i. high level, recommended for elderly people; ii. normal level, for new buildings and renovations; iii. moderate level, for existing buildings; iv. values outside of the criteria for the above categories, which should only be accepted for a limited part of the year.

EN 16798 expands on EN 15251 in terms of applicability, with a lower threshold of the prevailing mean outdoor temperature (10 ºC instead of 15 ºC) and lower comfort limits (reduced by 1 ºC). Specifically, the extended boundaries for category II and III are characterised by upper limits set at + 3 ºC and + 4 ºC and lower thresholds at – 4 ºC and – 5 ºC, respectively.

- **Portuguese steady-state thermal comfort method:** The Regulation of Energy Performance of Residential Buildings (REH) employs a seasonal calculation based on climate reference data. This assumes that dwellings are permanently heated or cooled, where buildings are defined as a single zone permanently kept within a reference temperature range (18 ºC-25 ºC).
- **Portuguese *context-adapted thermal comfort model* (PTC):** The PTC is specifically tailored to Portuguese context as it was informed by indoor environmental monitoring (air temperature, operative temperature, air velocity, relative humidity) of 40 mechanically and naturally-conditioned buildings, and occupant surveying. The model proposes a thermal comfort range for both mechanically and naturally-conditioned buildings, and suggests that occupants of residential buildings may tolerate a wider temperature range than that indicated for mechanically-conditioned ones, allowing higher summer and lower winter temperatures (31 ºC and 15 ºC, respectively) to be considered, due to dwellings' high adaptability level. In this feature lied the novelty of the model, which its authors concluded to better suit the reality of the Portuguese building stock [30,31]. Additionally, it considers the strong influence of outdoor temperature on occupants' thermal perception, who may freely adapt their clothing to the thermal environment. The T_o boundaries are set at - 3 ºC/+ 3 ºC to ensure 90 % thermal satisfaction, matching the recommendation for category II buildings in EN 15251 (80 % of acceptability and normal thermal expectation level), based on the exponentially weighted outdoor running mean temperature (T_{erm}). Further conditions for the model's valid implementation are outlined in Table 4.

Even though ASHRAE or EN 15251 were a priori the obvious choice for this research due to being the most employed for adaptive thermal comfort evaluation in vernacular dwellings, the PTC model based on EN 15251 was selected [30,31]. This considered the following factors:

- Although not originally devised to evaluate vernacular architecture, the PTC model was applied in two studies [28,32] that found evidence of its adequacy to assess thermal comfort in Portuguese vernacular dwellings in the same region as the present case studies.
- It was noteworthy that retirement homes accounted for over half of the environmental monitoring database that informed the PTC model, with an elderly focus group suiting the scope of the current research.

3. Materials and methods

This research follows a mixed-methods approach integrating quantitative and qualitative data collection to comprehensively evaluate the indoor thermal comfort in vernacular dwellings in São Vicente e Ventosa (SVV). The case studies selection criteria, the as-built survey, *in situ* environmental and thermophysical monitoring were described in depth in [33]. The ensuing section describes the case study dwellings, the data collection methods employed, and assessment/analysis approaches used.

3.1 Overview of the case studies

SVV is characterised by a hot dry-summer Mediterranean climate, i.e. Csa according to the Köppen Climate Classification [34]. The case study 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.

Each of the selected 22 case study dwellings is detailed in the technical sheets in Appendix A. The typical layout of these dwellings consists of a rectangular floor plan with average dimensions of 6.00 m x 10.00 m, divided into a sleeping space and a living space, where all indoor activities take place. The 0.60 m thick heavy thermal mass walls consist of limestone and earth masonry with lime wash finish and have a thermal transmittance of 1.32 $W/m^2.ºC$ and 1.17 $W/m^2.ºC$ [33,35], for internal and external walls respectively. The high thermal stability linked to their heavy thermal mass and its symbiotic role with natural ventilation was addressed in depth in a chapter dedicated to walls of high thermal inertia in vernacular heritage [36], along with other vernacular case study dwellings, and previous research on the indoor environmental conditions of these case studies [33]. The roof is composed of single hollow clay bricks and Arabic tiles with a computed U-value of 3.13 $W/m^2.ºC$ [37], and the ground is made of ceramic floor tiles laid upon lime mortar and earth (estimated U-value 1.53 $W/m^2.ºC$ [33,35]). The large fireplace and chimney (1.73 - 1.50 $W/m^2.ºC$ [33,35]) are a significant feature of the case studies' floor and façade layout.

During the cooling season, the case studies could be classified according to five main 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%). In respect to the heating season, these were electric heating (59%), wood-based heating (14%), gas heating (4.5%), and no heating (9%).

3.2 Environmental monitoring: thermal comfort parameters

An as-built survey of all case studies, encompassing photographic records, floor plans, sections, elevations, and constructive systems was undertaken. Following this, environmental monitoring was implemented from July 5th to August 16th and from January 16th until February 27th, in 2015, entailing the following thermal comfort variables: outdoor and indoor air temperature, relative humidity, globe and surface temperature, and air velocity. An *in situ* monitoring approach [23] was adopted for outdoor and indoor temperature and relative humidity, in combination with short-term monitoring for the remaining parameters. This research refers to monitoring periods under three months as short-term monitoring, while those that exceed a three-month period as a whole are referred to as long-term monitoring [23]. The measurements complied with ISO 7726 [38] and ASHRAE 55 [23]. The methods and materials employed for the quantitative monitoring, as well as the standards complied with, were outlined in depth in [33] and the details of the measurements conducted are listed in the Appendix B. The summer and winter thermal monitoring data can be found in the Appendix C.1. and C.2.

3.3 Occupant survey

To comprehensively assess the case studies' indoor environment, a questionnaire-based survey was developed to evaluate occupants' comfort acceptability and satisfaction levels, and whether their thermal perceptions correlated with the on-site measurements. It additionally provided insight into the occupants' adaptive behaviour and its influence on the dwellings' thermal performance. The survey was based on the thermal environment point-in-time and satisfaction survey from the appendix K of ASHRAE 55 [23], combining short-term evaluation with environmental measurements and long-term comfort perception, measured on seven-point thermal sensation and satisfaction scales. Additional sections focused on occupant adaptive behaviour and identifying the source and time of discomfort. In single-person and two-person households (94 %), one survey per household was administered to a total sample of 20 respondents. In multi-person households, an individual who accurately reflected the occupancy behaviour of said dwelling was designated as the 'representative' occupant (Table 1). The representative occupants' clothing and activity level data was also documented 15 minutes prior to the measurement so that the metabolic rate or metabolic equivalent of task (in met) and the total thermal insulation (in clo) could be estimated [23], encompassing the adjustment for seated occupants in wooden chairs [23].

Prior to conducting the survey, the respondents had been sitting for more than 15 minutes and confirmed how long they had been living in the dwelling to ensure the reliability of the long-term comfort perception results. Table 2 presents the occupancy profile based on the self-reported data, as well as the occupants' average garment insulation value and metabolic rate.

3.4 Data process and analysis

Linear regression was adopted to derive the quantitative relationship between the Thermal Sensation Votes and the indoor air temperature, and the indoor operative temperature and the outdoor running mean temperature. The coefficient of determination (R^2) was determined, the hypothesis testing method Pearson's chi-squared test (p-value) was applied to verify its significance, the standard error of estimate (S_e) examined to characterise the correlation, and the homogeneity of the regression slopes was tested with a covariance analysis (ANCOVA). Furthermore, to test the differences between the thermal comfort models in their predictions of discomfort hours, a multi-factor analysis of variance (ANOVA) was run. Afterwards, the normality of residuals was tested through the Shapiro-Wilk test, which is recommended for sample sizes under 50 and was found to provide better power for a given significance through Monte Carlo Simulation [39,40], i.e. the ability to detect whether a sample comes from a non-normal distribution, and inspected visually through the respective normal plots. The homogeneity of variance of residuals was formally tested through the Levene's test of Equality of error variances. Finally, an ANOVA multiple-comparison post hoc testing, Tukey's Honest Significant Difference (HSD) test, was applied to the thermal comfort model results so as to establish pairwise multiple comparisons of the different models and determine where the significant differences occur to assess the consistency of findings.

The statistical package for social sciences SPSS v. 28.0.1.1. was used for data processing and the significance level was set at 0.05 (confidence intervals at 95 %).

3.5 Thermal comfort modelling: application of the PTC model

The application of the PTC model to the case studies involved the following steps.

1 - For the adaptive thermal comfort evaluation, the operative temperature and the exponentially weighted outdoor running mean temperature were computed. The former was estimated per the formula [23]:

$$T_o = AT_a + (1 - A)\,T_{mrt}$$

Where T_o is the operative temperature (ºC), T_a is the average air temperature (ºC), A is a function of the relative air velocity (V_a) (set at 0.5 for relative V_a under 0.2 m/s), and T_{mrt} is the mean radiant temperature (ºC).

2 - The exponentially weighted outdoor running mean temperature was obtained through the subsequent equation and based on the data for the seven previous days [23,24]:

$$T_{erm} = (1 - \alpha).[t_{e\,(d-1)} + \alpha . t_{e\,(d-2)} + \alpha^2\, t_{e\,(d-3)} + ...]$$

Where T_{erm} is the daily running mean temperature, α is a constant set at the recommended value of 0.8 [23,24] that controls the velocity at which the running mean responds to changes in the outdoor temperature, $t_{e\,(d-1)}$ is the daily mean external temperature for the previous day, $t_{e\,(d-2)}$ is the daily mean external temperature for the day before, and so on.

3 - The PTC model establishes T_o limits for naturally and mechanically-conditioned buildings, as follows:

$T_o = 0.43\ T_{erm} + 15.6$ (1) naturally conditioned

$T_o = 0.30\ T_{erm} + 17.9$ (2) mechanically conditioned

Where T_o is the operative temperature and T_{erm} is the outdoor mean temperature.

Table 1
Profile of the respondents.

Gender distribution	Average age	Household size	Educational attainment	Employment status	Income bracket
Male (43.75 %)	75.45	Single-person (44 %)	No education (6.25 %)	Unemployed (6.25 %)	Below minimum wage brac
Female (56.25 %)	75	Two-person (50 %)	Primary education. Literacy (25 %)	Pensioners (93.95 %)	(81.25 %)
		Multi-person (6 %)	Primary education. Functional illiteracy (62.50 %)		650-1000 euros bracket (12,
			Lower secondary education (6.25 %)		

Table 2
Occupancy and behavioural profile.

		Living room	Bedroom
	Activity and metabolic rate [(1)]	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 W/m^2	Sleeping: 0.7 met/40 W/m^2
Summer	Occupancy profile	07:30-23:00	23:00-07:00
	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 evenin Cross ventilation 07h00-09h00/22:00-2 No shading mechanisms apart from the
	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
	Strategies and equipment	Heating from 07:30 to 23:00/ twice-daily from 07:30-09:30 and 17h00-23h00. 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.

4. Data analysis

4.1 Environmental performance monitoring: data analysis

4.1.1 Thermal performance

During the cooling season, four strategies that occupants employed to cope with heat were identified: natural ventilation supplemented by mechanical ventilation in the early morning and evening, stand-alone natural ventilation, nighttime natural ventilation with mechanical ventilation, and stand-alone mechanical ventilation, with the first strategy being the most prevalent (40 %). The results highlighted the convective cooling potential of nighttime natural ventilation, presenting the most favourable thermal behaviour, lowering minimum and maximum temperatures by more than 1.5 ºC and 2 ºC, and shortening thermal amplitudes compared to the remaining categories.

Despite being the most used strategy, early-morning or evening natural ventilation with mechanical ventilation exhibited the least favourable thermal stability. Its hourly analysis evidenced an inadequate climate adaptation due to being conducted during poor conditions for attaining cooling comfort from natural ventilation (40 ºC outdoors), potentially exacerbating the thermal load. The outdoor-indoor heat transfer delay occurred across all categories, stressing the role of thermal mass in damping the outdoor thermal wave and avoiding excessive peaks [33,36,41]. High thermal stability (average coefficient of 0.30 [41]) took place throughout the morning until the early afternoon, especially in dwellings applying nighttime natural and mechanical ventilation, where the daily fluctuation did not exceed 2 ºC against a 14 ºC thermal jump.

During the heating season, the dwellings' indoor thermal environment exposed occupants to cold temperatures, mouldy spaces, and airborne toxins, with possible associated health risks [24,33]. Four main strategies were identified to cope with cold: electric heating, wood-based heating, gas heating, and heating off. All-day electric heating in the living room was the most common (45 %), with bi-daily electric heating underperforming compared to all-day electric and wood-based heating. The high thermal inertia of the dwellings' envelope, with heat storage and strong outdoor thermal wave attenuation capacity, was attested by the conspicuous indoor-outdoor time lag. Thermal stability coefficients confirmed very high thermal stability (0.29 [41]), bettering their summer counterpart. The performance of radiant heating systems, i.e. wood-burning stoves and fireplace, performed superiorly than convection ones, i.e. electric oil heating, even though the latter are the most diffused, providing peak temperatures near 20 ºC. Furthermore, its slow heat-release rate and lingering radiant heat effect were shown to sustain indoor temperatures at their maximum level for a couple of hours after being turned off. The unoccupied and unheated categories recorded maximum temperatures (T_{aMAX}) under the maximum outdoor temperature at all times (<10 ºC), with the unoccupied dwellings exhibiting steeper thermal amplitudes and lower minimum temperatures. The impact of thermal loads from miscellaneous heat sources, inexistent in unoccupied dwellings, could be an explaining factor for this difference. The indoor thermal variations overall reflected the reported occupancy patterns across all categories, which were used as a reference to verify any inconsistencies.

For both seasons, the difference between the inner wall surface and the indoor air temperatures (T_{as}), which peaked in the early morning in summer and during nighttime until midday in winter, was negligible. The results reveal the impact of high thermal mass walls on the modulation of surface temperatures, regulating thermal comfort by preventing sharper nighttime thermal drops. The disparities between T_{as} and mean radiant temperatures were negligible under moderate outdoor temperatures, with wider gaps during the hottest hours of the day, in line with earlier studies on the thermal performance of traditional dwellings [42–44]. A possible explanation could lie in the limited impact of radiant heat due to the lack of windows, corroborating the causal parameters identified in previous thermal assessments of traditional dwellings [45].

4.1.2 Relative Humidity (RH)

In the heating season, the unheated, unoccupied, and electrically-heated case studies had a very high indoor RH. Along with the lack of adequate ventilation, this could lead to moisture condensations and detrimental health impacts by causing microbial growth [24] and long-term discomfort [46]. Only wood-heated dwellings presented RHs under 65 %. Conversely, in summer, low to normal levels of airborne moisture were found. While the average indoor daily RH (minimum 36.4 % and maximum 50.9 %) are within EN 16798's suggested RH values for category I and II, i.e. 30-50 % and 25-60 % respectively, some days ranged between 25 %-37 %, which is quite low, yet, in line with previous vernacular research in the region [6].

4.1.3. Air velocity (V_a)

The V_a conformed to still air conditions, averaging 0.15 m/s for unsealed-chimney case studies and 0.05 m/s for sealed ones, with the latter compromising fresh-air intake [23]. Yet, a high air leakage rate through the doors and roof was denoted, with a two-fold effect: assisting in dissipating pollutants and moisture but facilitating the leakage of warm air into the dwellings while under-ventilating them, possibly contributing to summer overheating, and winter cold drafts and decreased thermal comfort.

4.2 Thermal comfort perception: occupant survey data analysis

The overall occupant survey response rate was 80 % (N = 16), meeting the ASHRAE's requirements for 20-45 survey samples.

4.2.1 Comfort acceptability and satisfaction levels: data analysis

For this analysis, the raw data was extracted from the satisfaction survey with a focus on long-term perception measured on a seven-point satisfaction scale, ranging from "very satisfied" to "very dissatisfied”. The acceptability was established by determining the percentage of occupants who responded “neutral” through “very satisfied” (0 to + 3) [23].

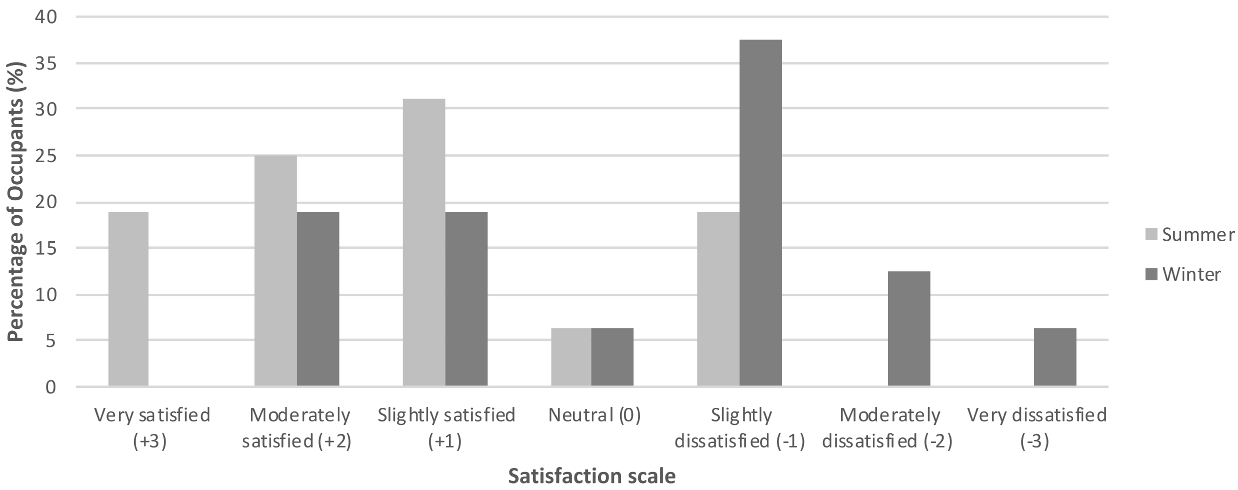


Figure 1. Indoor thermal satisfaction levels in summer and winter.

The key findings of this analysis are as follows:

- ***The high summer thermal acceptability rate of occupants***

As seen in Fig.1, there is a mirror effect among the self-reported thermal responses between both seasons: the winter-related satisfaction responses ran from “moderately satisfied” to “very dissatisfied”, with “slightly dissatisfied” accounting for most of the focus group’s perception, while the summer satisfaction ranged from “slightly dissatisfied” to “very satisfied”, with “slightly satisfied” representing the bulk of that season’s perception. Overall, despite the large satisfaction dispersion exhibited within each season, winter is less tolerated, even with heating systems in most case studies, as their summer thermal acceptability (81 %) nearly doubled that of winter conditions (44 %).

- ***The use of wood-based heating as the sole winter strategy linked to moderate-to-high satisfaction levels***

The follow-up questions on the nature and causes of dissatisfaction aid to inform the dwellings' diagnosis and develop future interventions. Over half of the occupants perceived the dwellings to be occasionally too cold during the winter, while 10 % felt that it was often too cold, and 20 % that it was always too cold. Moreover, the thermal dissatisfaction rate largely exceeded 10 %, which is the maximum dissatisfaction linked to acceptable thermal conditions [23]. When looking at the average winter monitored temperature, i.e. 12.1 ºC for electrically-heated dwellings, the thermal perceptions reported seem logical. On top of this, it is relevant to note that the respondents who felt moderately satisfied with their winter thermal environment occupied wood-heated case studies and that 70 % of dissatisfied respondents added that had they kept the fireplace as a heating system they would have been "very satisfied". As for the wintertime sources of discomfort, indoor humidity and dampness, drafts from doors and chimneys, and water infiltrations were singled out with major consensus (90 %). The average 75 % of indoor RH registered substantiated the reported excessive humidity and the as-built survey corroborated the substantial cold air infiltration due to the lack of envelope airtightness, as stated in the monitoring analysis.

- ***Broader occupant summer thermal comfort ranges***

In summer conditions, the respondents that reported dissatisfaction either felt that their indoor environment was often too hot (50 %) or occasionally too hot (50 %), with the afternoon (after 14:00) and evenings (after 17:00) being the most troublesome time. The occupants attributed this discomfort to lack of air movement and windows, and overexposure to direct solar radiation. Nonetheless, as mentioned earlier, there is a high summer thermal acceptability rate, which would suggest that T_{as} fluctuate within a comfortable range and yet, the monitoring results indicated otherwise: with an average 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. This points to the focus group displaying a broader summer comfort range than the average tolerance, exceeding the maximum threshold set in the national regulation at 25 ºC [47], 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 [24].

These results are in line with previous vernacular dwellings studies [4,28,48,49] and should be framed within the rural vernacular socio-cultural context and thermal expectations of inhabitants, as these bear influence on thermal comfort acceptability [50]. It should be noted that previous studies in this field found that while the elderly had a higher sensitivity to extreme thermal conditions [50,51], age had a negligible impact on thermal comfort preferences [51].

4.2.2 Point-in-time survey: statistical data analysis

A linear regression analysis was undertaken to investigate the relationship between the occupants' thermal sensation votes (TSVs), based on the ASHRAE's scale from "hot" (+ 3) to "cold" (- 3), and the point-in-time monitored data of the indoor and outdoor T_{as}, and illustrated in the scatter plots in Fig. 2 and 3. Due to the lack of availability of as many globe thermometers as case studies, the point-in-time survey retrieved the indoor T_{as} alongside the occupants' thermal perceptions, which was the basis for the linear regression. A summary table characterising the TSV-T_a relationship with the determination coefficient (R^2), Pearson's Chi-Squared value (p-value), and the Standard Error of Estimate (S_e) can be found in the Appendix D.

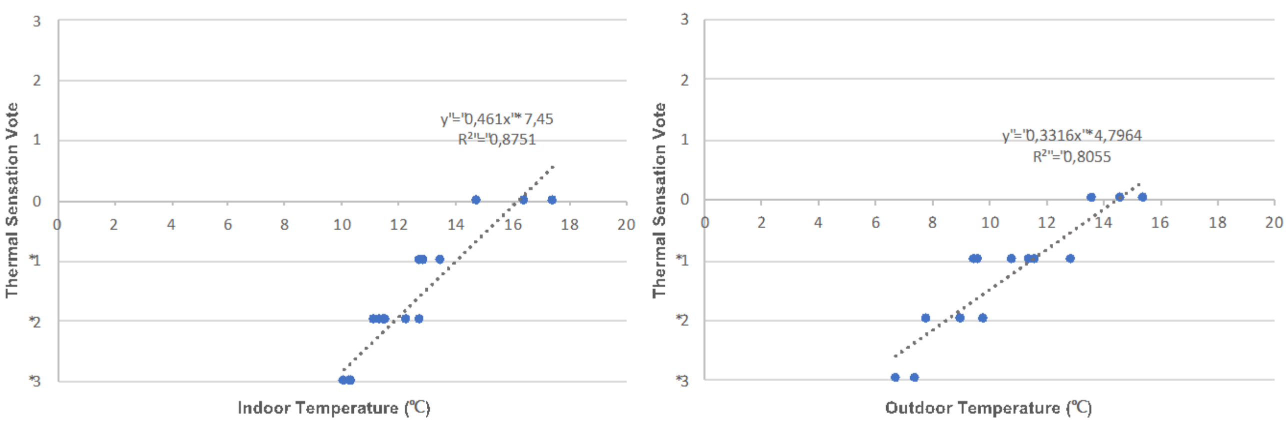


Figure 2. Point-in-time survey data: side-to-side correlation between TSVs and indoor (left) and outdoor air temperatures (right), in winter.

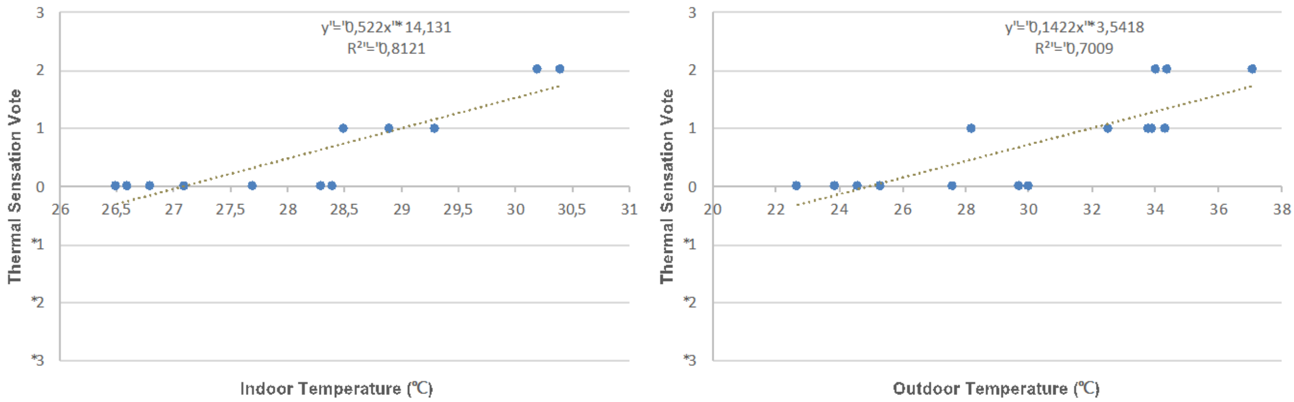


Figure 3. Point-in-time survey data: side-to-side correlation between TSVs and indoor (left) and outdoor air temperatures (right), in summer.

In spite of the limited sample data for this particular study, the analysis of the survey data pointed to strong and statistically significant correlations between the survey data and the point-in-time monitored data, with relatively small predicting error. Specifically, the key findings of this data analysis are as follows:

- ***A strong and statiscally significant correlation, with small standard error, between occupants' thermal sensation votes and point-in-time monitoring data, especially for winter***

The winter correlation is stronger than that of summer for both indoor and outdoor temperatures; the estimated equation relating TSVs and indoor temperatures is as follows:

$$TSV = \underset{(0.047)}{0.461}\, T_a - \underset{(0.590)}{7.450},\ R^2 = 0.875, S_e = 0.394$$

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 thermal sensitivity, i.e. the slope of the regression line, was 0.461 ºC^{-1} for the indoor winter correlation, meaning that for each 1 ºC in T_a, TSV increased by 0.461 units of scale. The R^2 value of nearly 0.9 implies a very strong positive correlation, which is statistically significant (p-value < 0.001, the variable association is significant when p-value is inferior to 0.05), and with a quite low S_e (0.39). In being a positive correlation, the TSVs is observed to increase proportionally to the T_o. For its part, the TSVs and the outdoor temperature displayed a stronger correlation coefficient than its summer counterpart, and is characterized by the following estimated equation:

$$TSV = \underset{(0.044)}{0.332}\,T_a - \underset{(0.478)}{4.796},\ R^2 = 0.805,\ S_e = 0.425$$

As can be seen, there is anew a very strong linear relationship ($R^2 = 0.8$), which is statistically significant (p-value < 0.001) and with a low S_e (0.43). The occupants reported feeling comfortable under indoor temperatures as low as 15 ºC and up to 17.5 ºC, which was the T_{aMAX} registered during the point-in-time surveys, with the occupant survey-based neutral temperature being estimated at 16.2 ºC. This also points to a broader thermal tolerance, below the threshold established at 18 ºC in the national thermal regulation [47] and the EN 16798 for category III buildings [24]. Furthermore, this analysis suggested that the occupants were sensitive to a greater degree to winter's indoor temperature variations than in summer; while it would take a variation of over 3.5 ºC to alter the occupants' summer thermal perception, 2 ºC would suffice during winter. Further statistical analysis of covariance (ANCOVA), allowed the checking of the assumptions of linearity and homogeneity of regression slopes. The variables' linearity was verified through visual inspection of the scatter plots, confirming their linear relationship which could be explained by an elliptical shape. Moreover, testing the assumption of homogeneity of regression slopes suggested that there was no statistical difference between the regression slopes, therefore accepting the first null hypothesis of ANCOVA that regression slopes are similar, and an F test indicated that there was no interaction: F (19, 12) = 0.959, p-value = 0.547.

The summer estimated equation relating TSVs and indoor T_{as} is described as:

$$TSV = \underset{(0.067)}{0.522}\,T_a - \underset{(1.891)}{14.131},\ R^2 = 0.8121,\ S_e = 0.326$$

The values evidence a very strong ($R^2 = 0.81$) and statistically significant (p-value < 0.001) positive correlation, with the lowest S_e (0.33) regarding the indoor variables studied. Although, the summer indoor R^2 is lower than that of winter, all results were equally statistically significant. Despite the strong impact of outdoor temperatures on thermal perception in naturally-ventilated buildings, when exploring the correlation between the TSVs and the outdoor T_{as}, the correlation is borderline between moderate and strong (R^2 decreased to 0.7), albeit still statistically significant (p-value < 0.001) and a relatively low S_e (0.45), via the estimated equation:

$$TSV = \underset{(0.025)}{0.142}\, T_a - \underset{(0.747)}{3.542},\ R^2 = 0.701,\ S_e = 0.449$$

A possible explanation could lie in the sharp indoor-outdoor temperature gap brought about by the high thermal inertia of the dwellings, providing a cooler indoor environment and facilitating a more comfortable perception during extreme summer heat. Additionally, the occupants display low thermal expectations and a broad thermal acceptability of summer indoor temperatures that exceed average comfortable ranges, which is in accordance with the indoor neutral thermal range and acceptability previously found for elderly people [31]. Additionally, we verified the linear relationship between the variables through the ANCOVA results and anew no statistical difference was found between the regression slopes, meeting the assumption for homogeneity, and an F test indicated that there was no interaction: F (13, 18) = 1.231, p-value = 0.335.

- ***Wider neutral temperature range of vernacular dwellings***

Based on the survey data **the summer indoor neutral temperature range** was estimated between 26.5 ºC- 29.4 ºC and the neutral temperature 27.9 ºC. Thus, there is a mismatch between the expected summer thermal perceptions based solely on the monitored data, whose findings indicate that the operative temperatures exceed comfortable thresholds, and the occupants' actual thermal perception [4,52]. Furthermore, there was possible contamination of the point-in-time survey results with some feedback incongruities related to their ability to recall acceptability and satisfaction of the seasons as a whole.

In winter, the occupant survey-based neutral temperatures were higher and lower than those found in previous studies on thermal comfort in Portugal [31], which further corroborates the wide spectrum of thermal tolerance in vernacular dwellings compared to conventional dwellings.

4.2.3 Occupant adaptive behaviour

- ***Occupant dissatisfaction with personal environmental control***

Occupant adaptive behaviour, which is strongly interrelated with thermal comfort perception, has been recorded to further the understanding of its influence on the indoor environment and explain any atypical data fluctuations. The focus group findings confirmed that the occupants' adaptive behaviours were perceived as more limited during winter, mainly encompassing personal environmental control measures, i.e. wearing additional garment layers and bed clothing for increased insulation (Table 2), hot water bottles and beverages, and environmental adjustments such as turning the heating on (86 % of case studies). Given the close link between the occupants' perceived personal control over their environment, their adaptive behaviours, and subsequent thermal perception [53], it is not surprising that the heating season, where most occupants are dissatisfied with thermal environmental conditions, had a lower level of perceived environmental control. During summer, coping strategies ranged from operating the wickets or doors for natural ventilation to mechanical ventilation with fans and sitting in outdoor shaded spaces. Interestingly, the occupants failed to identify wearing fewer garments as an adaptive opportunity during summer.

Even though the occupants' wide thermal tolerance points to the relevance of their adaptive behaviour, particularly during summertime, the dwelling envelope is mentioned as a hindrance to its implementation, emphasising dissatisfaction with their degree of environmental control.

4.2.4 Operative and outdoor running mean temperature: statistical data analysis

Prior to discussing the adaptive thermal comfort evaluation of the case studies, the authors examined the relationship between the mean T_{os} and the T_{erms}, for the three most representative categories per season: wood-based heating, electric heating, and no heating system in the heating season, and natural ventilation, natural and mechanical ventilation combined, and nighttime coupled with mechanical ventilation in the cooling season (Figure 4) through a linear regression analysis. Table 3 displays the correlation parameters for two weeks of data.

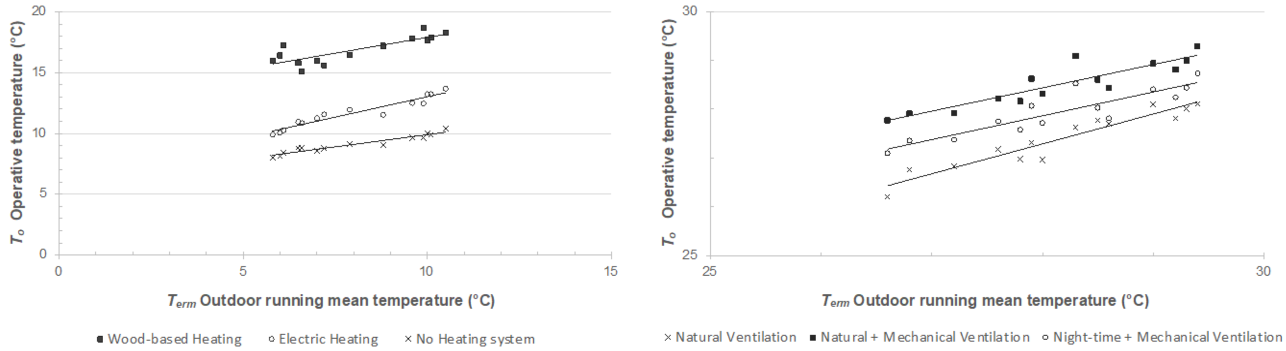


Figure 4. Correlation between the mean operative temperatures and the outdoor running mean temperatures, in the heating season (left) and in the cooling season (right).

Table 3

Correlation parameters between the operative and the outdoor running mean temperatures obtained by linear regression, in winter and summer for each representative category.

Season	Case study category	**T_o = A.T_{erm} + b**		**R^2**	**p-value**	**S_e**
		A	b			
Summer	Natural Ventilation	0.58	11.65	0.91	<0.001	0.28
	Natural + mechanical Ventilation	0.48	15.05	0.82	<0.001	0.40
	Nighttime + mechanical Ventilation	0.51	12.95	0.80	<0.001	0.42
Winter	Wood-based heating	0.52	12.71	0.68	<0.001	1.03
	Electric heating	0.51	07.87	0.86	<0.001	0.68
	No heating	0.40	05.90	0.92	<0.001	0.52

A: coefficient of T_{erm}, the slope of the regression line, how much T_o changes for each change in T_{erm}; p-value: Pearson's chi-squared; b: constant, equals the value of T_o when the value of T_{erm} = 0; R^2: Coefficient of determination; S_e: Standard error of estimate; T_{erm}: Running Mean Temperature; T_o: Operative Temperature.

The key findings of this analysis are:

- ***Very strong and statistically significant correlation between mean operative and outdoor running mean temperatures***

To start with, very strong correlation coefficients were found for fully naturally-conditioned dwellings, specifically, summer naturally-ventilated dwellings (R^2 = 0.91) and winter unheated dwellings (R^2 = 0.92), both statistically significant (p-value < 0.001). These high R^2 would indicate a very good fit for the model, and the low S_e (0.28-0.50) would imply that the neutral temperature would be estimated with a good degree of accuracy, i.e. a margin of error of 0.56 ºC for the best-case scenario. All remaining categories displayed a strong correlation except for the wood-based heating one, with a moderate (R^2 = 0.68) but still statistically significant (p-value < 0.001) positive correlation and the highest S_e of all equations. The effect of coupling radiant wood-based heating with high thermal inertia on indoor temperature and thermal perception has been previously established in this research and it would be reasonable to assume that in wood-heated spaces indoor temperatures have a stronger impact on occupants' thermal perception than outdoor running mean temperatures. As for the remaining mechanically-conditioned dwellings, a strong (R^2 = 0.86) and statistically significant (p-value < 0.001) correlation was found, which aligns with previous Portuguese research [31] but challenges the premises of current adaptive standards, where indoor operative reference design values are suggested for spaces with active conditioning systems. As for the summer, the strong and statistically significant (p-value < 0.001) correlation between T_{os} and T_{erms} in dwellings combining natural and mechanical ventilation was akin to that of those using nighttime natural and mechanical ventilation, i.e. R^2 = 0.82 and 0.80, respectively. These follow the very strong and statistically significant R^2 value yielded for natural ventilation alone at 0.91, for which the widest summer comfort range can be found (26.3 ºC - 28.1 ºC). This evidences the dependence of operative temperature on outdoor running mean temperature, in other words, the strong impact of outdoor conditions on the indoor thermal environment and perception in naturally-conditioned dwellings: specifically, for each 1 ºC increase of outdoor sunning mean temperature, the operative temperature increased by units of scale for this conditioning mode. Additionally, the

ANCOVA revealed that there was no significant difference between the summer regression slopes ($p = 0.718$) while the winter regression slopes rejected the null hypothesis of homogeneity suggesting statistically significant differences ($p < 0.001$).

- ***Estimated summer neutral temperature matches point-in-time survey results***

The neutral temperature ranges predicted from the equations in Table 3 exhibited a lower limit (15.7 ºC) that exceeded the 15 ºC-threshold estimated on the point-in-time survey, pointing anew to the importance of including a qualitative approach in thermal comfort evaluation. Wood-based heating was once more linked to the most comfortable indoor thermal environment, which agrees with the occupants' thermal satisfaction levels, followed by electric heating. This analysis corroborates the broad thermal tolerance established, well below the thermal comfort threshold of 18 ºC in the national REH [47] and EN 15251 for category III buildings [24].

- ***Slight winter overestimation but overall good concordance with occupants' perception***

The overall neutral temperature range estimated based on Table 3 stands between 26.3 ºC and 29.2 ºC, matching the point-in-time survey range (26.5 ºC-29.4 ºC). The estimated neutral temperature (27.9 ºC) and the survey neutral temperature (27.9 ºC) also seem to be in concordance, and overall, it would be fair to say that there is a good agreement between the data in Fig. 4 and the occupants' feedback.

5. Results and discussion: adaptive thermal comfort evaluation of the case studies

5.1 Thermal comfort evaluation according to the Portuguese *context-adapted thermal comfort model*

Table 4 below compares the scope of the PTC model to the case study conditions. A few out-of-range parameters were identified, these include the metabolic rate of the cooking and house cleaning activities, which was set at 2.0 met/115 W/m^2 based on the value given in ASHRAE 55-2020 compared to the 1.0-1.3 met in the PTC model. The fact that the field study informing the PTC model included few conventional residential buildings and the retirement homes did not encompass cooking or cleaning activities may offer an explanation. Similarly, the winter nighttime clothing thermal resistance, computed as 1.5 clo based on ASHRAE 55-2020, slightly exceeds the model's winter 1.4 clo, which could easily be explained by the model being based on morning and afternoon short-term measurements and not contemplating nighttime thermal comfort needs. These disparities do not hinder the model's application to our case studies, but rather have implications regarding discomfort hours, which will be discussed in detail in the following section.

Table 4
Portuguese *context-adapted thermal comfort model* conditions [31] versus case study conditions.

	Ranges required for model implementation	**Case study conditions derived from monitoring**
Metabolic rate (1)	1.0 met to 1.3 met	Seated, quiet/watching TV: 1.0 met/60 W/m^2)/ sewing: 1.0 met/55 W/m^2 Miscellaneous (cooking, house cleaning): 2.0 met/115 W/m^2 Sleeping: 0.7 met/40 W/m^2
Clothing thermal Resistance (2)	0.4 clo (summer) to 1.4 clo (winter)	Summer: 0.54-0.57 clo (living room) - 0.42 clo (bedroom) Winter: 1.14 clo (living room) - 1.50 clo (bedroom)
Air velocity (V_a)	0 to 0.6 m/s	Average 0.15 m/s for the unsealed-chimney case studies and 0.05 m/s for the sealed ones.
Operative temperature	10 ºC to 35 ºC	Winter: 11.0 ºC to 15.5 ºC (3) Summer: 26.4 ºC to 28.5 ºC (3)
Exponentially weighted outdoor running mean temperature	5 ºC to 30 ºC	5.8 ºC to 29.4 ºC

(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) Range of average values for operative temperatures, including the category without heating in winter.

5.2 Application of the PTC model to the case studies

The daily correlation between the operative temperatures and the exponentially weighted outdoor running mean temperatures with the thresholds of the PTC model was examined using two weeks of data of the selected case studies. As previously mentioned, the comfort boundaries were established at - 3 ºC/+ 3 ºC to ensure 90 % of thermal satisfaction, which matched the recommendation for category II buildings in EN 15251 (80 % of acceptability and normal level of thermal expectation). EN 15251 has since been replaced by EN 16798, and the boundaries of category II have expanded to - 3 ºC/+ 4 ºC, as described in further detail in the next section. The following analysis will consider firstly the original model boundaries, after which adjustments to said boundaries are discussed. Moreover, while the model was based on short-term measurements, our study had enough data to present an hourly analysis (Fig. 5), which was deemed more relevant.

First off, the comfort temperature range estimated by the model and linked to naturally-conditioned dwellings, i.e. 13 ºC to 31.2 ºC, stands out in comparison to that of mechanically-conditioned ones, i.e. 15.2 ºC to 29.9 ºC, exceeding it by 3.5 ºC, and hence suggesting an overall wider thermal tolerance in naturally-conditioned spaces in both summer and winter.

The main findings include:

- ***Higher winter underheating percentage compared to occupant reports***

From the overlay of the winter data with the model's comfort thresholds, it is evident that unheated dwellings, as well as electrically-heated ones, are far out of the comfort boundaries for 90 % thermal satisfaction. Those using wood-based heating, however, partially stand within the thermal comfort range predicted by the model. These preliminary findings are aligned with the previous monitoring data analysis.

When examining the hourly results in Fig. 5, over 190 underheated hours were found, roughly equivalent to 50 % of the two-week span, versus 47 % of hours within the thermal comfort range. It is significant that the most thermally comfortable case studies spend 50 % of two weeks below the estimated comfort threshold, with the daily average analysis only tipping the scale further towards discomfort: 60 % of daily hours, or 14 hours, are estimated to be underheated and thus spent under uncomfortable conditions. As such priority should be given to improve cold-related risks and discomfort through accessible and efficient solutions

- ***No summer overheated or underheated daily hours estimated for natural ventilation***

During the cooling season, both natural ventilation and nighttime natural ventilation combined with mechanical ventilation stand for the most part within the predicted thermal comfort range. Only the category of daytime natural and mechanical ventilation partially stands outside of it. Considering the hourly results, it was noteworthy that the nighttime natural and mechanical ventilation category averaged less than 3 % of daily overheated hours, in the late afternoon and evening, and the two-week data. By the same token, naturally-ventilated environments presented less than 1.5 % of the two-week data marginally over the estimated comfort threshold, with no estimated underheated nor overheated hours per day. These results corroborate the monitoring data analysis but add nuance to it, as despite exhibiting better thermal stability performance, nighttime natural and mechanical ventilation displays more overheated hours than fully naturally-conditioned environments. Hence, the latter would provide for more comfortable spaces, which can be attributed to the model's wider limits for naturally-conditioned spaces.

- ***Significant daily overheating for daytime natural and mechanical ventilation***

Exceeding these by more than 13 times in percentage of overheated hours, the natural and mechanical ventilation presents the significant average of 40 % of daily overheated hours, i.e. more than nine hours a day over the estimated thermal comfort range, and computing approximately 130 hours for the two-week data. Yet, one could also argue that because the mechanical systems available consist of small pedestal fans, the wider boundaries linked to naturally-conditioned spaces could apply to this category, reducing the estimated daily overheating by 60 % and weekly overheating by 55 %. Overheating would still be an issue but it would be more aligned with the occupants' thermal comfort perception.

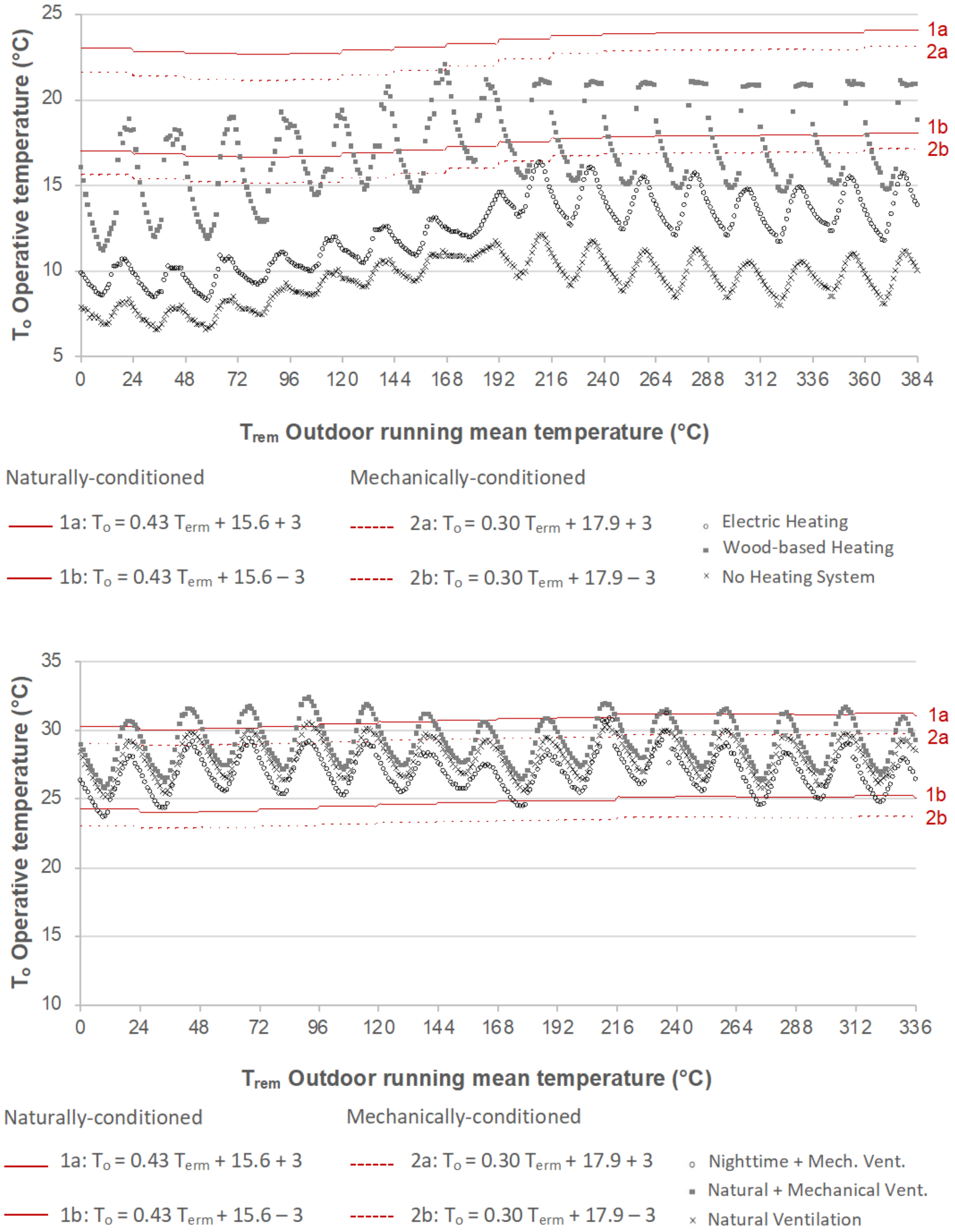


Figure 5. Hourly display of the mean operative temperatures with the comfort limits of the model, in the heating season (top) and in the cooling season (bottom).

- ***Winter nighttime adjustments to the PTC model increase the predicted underheating time***

It could be argued that the underheating time estimated by the PTC model may be overestimated since it does not include quantitative nor qualitative (clothing thermal resistance and metabolic rate data) nighttime data, and therefore does not consider nighttime thermal comfort needs. According to

ASHRAE 55-2020, an increase in 1.0 met is approximately equivalent to an increase of 0.8 ºC or 0.5 ºC in operative temperature. For near-sedentary activities, the effect of changing clothing insulation on the optimum operative temperature would roughly be 6 ºC per clo [23]. On this basis, nighttime adjustments were calculated regarding the model's thermal comfort boundaries.

As aforementioned, the case studies' nighttime clothing thermal resistance was computed at 1.5 clo [23], exceeding the model's value for wintertime, which could lower the operative temperature by 0.6 ºC. Other adaptive measures such as hot water bottles and beverages can potentially assist in lowering nighttime thermal discomfort. On the other hand, the metabolic rates experience a dip during this time, which was estimated at 0.7 met against the 1.0 met considered in the model, leading to an estimated increase of 1.8 ºC in operative temperature. Contrary to what was initially expected, the overall nighttime adjustment would entail an increase of 1.2 ºC in the optimum operative temperature, rather than reducing the predicted underheated hours by more than 15 %. This would mean spending around 58 % of two weeks below the comfort threshold and 64 % of daily hours. While some research has addressed nighttime thermal comfort evaluation [8,54–56] and the modification of Fanger's comfort model has been suggested for sleeping environments [57], current thermal comfort standards mainly focus on occupants in an awakened state. Finally, although the percentage of underheated hours could temporarily diminish due to a higher metabolic rate than that of the model, linked to daily household tasks (2.0 met), this wasn't computed into the adjustment due to the ephemeral nature of the 4 ºC reduction in operative temperature.

When comparing these findings with the occupant surveys, for which a minimum 15 ºC-threshold was reported, the electrically-heated spaces would in the second week of the sample partially reach a comfortable range per the occupants' criteria, amounting to 8 % of the plotted hours and a daily maximum of 40 % of hours within the thermal comfort range. Performing the same examination for the wood-based heating category, the average 60 % of daily underheated hours would scale down to 52 % for the first four days of the sample and to only 15 % for the remaining days, with six full days within a comfortable range. The fact that the PTC model, which is characterised by wider thermal comfort thresholds than current standards, provides a higher percentage of winter underheated hours than that stemming from the occupants' reports, stresses their low thermal expectations. Additionally, this information is relevant apropos its accuracy for evaluating thermal comfort in vernacular dwellings, as is the fact that it does not contemplate nighttime thermal comfort. On the one hand, this discussion pointed to the need for even broader thresholds for the model to be representative of winter conditions in vernacular dwellings and the specific adaptive behaviour carried for nighttime cold relief. On the other hand, this does not detract from the fact that this amount of underheated hours exposes vulnerable occupants to discomfort and health risks, as nighttime underheated hours may be underestimated by the model. All in all, priority should be given to improve cold-related risks and discomfort by focusing on accessible, efficient, and renewable solutions. These findings are also aligned with previous vernacular research in the region [6], which concluded that a heating system (wood-burning stove) was required to achieve thermal comfort conditions during the winter season.

- ***Summer nighttime adjustments to the PTC model significantly reduced daily overheating hours***

Contrary to the heating season, the adjustments in clothing thermal resistance and metabolic rate data lower the percentage of overheated hours, especially for the natural and mechanical ventilation category. The overall nighttime adjustment would lead to an increase of 1.8 ºC in operative temperature, resulting in a reduction of estimated daily and biweekly overheating to 26 % (88 hours outside the estimated thermal comfort range and an average of six daily overheated hours). Anew, the rise in metabolic rate from household tasks, and its indoor thermal loads, were excluded from these adjustments.

These results align with the thermal satisfaction and acceptability levels found, pointing to thermal comfort sensation during this season (> 80 % of respondents). The model's upper comfort threshold slightly exceeded that of the occupant survey (> 29 ºC for all categories) in the mechanically-conditioned environments and 2 ºC for the naturally-conditioned environments. This was an unexpected finding, as the occupant survey already pointed to a wider thermal tolerance in vernacular dwellings. The different activity levels between the retirement homes and the case studies could come into play in this.

- ***Applicability of the PTC model for assessing naturally-conditioned vernacular dwellings***

Based on the above the PTC model is deemed to accurately represent summer conditions in vernacular dwellings in Alentejo. This is especially true for naturally-conditioned environments, encompassing more extreme temperatures within the acceptable range due to the adaptive capacity of the occupants. These findings are in line with previous research which found that the PTC model was adequate to analyse the thermal comfort conditions in Portuguese vernacular buildings [6], however, this study suggests the PTC would be better fit specifically for summer conditions and that nighttime adjustments would enhance its accuracy. This reinforces the finding that the occupants experience a higher degree of thermal comfort in the cooling season than the heating season, and the subsequent need to target these issues through informed retrofit interventions.

- ***Impact of comfort thresholds adjustments to the PTC model***

As previously mentioned, the operative temperature boundaries were set at - 3 ºC/+ 3 ºC, matching the recommended category II in EN 15251 in which a building can be considered comfortable without mechanical means. As described in the background section, the updated standard, i.e. EN 16798, presents extended boundaries for its category II and III, with the upper limits set at + 3 ºC and + 4 ºC and the lower thresholds at – 4 ºC and – 5 ºC, respectively. In considering the outcome of adjusting the model's comfort limits the results for the daily percentage of underheated and overheated hours were compared. This included the original model boundaries, the model with nighttime adjustments, the model with the updated thresholds of categories II and III, the EN 16798 model categories, and the REH in the side-by-side bar chart in Fig. 6. The latter two will be addressed in the next section (4.4.2.).

In summertime, the comfort thresholds' adjustment according to the updated category II does not incur in any changes since only the lower comfort limit is altered. Expanding the comfort limits to those of category III was considered due to the analogy between this category's thermal expectation, i.e. an acceptable, moderate level, and the survey results. While no difference can be found for naturally-ventilated dwellings, there would be a reduction in overheating time by 50 % and 43 % for the nighttime and mechanical ventilation, and the natural and mechanical ventilation, respectively, when considering category III limits. The results found for naturally and mechanically-ventilated environments with these limits are akin to those of the nighttime adjustments, suggesting that these would more accurately represent the dwellings' summer indoor conditions.

In wintertime, the main variation can be found for the wood-based heated environments, where for category II boundaries a 13 % decrease in underheated time is yielded regarding the original model, and for category III limits, a significant decline by more than 60 % is revealed, down to 23 % of daily hours. No deviation from the reference model was found for the unheated and electrically-heated categories, at 100 % of daily underheated hours. Even with wider comfort limits aligned with moderate thermal expectations (category III), most case studies still endure unhealthy low temperatures, with the best-case scenario exceeding five daily underheated hours, with all the inherent health risks these entail.

It could be argued that due to the occupants' age, the case studies' thermal comfort should be evaluated according to more restrictive boundaries (category I), recommended for spaces occupied by very sensitive and fragile people, with a high level of expectation, including disabled, sick, elderly people, and very young children [29]. This would constitute grounds for a deeper discussion on which category would best fit the thermal comfort evaluation of not only these case studies, but vernacular dwellings overall, given the dichotomy between the sanitary criteria based on risk assessment for vulnerable population groups to extreme temperatures [58] and the actual moderate thermal expectation shaped by their socioeconomic background.

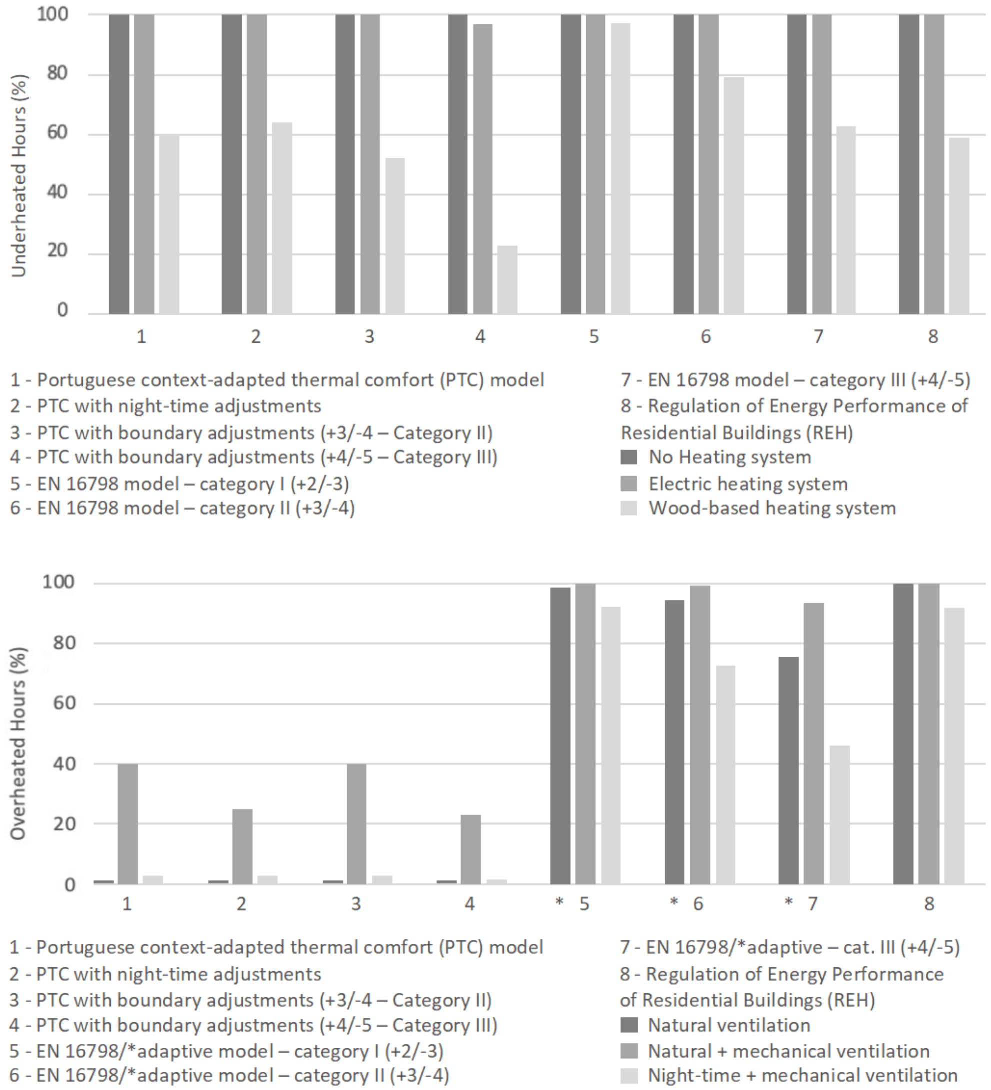


Figure 6. Side-by-side comparative chart illustrating the percentage of underheated and overheating hours, in the heating (top) and cooling season (bottom), respectively.

5.3 EN 16798 and REH comparative results

- ***Key limitations in applying EN 16798 to vernacular case studies***

For EN 16798, the case studies' exponentially weighted outdoor running mean temperature did not meet its validity requirements, i.e. 10 ºC < T_{erm} < 30 ºC, as the bulk of the winter data lies below 10 ºC. Additionally, most case studies had heating systems operating, and therefore the analysis is based on the design values of indoor operative temperature established in the standard for residential buildings with sedentary activity (1.2 met) [29]. This is a drawback compared to the PTC model, which takes a more comprehensive approach to thermal boundaries. During summer, the adaptive model of EN 16798 was applied to the naturally-conditioned dwellings.

During winter, the unheated and electrically-heated dwellings are below EN 16798's indoor operative temperature design value at nearly all times and would classify as category IV, which should only be accepted for limited time due to its cold conditions. Wood-heated case studies would qualify for category II and III for part of the time, 21 % and 37 % respectively. None of the dwellings could qualify as category I, recommended for the elderly, with the wood-heating strategy alone reaching it for 3 % of daily hours. This falls significantly below comfort requirements without active conditioning systems. Compared to the PTC model, using EN 16798 would result in a 32 % increase in underheated hours per category II boundaries and by 170 % for category III. The underheated hours for category IV would still exceed those found for the PTC model with category III limits by 26 %.

- ***Comparative results of EN 16798 versus the PTC model***

When evaluating the summer comfort conditions of naturally-conditioned dwellings, the contrast with the PTC model was striking: while no overheating was found for naturally-ventilated dwellings according to the original or adjusted PTC model, all categories of EN 16798 presented substantial indoor overheating time, i.e. 99 % (category I), 95 % (category II), 76 % (category III), 49 % (category IV) of daily hours. This is very noteworthy, as it runs counter to previous conclusions and occupants' thermal perceptions. The fact that the field studies leading to EN 16798 focused on office environments could partially explain these results, given the thermal comfort thresholds' discrepancy found regarding dwellings.

As such, it be reasonable to assume that EN 16798's adaptive thermal comfort model does not accurately reflect the case studies' indoor conditions or needs for both seasons, as the operative temperatures are largely outside of specified limits. That the occupants accept comfort temperatures well below and above those stipulated in EN 16798 would justify its boundaries extension for naturally-conditioned vernacular dwellings, particularly in summer.

- ***Comparative results of REH versus the PTC model***

In regards to REH, winter thermal comfort would only be reached during 40 % of daily hours by using wood-based heating, with the remaining time spent in underheating conditions, which is akin to the findings for the original and adjusted PTC model, as well as EN 16798's category III. Its summer counterpart, however, exhibited an overheating overestimation that exceeded that found for EN 16798 across all cooling strategies, displaying 100 % of daily underheated hours for naturally-ventilated and naturally and mechanically-ventilated dwellings, and 92 % of underheating time for nighttime and mechanical ventilation. These findings present an even wider deviation from the PTC model than EN 16798, increasing overheating time by 10000 % in naturally-ventilated dwellings, 150 % in naturally and mechanically-ventilated dwellings, and over 2900 % in dwellings implementing nighttime and mechanical ventilation, evidencing that the thermal comfort reference temperatures in the national regulation are not representative of thermal comfort conditions in vernacular dwellings. As is the case with EN 16798, this simplified calculation method does not reflect the reality of the Portuguese housing stock, as previously found in [31], all the more so when it comes to vernacular dwellings, and render it inadequate for their evaluation.

5.4 Statistical verification of model comparison

A multi-factor analysis of variance (ANOVA) was run to statistically verify the previous results, specifically to examine whether the predictions in discomfort hours differed between the thermal comfort models. Preliminary checks were completed to assess the assumption of normality and homogeneity of variance for both seasons, i.e. that residuals (residual observed value minus the predicted data value) are homoscedastic where the variance of residuals is constant, and normally distributed.

For the summer models, the Levene's test of Equality of error variances was adopted to test the null hypothesis that the error variance of the dependent variable is equal across all models. The equality of variance condition was considered satisfied as there was no violation of the homogeneity hypothesis assumption: F (23, 0) = 0.421, p-value = 0.986 (> 0.05). Complementarily, the variation of residuals presented a similar spread (Appendix E.1.), corroborating Levene's test in that no significant differences were found. A Shapiro-Wilk test indicated that the observed residuals were normally-distributed, W(24) = 0.928 and p-value = 0.088, hence meeting the normality null hypothesis. In addition, the normality plots (Appendix E.1.) showed that the residuals closely followed the condition for a true normal distribution (diagonal).

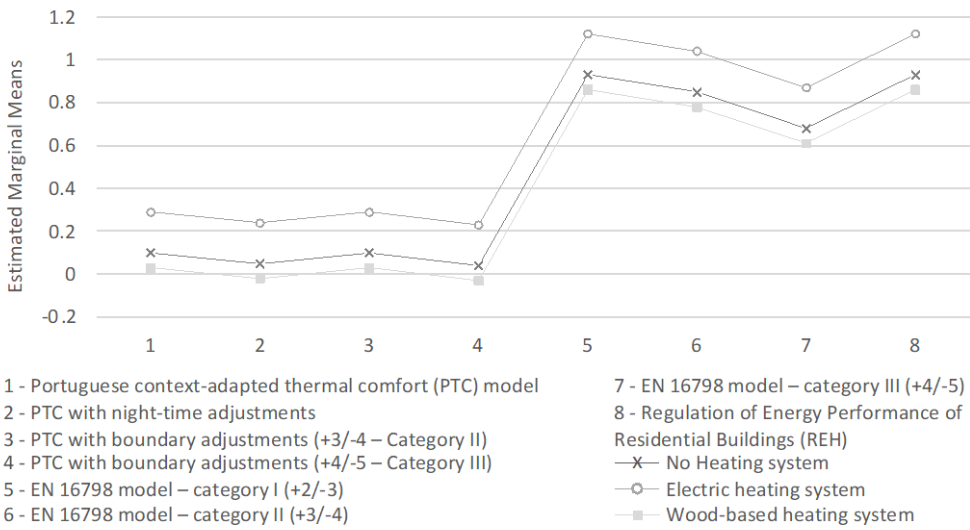
The ANOVA's test of between-subjects effects reveals that there is a significant difference between the predictive effects of the thermal comfort models (profile plot in Fig.7., p < 0.001), with no interaction between factors, while suggesting no significant difference regarding the conditioning modes (natural ventilation, natural and mechanical ventilation, nighttime natural and mechanical ventilation, p = 1.000). The prior verifications of normal distribution and variance homogeneity allow us to accept the ANOVA diagnosis and reject the null hypothesis that the models had equal effects. Subsequently, a Tukey's test, i.e. ANOVA multiple-comparison post hoc testing, was applied to the thermal comfort model results to determine where the significant differences occurred by contrasting the different models. First off, in the table of means for groups in homogeneous subsets based on observed means (Appendix E.1.), two main levels of subsets were identifiable: on the one hand, the PTC model including the original and adjusted versions, and on the other hand, the EN 16798 model and the REH, which explains the significant difference between the models found by the ANOVA and validates the prediction performance results discussed in previous sections. The multiple comparison analysis corroborated that there was no statistically significant difference in the predictive performance between the original PTC model and the PTC model with nighttime adjustments, and category II and III adjustments (p = 0.998-0.994, $S_e = 0.08$) while revealing statistically significant differences regarding the EN 16798 and REH models (p < 0.001, $S_e = 0.08$). Although the analysis of discomfort hours pointed to the nighttime and comfort limits adjustments to enhance the accuracy of the PTC model in approximating the occupants' thermal perception and expectations, the ANOVA post hoc testing suggests these differences are not statistically significant.

Yet, when we look at the mean values the ANOVA does however suggest that REH would exhibit the worst performance amongst all models (mean = 0.9733), followed by EN 16798 category I (mean = 0.9703), EN 16798 category II limits (mean = 0.8887), and EN 16798 category III limits (mean = 0.7173), with a significant difference from the PTC-based models, which is in line with previous results. Moreover, and within the best-performing group, we found that the original PTC model and the PTC model with the updated category II limits seem to have an equivalent performance (mean = 0.1433), and it could be inferred that the model's nighttime and category III limits adjustments are linked to a higher level of accuracy (means = 0.0933 and 0.0817, respectively). The conditioning mode multiple comparison detailed analysis corroborated that there was no statistically significant difference between the natural ventilated, nighttime natural and mechanical ventilation, and natural and mechanical ventilation mode, but from the means provided by the ANOVA it could still be inferred that the logic of the analysis conducted earlier remains, with nighttime natural and mechanical ventilation (mean = 0.392) and natural ventilation strategies (mean = 0.461) yielding the best thermal comfort performances.

The analysis of the winter models followed the same procedures, where the Levene's test showed that we accepted the homogeneity hypothesis assumption: $F(23, 0) = 0.378$, p-value = 0.993 (> 0.05). Complementarily, the variation of residuals presented a similar spread (Appendix E.2.), corroborating Levene's test in that no significant differences were found. The Shapiro-Wilk test indicated that the observed residuals were normally-distributed, $W(24) = 0.921$ and p-value = 0.063, hence meeting the normality null hypothesis.

However, the winter ANOVA diagnosis determined that thermal prediction was not significantly different between models ($p = 0.407$), while remaining statistically significant for the conditioning mode ($p < 0.001$). Based on the analysis conducted previously, one might suspect these differences would stem from the wood-based heating case studies. Indeed, after applying the post hoc testing and observing the homogeneous subsets for the conditioning mode alone, we identified two distinct groups: the wood-based heating mode (mean = 0.622) and the electrical and no heating modes (mean

= 0.996 and 1.000, respectively), which is aligned with wood-based heating only providing a better performance, thermal comfort-wise. This would mean that even though the PTC model suggests a thermal comfort framework for mechanically and naturally-conditioned buildings suggesting, based on fieldwork entailing environmental monitoring and occupant surveying of both types of conditioning modes, and suggests that occupants of residential buildings may tolerate a wider temperature range than that indicated for mechanically-conditioned buildings due to dwellings' high adaptability level, statistically speaking, there was no significant difference that could be ascertained between the discomfort hours predicted by the models in regard to the winter period, which aligns with the findings that the PTC model could be considered fit for accurately representing summer thermal comfort conditions in the vernacular case studies.



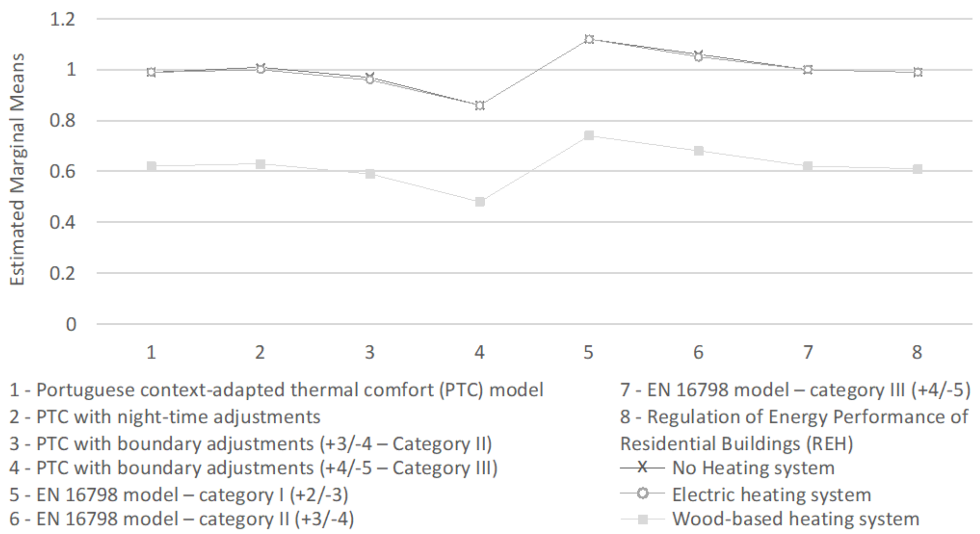


Figure 7. Profile plots illustrating the estimated marginal means for all models and conditioning modes, in the cooling (top) and heating season (bottom), respectively.

6. Conclusion

6.1 Summary of main findings

This paper detailed the evaluation of thermal comfort in Portuguese vernacular case studies. Although this research did not set out to specifically investigate the thermal comfort of an elderly population, the findings are inevitably linked with this age bracket as a by-product of the nature of the case studies analysed. Nonetheless, given the dichotomy between the occupants' thermal perception and the sanitary criteria based on risk assessment for vulnerable population groups, moderate thermal expectation, shaped by socioeconomic background rather than age, is suggested to play significantly into thermal perception in the case studies. The key findings are summarised hereunder:

- Thermal comfort perception from the occupant survey: a wider thermal tolerance compared to conventional dwellings and the national and international legislation was found, especially in summer. This was 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. The higher sensitivity to winter's indoor temperature variations and the overall dissatisfaction with winter conditions may also be aggravated by occupants' discontent over their degree of personal environmental control.
- Thermal comfort assessment with the PTC model: a wider thermal tolerance in naturally-conditioned spaces was predicted for both seasons. The PTC model provided a higher percentage of underheated hours than the occupants' reports, emphasising the cold-related risks and discomfort, with only wood-based heating partially standing within the thermal comfort range. The model could be considered fit for accurately representing summer thermal comfort conditions in naturally-

conditioned vernacular dwellings in the Alentejo region, as validated by an ANOVA diagnosis, with nighttime and mechanical ventilation combined and natural ventilation yielding the best thermal comfort performance (albeit not statistical significant different). Nonetheless, adjustments regarding nighttime thermal resistance and the model's comfort limits according to category III would enhance its accuracy and approximate the estimations to the occupants' actual thermal perception and expectations, as confirmed by a multiple-comparison post hoc testing.

- Comparative analysis of underheated and overheated time with EN 16798 and REH: EN 16798's adaptive thermal comfort model does not accurately reflect the case studies' indoor conditions and its drawbacks were outlined for both seasons. Apart from the winter outdoor running mean temperature thresholds and not accounting for mechanically-conditioned dwellings in its adaptive approach, its unsuitability was especially highlighted with substantial indoor summer overheating found for all categories of EN 16798 versus no overheating on the PTC model, suggesting that a boundary extension would be warranted for naturally-ventilated dwellings. REH's reference values are unrepresentative and inadequate to evaluate thermal comfort in vernacular dwellings, as established through the ANOVA diagnosis.

6.2 Potential for thermal comfort improvement in the case studies

Reversing the decline of vernacular dwellings requires intentional investment in improving their indoor thermal comfort. In the case studies, the priority should be improving cold-related risks through accessible and efficient solutions compatible with its conservation. Additionally, awareness-raising campaigns could be undertaken, focusing on best practices for the use, maintenance, and conservation of heritage dwellings. Some of the key actions for thermal comfort improvement 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 levels. The system for nighttime ventilation should consider the combined use of ceiling fans to help achieve a higher ventilation rate and, thus, increase its efficiency.
- 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.
- Incorporating vegetation shading to control summer excess solar gains and improve thermal performance.

6.3. Limitations of the study

The advanced age of the focus group could have introduced bias into the occupant survey results due to, due to selective memory and telescoping effect. While a large part of the survey must be taken at face value, special attention was given to identifying occupancy behaviour through the monitored data and photographic records to address possible bias. Furthermore, regarding the point-in-time survey statistical analysis, a larger sample of survey data would have been desirable to characterise the correlation with the temperature data. Nonetheless, the sample highly exceeds the work previously conducted in the area, representing a major contribution to the knowledge of Southern Portugal vernacular architecture, and as evidenced by the statistical analysis, there was a strong and statistically highly significant correlation ($P < .001$) between the variables. Moreover, the linear regression analysis was based on indoor air temperature due to limited material means. Nonetheless, the negligible differences found between the T_{mrt} and the T_{as}, on top of the successful implementation of this approach in previous vernacular thermal comfort studies [42–44], support the use of T_a as a proxy for T_{mrt} for the purpose of thermal perception analysis.

6.4. Practical implications of the study and suggestions for further work

The findings of the present research constitute a major contribution to the knowledge and preservation of Southern Portugal vernacular architecture, which had been reviewed from a predominantly heritage perspective. Quantitative research entailing monitoring in the area is scarce and [28,32,59,60] 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. Faced with this gap, the present research strove to contribute with a longer-term study of a larger sample than the bulk of previous work, by examining a never-before explored typology. It addressed the lack of robust evidence-based research on vernacular dwellings' indoor comfort by examining the case studies' thermal performance based on environmental monitoring, delving into the occupants' broad thermal satisfaction and acceptability, and adaptive actions to mitigate discomfort, through occupant surveying, assessing the case studies' thermal comfort based on a *context-adapted approach*, and performing a comparative discussion of underheated and overheated hours in reference to EN 16798 and the national regulation REH. Longer-term and larger-scale approaches to vernacular dwellings' indoor conditions are crucial to their preservation and legacy.

Furthermore, the study set forth for the first time adjustments to the *Portuguese context-adapted thermal comfort model*, further tailoring it for thermal comfort evaluation in vernacular dwellings. Fine-tuning existing models to local conditions and the development of new context-based thermal equations are required for the overall preservation of vernacular dwellings.

Additionally, this research established the statistically validated comparative analysis of the comfort predictive performance of the different models, bringing attention to the limited suitability of current comfort models for thermal sensation evaluation in vernacular dwellings, which may lead to unnecessary energy consumption.

On a final note, having conducted this research allowed to determine the following future lines of work:

- It is imperative to include an adaptive approach with less rigid thresholds into national energy standards and has been so for over a decade;
- Further research on nighttime thermal comfort evaluation is needed for a more comprehensive evaluation of dwellings;
- It would be interesting that future research reflects on what would happen thermal-comfort-wise if these dwellings would start getting inhabited by a younger population with conventional thermal comfort standards. Would they develop *context-adapted* thermal comfort expectations and similar thermal comfort acceptability?
- Moreover, the current research introduced the thought-provoking dichotomy between the sanitary criteria based on risk assessment for vulnerable population and the vernacular occupants' actual moderate thermal expectation, which is worthy of further development and very relevant for vernacular dwellings occupied by an older population bracket.
- Future research contributing to the limited Portuguese vernacular thermal comfort database is still warranted, including large sample sizes combining *in situ* monitoring with occupant surveying, to mitigate the lack of robust evidence-based research on vernacular dwellings' indoor comfort.
- Further tailoring of existing models to local conditions and the development of new context-based thermal equations are needed for preserving vernacular dwellings worldwide.

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Declaration of Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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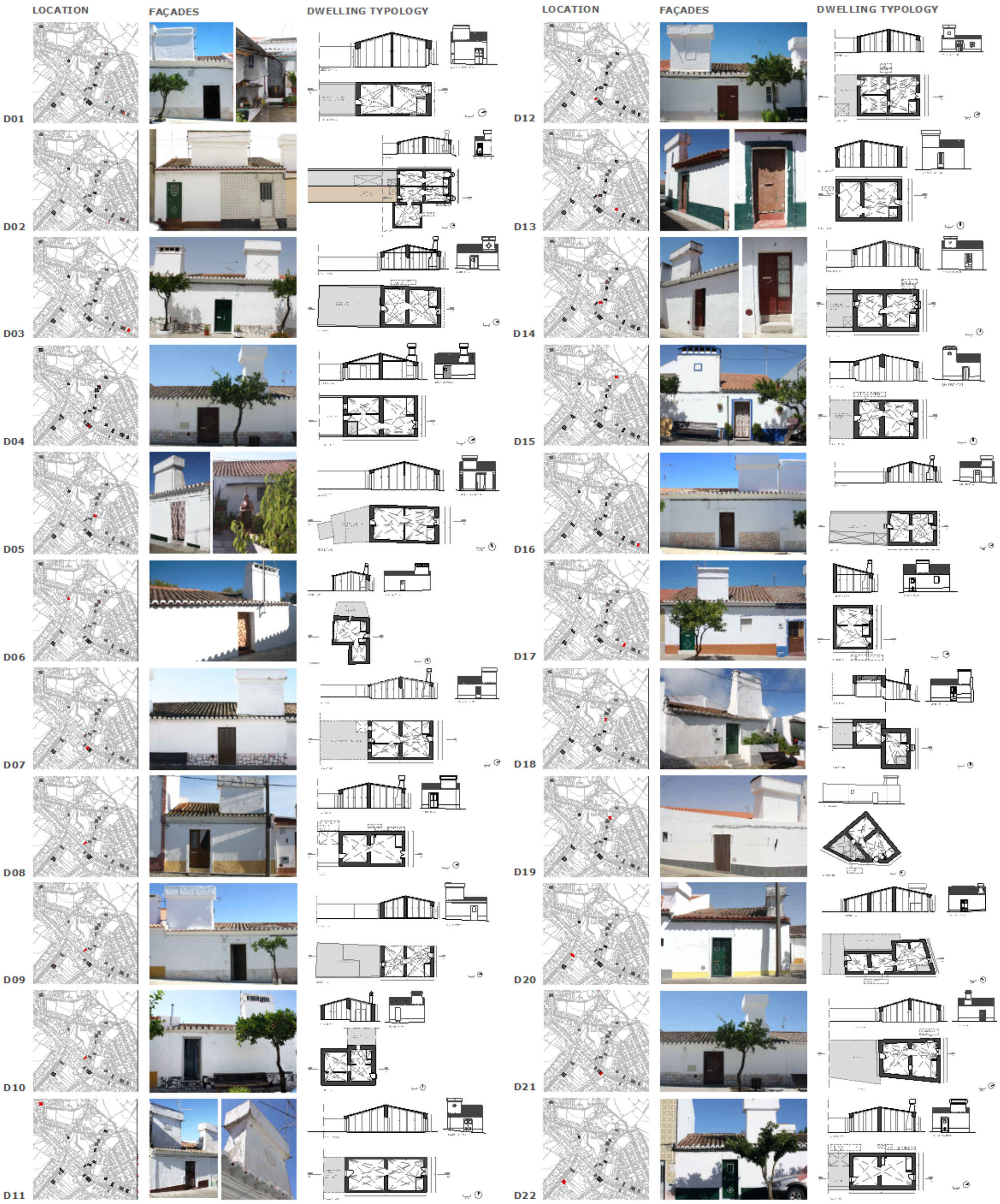
Appendix

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

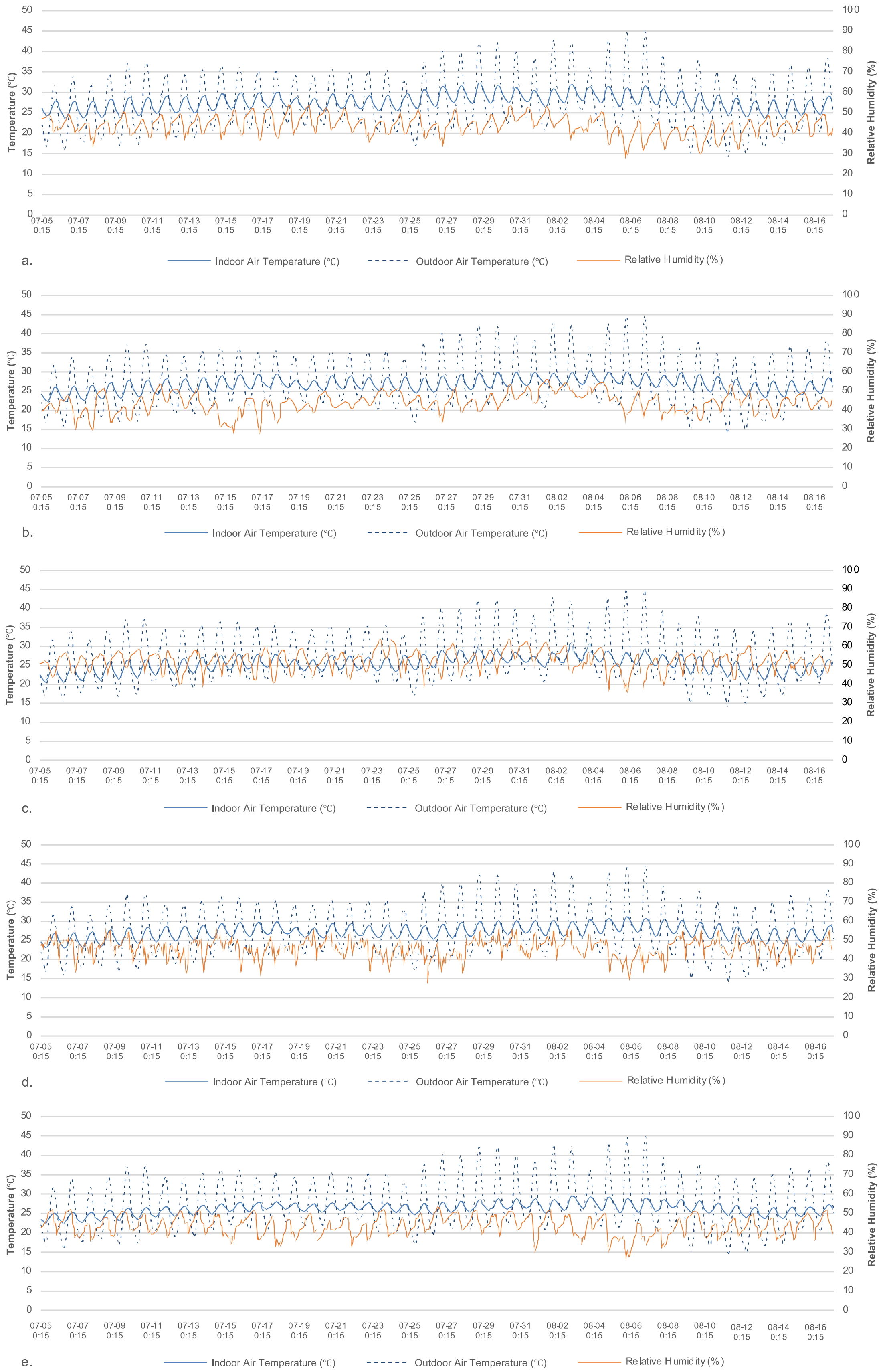


Appendix B. Details of the measurements conducted

	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 [38] 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
	Relative humidity	■			Living room, bedroom, outdoors	ISO 7726, ASHRAE 55	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
	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

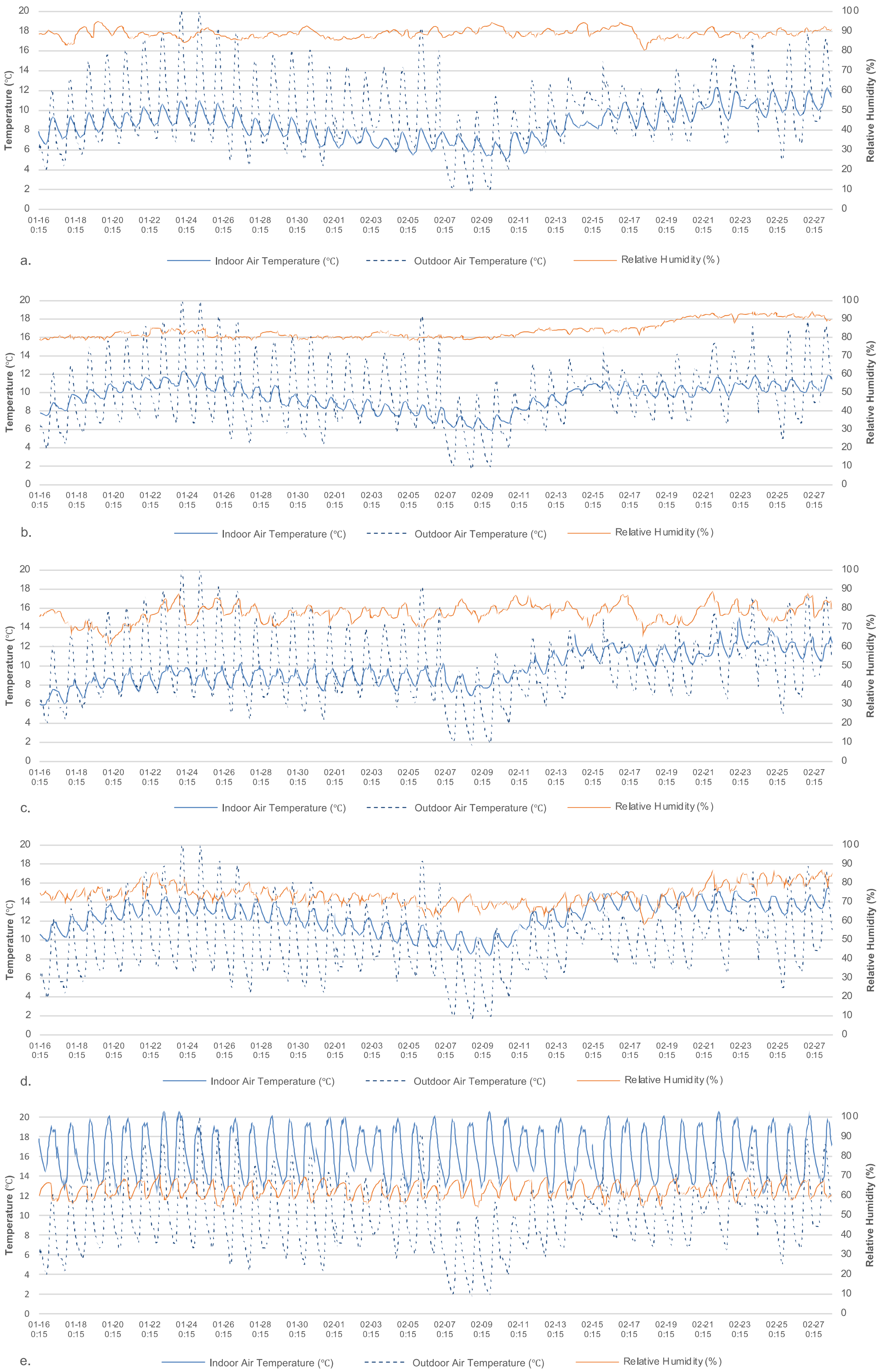
(1) Long-term; (2) Short-term; (3) Point-in-time.

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



D02 (e)

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



Appendix D. Linear regression study between the survey's thermal sensation votes (TSVs) and the indoor air temperature (T_a).

Season	Case study category	**TSV = A.T_a + b**		**R^2**	**p-value**	**S_e**
		A	b			
Summer	Indoor	0.52	- 14.13	0.81	<0.001	0.33
	Outdoor	0.14	- 3.54	0.70	<0.001	0.45
Winter	Indoor	0.46	- 7.45	0.88	<0.001	0.39
	Outdoor	0.33	- 4.80	0.80	<0.001	0.43

A: coefficient of T_a, the slope of the regression line, how much TSV changes for each change in T_a; p-value: Pearson's chi-squared; b: constant, equals the value of TSV when the value of $T_a = 0$; R^2: Coefficient of determination; S_e: Standard error of estimate; T_a: Air Temperature; TSV: Thermal Sensation Vote.

Appendix E.1. ANOVA for summer thermal comfort predictive models.

Levene's Test of Equality of Error Variances

F	**df1**	**df2**	**p-value**
0.421	23	0	0.986

F: F statistic; df1: Degree of freedom 1; df2: Degree of freedom; p-value: Pearson's chi-squared.

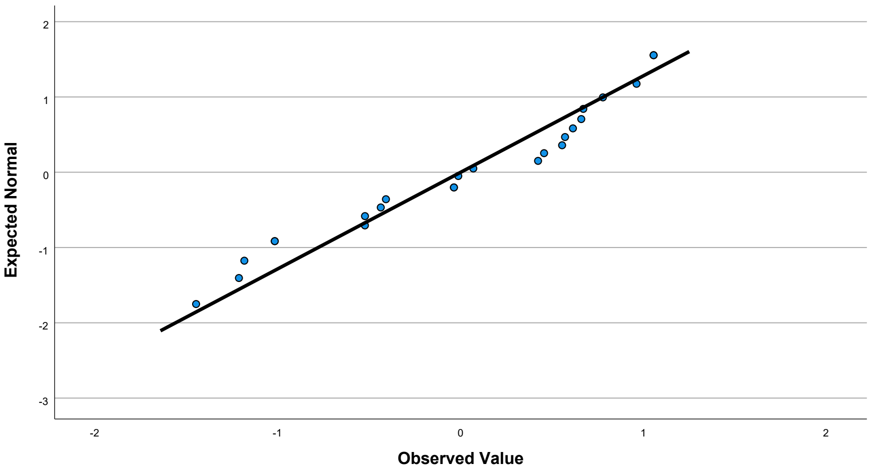
Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

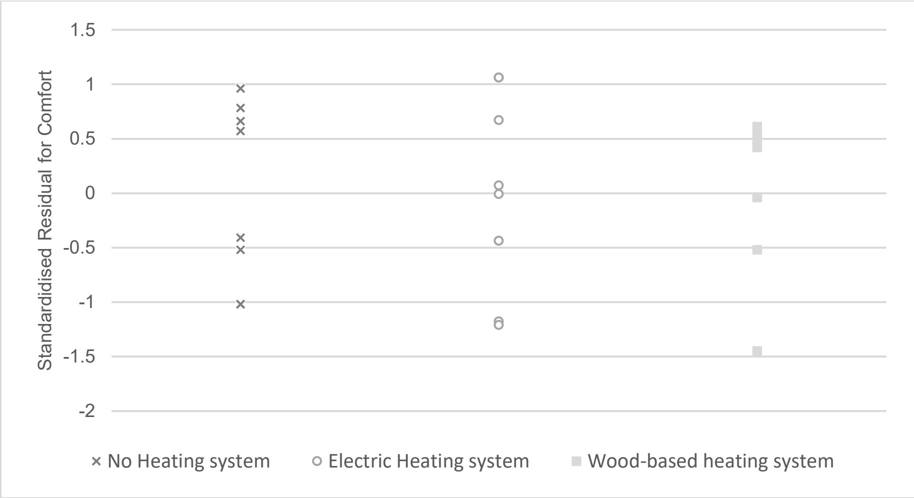
Normality tests

	Shapiro-Wilk		
	Statistic	df	p-value
Standardised Residual for Comfort	0.928	24	0.088

df: Degree of freedom; p-value: Pearson's chi-squared.
Reference value: > 0.05.

Normal Q-Q Plot of Standardised Residual for thermal Comfort





Multiple Comparisons – Tukey HSD

(I) Model	(J) Model	Mean Difference (I-J)	S_e	p-value	95% Confidence Interval	
					Lower Bound	Upper Bound
Portuguese context-adapted thermal comfort (PTC) model	2	0.050	0.083	0.998	-0.242	0.342
	3	0.000	0.083	1.000	-0.292	0.292
	4	0.062	0.083	0.994	-0.230	0.354
	5	-0.827*	0.083	<0.001	-1.119	-0.535
	6	-0.745*	0.083	<0.001	-1.037	-0.453
	7	-0.574*	0.083	<0.001	-0.866	-0.282
	8	-0.830*	0.083	<0.001	-1.122	-0.538
PTC with night-time adjustments	1	-0.050	0.083	0.998	-0.342	0.242
	3	-0.050	0.083	0.998	-0.342	0.242
	4	0.012	0.083	1.000	-0.280	0.304
	5	-0.877*	0.083	<0.001	-1.169	-0.585
	6	-0.795*	0.083	<0.001	-1.087	-0.503
	7	-0.624*	0.083	<0.001	-0.916	-0.332
	8	-0.880*	0.083	<0.001	-1.172	-0.588
PTC with boundary adjustments (+ 3/-4 – Category II)	1	0.000	0.083	1.000	-0.292	0.292
	2	0.050	0.083	0.998	-0.242	0.342
	4	0.062	0.083	0.994	-0.230	0.354
	5	-0.827*	0.083	<0.001	-1.119	-0.535
	6	-0.745*	0.083	<0.001	-1.037	-0.453
	7	-0.574*	0.083	<0.001	-0.866	-0.282
	8	-0.830*	0.083	<0.001	-1.122	-0.538

PTC with boundary adjustments (+ 4/- 5 – Category III)	1	-0.062	0.083	0.994	-0.354	0.230
	2	-0.012	0.083	1.000	-0.304	0.280
	3	-0.062	0.083	0.994	-0.354	0.230
	5	-0.889*	0.083	<0.001	-1.181	-0.597
	6	-0.807*	0.083	<0.001	-1.099	-0.515
	7	-0.636*	0.083	<0.001	-0.928	-0.344
	8	-0.892*	0.083	<0.001	-1.184	-0.600
EN 16798 model – category I (+ 2/- 3)	1	0.827*	0.083	<0.001	0.535	1.119
	2	0.877*	0.083	<0.001	0.585	1.169
	3	0.827*	0.083	<0.001	0.535	1.119
	4	0.889*	0.083	<0.001	0.597	1.181
	6	0.082	0.083	0.969	-0.210	0.374
	7	0.253	0.083	0.113	-0.039	0.545
	8	-0.003	0.083	1.000	-0.295	0.289
EN 16798 model – category II (+ 3/- 4)	1	0.745*	0.083	<0.001	0.453	1.037
	2	0.795*	0.083	<0.001	0.503	1.087
	3	0.745*	0.083	<0.001	0.453	1.037
	4	0.807*	0.083	<0.001	0.515	1.099
	5	-0.082	0.083	0.969	-0.374	0.210
	7	0.171	0.083	0.475	-0.121	0.463
	8	-0.085	0.083	0.963	-0.377	0.207
EN 16798 model – category III (+ 4/ - 5)	1	0.574*	0.083	<0.001	0.282	0.866
	2	0.624*	0.083	<0.001	0.332	0.916
	3	0.574*	0.083	<0.001	0.282	0.866
	4	0.636*	0.083	<0.001	0.344	0.923
	5	-0.253	0.083	0.113	-0.545	0.039
	6	-0.171	0.083	0.475	-0.463	0.121
	8	-0.256	0.083	0.106	-0.548	0.036
Regulation of Energy Performance of Residential Buildings (REH)	1	0.830*	0.083	<0.001	0.538	1.122
	2	0.880*	0.083	<0.001	0.588	1.172
	3	0.830*	0.083	<0.001	0.538	1.122
	4	0.892*	0.083	<0.001	0.600	1.184
	5	0.003	0.083	1.000	-0.289	0.295

6	0.085	0.083	0.963	-0.207	0.377
7	0.256	0.083	0.106	-0.036	0.548

*. The mean difference is significant at the 0.05 level.

p-value: Pearson's chi-squared; S_e: Standard error of estimate.

1: Portuguese context-adapted thermal comfort (PTC) model; 2: PTC with night-time adjustments; 3: PTC with boundary adjustments (+ 3/- 4 – Category II); 4: PTC with boundary adjustments (+ 4/- 5 – Category III); 5: EN 16798 model – category I (+ 2/- 3); 6: EN 16798 model – category II (+ 3/- 4); 7: EN 16798 model – category III (+ 4/- 5); 8: Regulation of Energy Performance of Residential Buildings (REH).

Homogeneous Subsets – Tukey HSD

Model	**N**	**Subset**	
		1	**2**
Portuguese context-adapted thermal comfort (PTC) model	3	0.082	
PTC with night-time adjustments	3	0.093	
PTC with boundary adjustments (+ 3/- 4 – Category II)	3	0.143	
PTC with boundary adjustments (+ 4/- 5 – Category III)	3	0.143	
EN 16798 model – category I (+ 2/- 3)	3		0.717
EN 16798 model – category II (+ 3/- 4)	3		0.889
EN 16798 model – category III (+ 4/- 5)	3		0.970
Regulation of Energy Performance of Residential Buildings (REH)	3		0.973
p-value		0.994	0.106

Means for groups in homogeneous subsets are displayed. The error term is Mean Square (Error) = 0.010. Uses Harmonic Mean Sample Size = 3.000 and Alpha = 0.05. N: Number of cases; p-value: Pearson's chi-squared.

Appendix E.2. ANOVA for winter thermal comfort predictive models.

Levene's Test of Equality of Error Variances

F	df1	df2	p-value
0.378	23	0	0.993

F: F statistic; df1: Degree of freedom 1; df2: Degree of freedom; p-value: Pearson’s chi-squared.

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

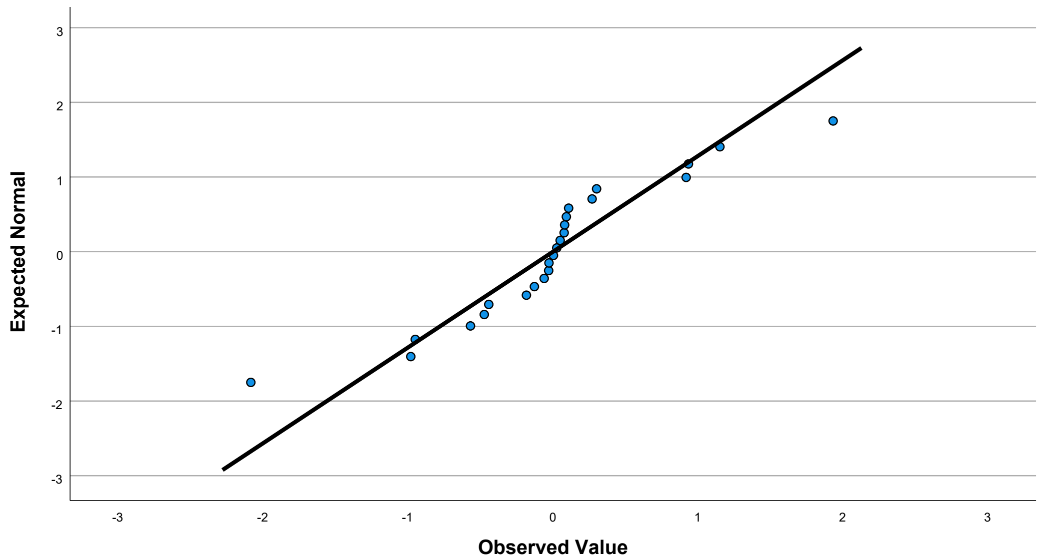
Normality tests

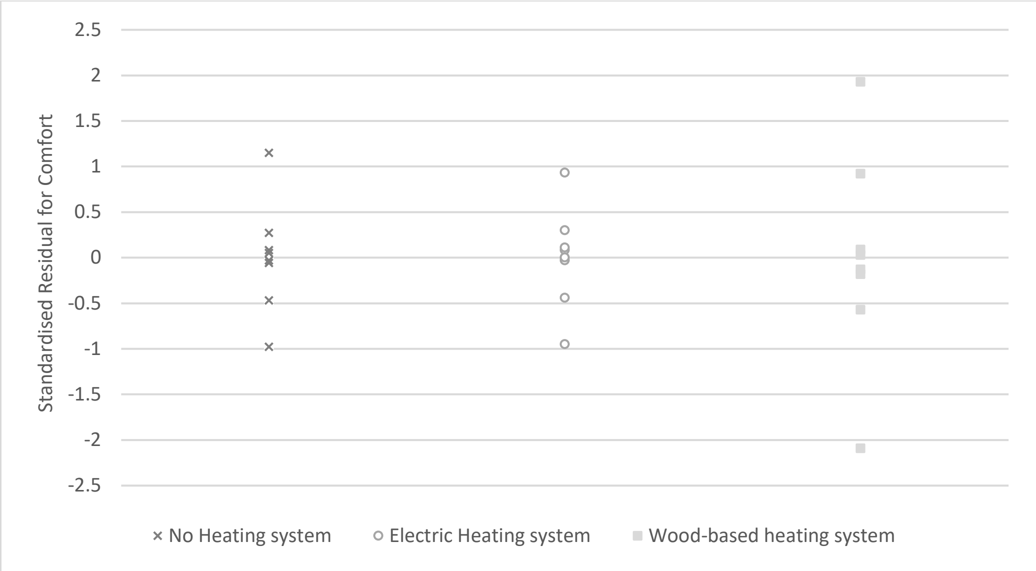
	Shapiro-Wilk		
	Statistic	df	p-value
Standardised Residual for Comfort	0.921	24	0.063

df: Degree of freedom; p-value: Pearson’s chi-squared.

Reference value: > 0.05.

Normal Q-Q Plot of Standardised Residual for thermal Comfort





Multiple Comparisons – Tukey HSD

(I) Model	(J) Model	Mean Difference (I-J)	S_e	p-value	95% Confidence Interval	
					Lower Bound	Upper Bound
Portuguese context-adapted thermal comfort (PTC) model	2	-0.013	0.098	1.000	-0.362	0.335
	3	0.027	0.098	1.000	-0.322	0.375
	4	0.133	0.098	0.865	-0.215	0.482
	5	-0.125	0.098	0.898	-0.473	0.224
	6	-0.063	0.098	0.997	-0.412	0.285
	7	-0.009	0.098	1.000	-0.358	0.339
	8	0.003	0.098	1.000	-0.345	0.352
PTC with night-time adjustments	1	0.013	0.098	1.000	-0.335	0.362
	3	0.040	0.098	1.000	-0.308	0.388
	4	0.147	0.098	0.803	-0.202	0.495
	5	-0.111	0.098	0.940	-0.460	0.237
	6	-0.050	0.098	0.999	-0.398	0.298
	7	0.004	0.098	1.000	-0.344	0.352
	8	0.0167	0.098	1.000	-0.332	0.365
PTC with boundary adjustments (+ 3/-4 – Category II)	1	-0.027	0.098	1.000	-0.375	0.322
	2	-0.040	0.098	1.000	-0.388	0.308
	4	0.107	0.098	0.951	-0.242	0.455
	5	-0.151	0.098	0.779	-0.500	0.197
	6	-0.090	0.098	0.980	-0.438	0.258

	7	-0.036	0.098	1.000	-0.384	0.312
	8	-0.023	0.098	1.000	-0.372	0.325
PTC with boundary adjustments (+ 4/- 5 – Category III)	1	-0.133	0.098	0.865	-0.482	0.215
	2	-0.147	0.098	0.803	-0.495	0.202
	3	-0.107	0.098	0.951	-0.455	0.242
	5	-0.258	0.098	0.229	-0.606	0.090
	6	-0.197	0.098	0.519	-0.545	0.152
	7	-0.143	0.098	0.823	-0.491	0.206
	8	-0.130	0.098	0.878	-0.478	0.218
EN 16798 model – category I (+ 2/- 3)	1	0.125	0.098	0.898	-0.224	0.473
	2	0.111	0.098	0.940	-0.237	0.460
	3	0.151	0.098	0.779	-0.197	0.500
	4	0.258	0.098	0.229	-0.090	0.606
	6	0.061	0.098	0.998	-0.287	0.410
	7	0.115	0.098	0.929	-0.233	0.464
	8	0.128	0.098	0.886	-0.220	0.476
EN 16798 model – category II (+ 3/- 4)	1	0.063	0.098	0.997	-0.285	0.412
	2	0.050	0.098	0.999	-0.298	0.398
	3	0.090	0.098	0.980	-0.258	0.438
	4	0.197	0.098	0.519	-0.152	0.545
	5	-0.061	0.098	0.998	-0.410	0.287
	7	0.054	0.098	0.999	-0.294	0.402
	8	0.067	0.098	0.996	-0.282	0.415
EN 16798 model – category III (+ 4/- 5)	1	0.009	0.098	1.000	-0.339	0.358
	2	-0.004	0.098	1.000	-0.352	0.344
	3	0.036	0.098	1.000	-0.312	0.384
	4	0.143	0.098	0.823	-0.206	0.491
	5	-0.115	0.098	0.929	-0.464	0.233
	6	-0.054	0.098	0.999	-0.402	0.294
	8	0.013	0.098	1.000	-0.336	0.361
Regulation of Energy Performance of Residential Buildings (REH)	1	-0.003	0.098	1.000	-0.352	0.345
	2	-0.017	0.098	1.000	-0.365	0.332
	3	0.023	0.098	1.000	-0.325	0.372

4	0.130	0.098	0.878	-0.218	0.478
5	-0.128	0.098	0.886	-0.476	0.220
6	-0.067	0.098	0.996	-0.415	0.282
7	-0.013	0.098	1.000	-0.361	0.336

*. The mean difference is significant at the 0.05 level.

p-value: Pearson's chi-squared; S_e: Standard error of estimate.

1: Portuguese context-adapted thermal comfort (PTC) model; 2: PTC with night-time adjustments; 3: PTC with boundary adjustments (+ 3/- 4 – Category II); 4: PTC with boundary adjustments (+ 4/- 5 – Category III); 5: EN 16798 model – category I (+ 2/- 3); 6: EN 16798 model – category II (+ 3/- 4); 7: EN 16798 model – category III (+ 4/- 5); 8: Regulation of Energy Performance of Residential Buildings (REH).

Homogeneous Subsets – Tukey HSD

Model	**N**	**Subset 1**
Portuguese context-adapted thermal comfort (PTC) model	3	0.733
PTC with night-time adjustments	3	0.840
PTC with boundary adjustments (+ 3/- 4 – Category II)	3	0.863
PTC with boundary adjustments (+ 4/- 5 – Category III)	3	0.867
EN 16798 model – category I (+ 2/- 3)	3	0.876
EN 16798 model – category II (+ 3/- 4)	3	0.880
EN 16798 model – category III (+ 4/- 5)	3	0.930
Regulation of Energy Performance of Residential Buildings (REH)	3	0.991
p-value		0.229

Means for groups in homogeneous subsets are displayed. The error term is Mean Square (Error) = 0.015. Uses Harmonic Mean Sample Size = 3.000 and Alpha = 0.05. N: Number of cases; p-value: Pearson's chi-squared.