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Research Article

Understanding the Impact of Thermal Performance on Thermal Comfort in Dwellings: A Large-Sample Study With a Homogeneous User Profile

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Initiatives abound for improving energy efficiency in existing dwellings stock, yet the impact in their indoor thermal comfort conditions, postretrofit performance, and comfort levels are insufficiently explored. Studies that evaluate this parameter, enabling the validation or adjustment of current policies of retrofit actions, would be essential. Thus, this paper details the thermal monitoring and behaviour of a sample of 92 dwellings with a homogeneous user profile, with the aim of identifying thermal and comfort patterns. For this purpose, continuous long-term monitoring is proposed for the comparative analysis of time series data for different climatic periods, instead of complex and individual data collection in situ. In order to correlate the envelope's thermal behaviour, buildings are characterised in terms of building typology and construction period, after which occupant behaviours are examined via questionnaires on self-reported thermal sensations and adaptive actions. Key results point to a lack of relationship between the building typology and construction period and thermal performance, even after the implementation of energy efficiency improvement measures. Additionally, thermal comfort was found to be intermittent, albeit more present in winter than summer, with a marked heterogeneity when it comes to individual habits. These facts indicate that it is necessary to include additional thermal performance driving factors for determining practical comfort implications and characterising its correlation with energy efficiency.

Keywords: building typology; energy efficiency; indoor air; monitoring; thermal comfort; thermal performance

1. Introduction

It is well known that buildings account for over a third of global primary energy use and related CO_2 emissions [1, 2]. Additionally, in the European Union (EU), the building trends in greenhouse gas emissions, that is, 36% of emissions, currently present a roadblock to attaining the goal of carbon neutrality all the while holding a major potential for mitigation [3–5] by virtue of their significant carbon intensity and rapid growth rates. What is more, according to the International Energy Agency, energy-efficient retrofit actions display the potential of bringing about an overall enhancement of energy intensity by 35% by 2050 [6]. In this sense, several policies have been established to lead the efforts towards energy-efficient and decarbonised building stock as the EU aims to improve energy efficiency by 32.5% by 2030 and reduce energy consumption to 956 Mtoe or primary energy consumption to 1.273 Mtoe [5]. Examples of these include the Directive 2018/844, which aimed at reducing greenhouse gas emissions by 80%–95% compared to 1990 and assisting the transformation of existing buildings into nearly zero-energy ones before 2050; the Clean Energy Package for All Europeans, putting forward EU 2030 objectives for competitive and decarbonised economy in accordance with the Paris Agreement; and the Energy Performance of Buildings Directive (EPBD) and the Energy Efficiency Directive (EED) are the main instruments to address the efficiency improvement of the building sector as they provide a policy framework for decarbonising the building stock [7]. Additionally, the European Green Deal sets a target of carbon neutrality by 2050, and the Renovation Wave Strategy put forth by the European Commission reinforces the EU's commitment to building retrofitting. Following these directives, each EU member state has established its specific targets and adopted energy and climate plans until 2030 [8].

Within the Spanish context, buildings are responsible for roughly 30% of the final energy consumption, just under the EU average. The national building stock, largely comprised of dwellings [9], is widely characterised as grossly inefficient, as over half of the properties were built prior to the first regulation approved in Spain, the NBE-CT-79 [10], which required a minimum level of thermal insulation in building envelopes [7]. On top of this, the retrofitting pace is still far from the 3% threshold advised by the European Commission towards achieving energy and climate targets [7]. In view of this, there is a strong interest in promoting actions to improve thermal and energy efficiency, and the government announced an energy efficiency investment by renovating half a million homes by 2026 to help achieve decarbonisation goals. As regards energy efficiency policies in the 2020–2050 Horizon in Spain, the National Integrated Energy and Climate Plan (NCEP) 2021–2030 focuses on furthering the energy retrofitting of the existing building stock, to which the long-term strategy for energy retrofitting in the building sector (ERESEE 2020) is added [11].

Key benefits of carrying out energy-efficient retrofitting actions have been published in the literature, such as energy savings, reduced emissions, health, productivity, and user satisfaction [12–15]. Moreover, the International Performance Measurement and Verification Protocol (IPMVP) proposes methods to quantify energy savings in retrofits [16], and methodologies have been published in the literature combining energy dynamic simulation and life cycle assessment for evaluating and comparing the energy and environmental effects of different refurbishment strategies of the envelope of residential EU building blocks, from micro- to macrolevel [17]. However, the actual link between these interventions and the postretrofit performance and comfort levels remains insufficiently examined [18–20] and may even fall short in terms of the positive correlation expected [21]. Residential postretrofit assessment studies have been carried out covering several typologies, most commonly resorting to building performance simulation adopting templates with historical meteorological data and theoretical calculations or adoption of standard values to appraise hypothetical postretrofit scenarios. The impact of occupancy patterns is often highlighted, as well as being a major source of uncertainty, despite being the subject of fewer studies than physical variables such as the thermal transmittance of the envelope [13, 19, 22–24]. However, retrofitting is only one driving factor as far as building energy consumption and thermal behaviour are concerned. Others would include climate [25], building envelope, building services and energy systems, building operation and maintenance, occupants' activities and behaviour, indoor environmental quality [26], building typology [27], and construction year and building regulations [28]. Out of these, human-related variables have been the less explored in the literature [26].

In Spain specifically, recent studies have delved into the determining factors for thermal performance, comfort, and energy efficiency in housing. Although seldom examined, occupancy behaviour in terms of preferences, habits, and uses has been singled out for its impact on building performance, energy efficiency, and well-being [29]. A study looking at public social rental housing in northern Spain strove to identify specific behavioural and occupancy patterns that could be applied in building simulation programs and building stock management for energy savings and enhancing the well-being of occupants [29]. Additionally, it was addressed as a meaningful factor in lockstep with envelope features such as infiltration rate and building age, which in turn were found to dictate occupant behaviour often to the detriment of energy efficiency [30]. The relationship between heating, ventilation, and air conditioning (HVAC) setpoint system control variables and occupant comfort perception and energy efficiency and consumption has also been explored based on a single-case study dwelling and thermal dynamic simulation in TRNSYS17 in three Spanish cities [31]. The indoor thermal comfort hours associated with a specific building typology, the H-typology social housing building stock in southern Spain, was also assessed by combining on-site monitoring methods with energy simulation and statistical techniques for data analysis; the topmost variables regarding thermal performance and comfort were a mix of construction features and occupancy behaviour: infiltration rate, people density, and nighttime natural ventilation [32]. Moreover, recent studies assessing the improvement of thermal comfort and energy efficiency subsequent to retrofitting have been developed either in small-scale samples combining monitoring and predictive simulation techniques and using steady-state and adaptive comfort approaches [33] or comparing actual building performance with standard values focusing on user comfort based on two case studies [14], centred energy through a social lens through postretrofit energy-affordability evaluation [20], using stand-alone simulation to evaluate potential energy savings from optimal carbon-neutral retrofit [34] or to examine the incorporation of standard passive strategies to reduce primary energy demand and subsequent emissions on the basis of three case studies with common patterns in Córdoba [35].

In view of the above and to the best of the authors' knowledge, there is a lack of studies entailing continuous long-term monitoring and large-scale samplings based on a mixed-methods approach, that is, monitoring and occupant surveying, looking at thermal performance driving factors for determining practical comfort implications and characterising its correlation with energy efficiency, within the Spanish context and the Extremadura Region.

Thus, to address the current research gap, the present paper proposes a methodology for thermal behaviour assessment by means of monitoring and surveying a large sample of dwellings in the Extremadura Region as the basis for identifying patterns linked to thermal comfort conditions in the dwellings under analysis. The case studies exhibit a very similar occupancy profile in terms of age range, economic and/or professional situation, family composition, and schedules, which leads to better results by excluding these interfering factors. The methodology applied makes it possible to deal with large samples and to avoid complex and individual identification studies in situ which would take up more time.

A selection of parameters of influence concerning thermal behaviour was analysed through multiple variables related to the construction period, building typology, the energy improvement interventions carried out, HVAC systems, and occupant behaviour, and the relationship between thermal comfort hours and occupant thermal perception was examined. Finally, the outcomes of this study intended to constitute a building block towards energy efficiency policy-making considering the possibility of adjustments for thermal comfort.

2. Materials and Methods

To carry out this study, a large-scale sampling of 92 dwellings was selected in the autonomous community of Extremadura as part of a project for the improvement, development, and exploitation of energy efficiency data. The case studies are owned by public administration workers, which certainly excluded energy-poor or vulnerable households. From the outset, users were assumed to activate HVAC systems during the heating and cooling seasons, as deemed necessary.

Firstly, an information system was designed to monitor the data necessary to carry out the proposed analysis. Secondly, the characterisation of the sample was undertaken according to several features: construction period, building typology, location, occupancy density, HVAC systems, and thermal sensation of the occupants. Said portrayal allowed for a deeper understanding of the sample and the verification of its representativeness. Data linked to the urban or building configuration and construction and HVAC systems were excluded from this research since the overarching goal was to infer thermal performance through the monitoring of thermal variables without the need to collect and check complex individual data on-site (please find the variables considered in this study shaded in Figure 1).

Finally, a time series data analysis was conducted to evaluate the thermal performance of the case studies' envelope and the user's comfort adaptation. To address the former, the building typology, the construction period and respective building regulations, and the energy retrofitting carried out were analysed. As regards the occupants' adaptive behaviours, these entailed, on the one hand, the use of HVAC systems and ventilation habits and, on the other hand, their comfort perception. It should be borne in mind that the monitoring campaign did not yield simultaneous data for all dwellings throughout the entire time span, as there were a few incidents of system malfunction (e.g., running out of battery, server crash, and voluntary disconnections). In this context, these limitations should be mentioned when citizen weather stations (CWSs) are used for data collection; however, the utilisation of these sources is highly beneficial and is currently being employed [36]. For this reason, each analysis contemplates distinct case studies and numbers within the sample (Appendix A displays the correspondence between the monitoring kit distributed in each dwelling and the number presented in each figure).

3. Information System

An information system was devised for the monitoring stage so as to detect, store, and analyse data from both static and dynamic sources and subsequently serve as a database for the analysis. The static data were extracted from the occupant questionnaire–based surveys based on a two-pronged approach (complete survey in Appendix B):

- Dwelling data enabling the determination of relevant variables as far as the construction period and building typology are concerned: location, land register reference, single-family or multifamily typology, age, energy renovations carried out, and HVAC systems.
- User data to screen relevant variables on occupancy and behaviours: number of occupants and under-age users, ventilation practices, HVAC setpoint temperatures, temperature, and comfort perception.

The dynamic data hail from outdoor and indoor sensors located in each dwelling for over a period of 2 years (June 2021 to May 2023). The devices integrate Nanoenvi Pico [37] boards with the Arduino bootloader, which allowed for open-source programming. The communication is established by way of messages in JSON format via MQTT protocol, through a Wi-Fi network, on a Raspberry Pi switchboard, model Zero W. An SSH service is used for remote access to the switchboard. This board runs on the Raspbian operating system, on which the EMONCMS web app [38] acquires and stores data on an SD card before sending it to the server's local database. Two devices were installed by the users: The first one measured outdoor hygrothermal conditions every 10 min, while the second one measured indoor hygrothermal conditions and CO_2 particle concentration every minute (technical specifications outlined in Table 1). Prior indications have been facilitated, including the advice that the devices should not be directly exposed to the sun's rays or placed in proximity to sources of heat or cold. To detect any anomalous installation, a quality control procedure has been developed (Appendix C). Additionally, the surveys (Appendix B) were employed to gather some information regarding the placement of the devices.

Two databases were adopted for data storage: In relation to static data, the PostgreSQL database [39] was employed, and dynamic data were sent to the central server and stored in the InfluxDB database [40], which is specific for time series schemes. Subsequently, different queries were performed through Python scripts, by applying the appropriate filters for each analysis and obtaining the relevant data according to different time ranges. In this way, static and dynamic data could be merged for further analysis.

4. Sample Characterisation

Firstly, the sample was characterised with respect to location, construction period, building typology, occupancy, and behaviours to check representativeness and sample scope.

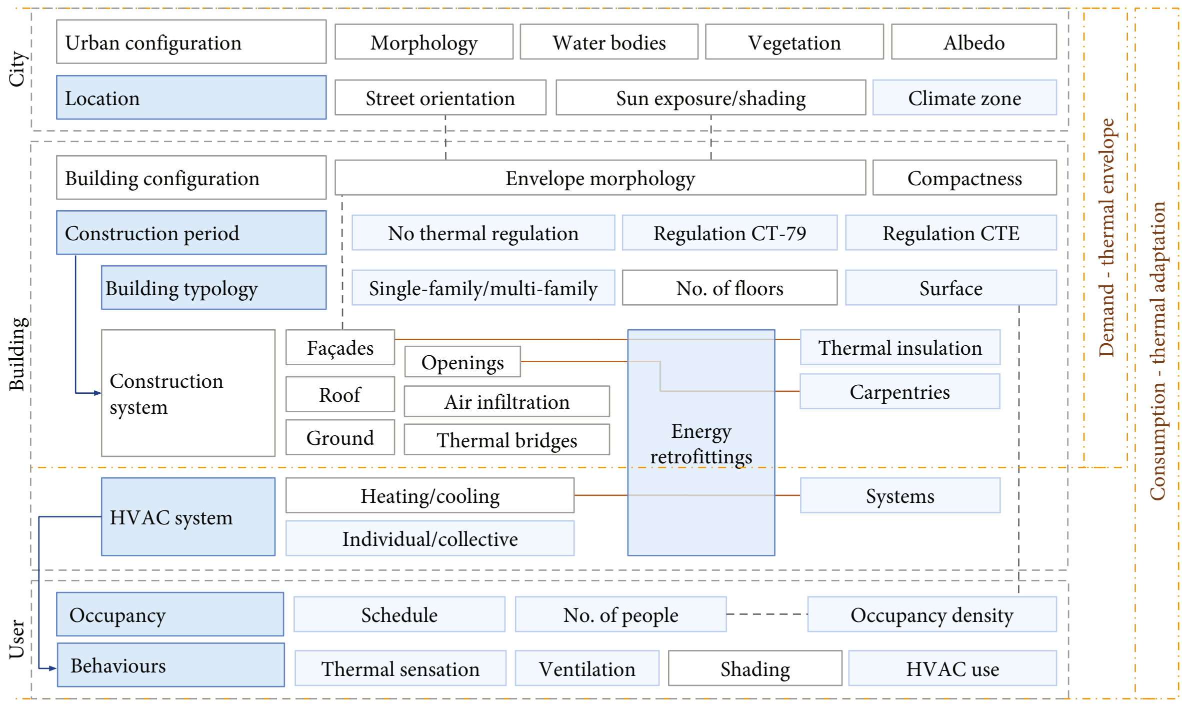


Figure 1: Flowchart of the variables involved in the thermal performance of dwellings (the variables considered in this article are shaded).

TABLE 1: Monitoring equipment technical specifications.

	Temperature and humidity (sensor model DHT-22)				CO_2 particle concentration (sensor model SCD30)	
Electrical data	3.3 W–6 V DC				3.3 W–5.5 V DC	
Measurement range	Temperature (°C)	−40 to 80	Humidity (% RH)	From 0 to 100	CO_2 concentration (ppm)	From 0 to 40,000
Accuracy		< ±0.5		±2% (Max ±5%)		±3%
Resolution		0.1		0.1		1
Repeatability		±0.2%		±1%		±10%
Dimensions (mm)	4 × 18 × 5.5				35 × 23 × 7	

4.1. According to the Construction Period and Building Typology. To start off, the construction period of the case studies was catalogued. The highest number of case study dwellings in the region (52%) predates 1980 and is enclosed by either common thick uninsulated walls (before 1940) or lightweight double-skinned cavity walls without insulation (between 1940 and 1980). In 1957, the MV (Ministry of Housing) standards [41] came into effect, albeit without thermal specifications. The second most represented period (37%) is comprised between 1981 and 2006, coinciding with the country's construction boom. These dwellings were built under the NBE-CT-79 [10], in which the study of the thermal envelope and the incorporation of insulation were prescriptive, although with minimum requirements. On the lower end of the spectrum, case studies are built after 2006 (11%), which saw the entry into force of the CTE DB-HE [42], updated in 2013 and 2019 and contemplating higher energy efficiency requirements.

Moreover, the majority of the dwelling sample (46%) pertains to the 1981–2006 period, followed by those ensuing 2006 (43%); it is likely that dwellings from earlier periods either no longer exist at present, are inhabited by the elderly, or are unoccupied. In practice, despite there being sampled dwellings predating 1980 (11%), these lacked data for the specific periods studied. For this reason, the construction periods investigated are restricted to those matching the CT-79 and CTE regulations (Table 2, the vertical envelope U values of the thermal transmittance have been incorporated to better understand the evolution of the thermal performance, from 1.65 to 0.49 W/m^{2}K).

To this, the construction typology variable was added. Multifamily dwellings were observed to be the most abundant housing type in the sample: 61% by adding those with less than (C) and more than (B) three floors, which doubles the number of single-family dwellings (39% (U)) in the two most represented periods. This suggests that housing blocks currently lead the residential trend in this autonomous community (Table 3).

4.2. According to Location and Construction Period. The sample is based in the regional capital and one of the two

TABLE 2: Sample distribution per construction period within Extremadura's housing stock.

Construction period		No. of dwellings constructed[a]	No. of dwellings in the sample	Thermal transmittance of the vertical envelope (W/m^2 K)
Traditional architecture	≤ 1940			1.65[b]
Postwar period	1941–1960	345,842 (52.4%)	10 (11.2%)	1.26[c]
Entry into force of the MV	1961–1980			
Entry into force of CT-79	1981–2006	241,995 (36.7%)	41 (46.1%)	1.03[d]
Entry into force of CTE	≥ 2007	72,034 (10.9%)	38 (42.7%)	0.49[e]
Total		**659,871 (100%)**	**89 (100%)**	
Unidentified			3	

Note: Most significant groups are bold highlighted for clarity.
[a]Data up to 2011 retrieved from [43]. Subsequent data extracted from [44].
[b]Usual value in this period for thick uninsulated walls, 0.60 m (with thermal inertia) [45].
[c]Usual value for lightweight double-skinned cavity walls without insulation, 0.27 m [42].
[d]Minimum value for climate and period regulation [10].
[e]Minimum value for climate and period regulation [42].

TABLE 3: Sample distribution per construction period and building type.

Construction period**	Building typology*			Total identified	Unidentified by typology	Total sample
	U	*C*	*B*			
≤ 1940	4	—	—	**4 (4.5%)**	—	4
1941–1960	—	—	—	**—**	—	—
1961–1980	2	1	3	**6 (6.7%)**	—	6
1981–2006	17	19	5	**41 (46.1%)**	—	41
≥ 2007	12	15	11	**38 (42.7%)**	—	38
Total identified and percentage of total	**35 (39.3%)**	**35 (39.3%)**	**19 (21.3%)**	**89 (100%)**		
Unidentified	*3*	—	—			*23*
Total sample	38	35	19		*0*	92

Note: Most significant groups are bold highlighted for clarity.
*According to segmentation into typological clusters: *U*, single-family dwellings; *C*, dwellings in multifamily buildings with two or more dwellings and up to and including three storeys; *B*, dwellings in multifamily buildings with two or more dwellings and more than three storeys [46].
**As per the land registry.

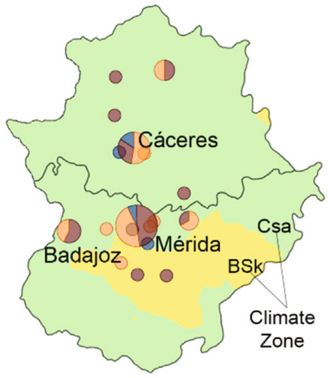
provincial capitals (Mérida (49%) and Cáceres (21%)). All sampled dwellings belong to the climate zone C4 as reported by CTE, with two distinctly marked seasons of cold winters and very hot summers. According to Köppen's classification, the majority of the sample cases are located in the Csa hot-summer Mediterranean climate zone with no dry season and hot summers; however, there are some dwellings in the centre of the province of Badajoz, which belong to the Bsk cold semi-arid (steppe) climate zone (this classification has shifted since 1981–2020 due to the current expansion of the arid climate [47, 48]). The average temperatures in Cáceres, Badajoz, and Mérida are, respectively, as follows (according to the State Meteorological Agency (AEMET), 1991–2020 period [49]): 16.5°C, 17.4°C, and 17.4°C annually; 3.8°C, 3.5°C, and 3.7°C, as the minimum in January; and 34.0°C, 35.6°C, and 35.3°C, as the maximum in July (Cáceres) or August (Badajoz and Mérida). As for the construction period, the number of case studies situated in Mérida and built between 1981 and 2006 is the highest, by virtue of the construction of regional government buildings (Table 4).

4.3. According to the Stocking Density. A large part of the case studies (44%) have a floor area between 100 and 149 m^2, followed by 50–99 m^2 (26%) and 150–199 m^2 (22%). These are for the most part occupied by four users (36%), followed by three- (29%) and two-person households (14%). In many cases (35%), there are no under-age users, with smaller percentages of dwellings being occupied by one and two minors, that is, 31% and 26%, respectively. All in all, the most common occupancy density is 30–59 m^2/person (51%) and secondly 15–29 m^2/person (29%). Thus, the profile of the case studies would match large dwellings, mostly occupied by nuclear families with dependent offspring and with a comfortable surface area per person (Table 5).

4.4. According to the HVAC Systems and Users' Thermal Sensation. The survey questionnaires entailed a section on HVAC systems and user behaviour. It should be noted that this section pertains to a second questionnaire carried out at a later time with decreased response rate, that is, 37%, albeit largely in compliance with the survey response rate thresholds determined in ASHRAE 55 [50].

The results indicate that the overwhelming majority of the case studies are in possession of individual heating systems (91%), of which almost all (68%) activate them whenever they feel uncomfortable; however, the same does not

TABLE 4: Sample distribution per location and construction period.



	≤ 1980	1981–2006	≥ 2007	Unidentified	Total
Cáceres	4 (4.3%)	10 (10.9%)	5 (5.4%)	—	**19 (20.7%)**
Mérida	3 (3.3%)	19 (20.7%)	20 (21.7%)	*3 (3.3%)*	**45 (48.9%)**
Badajoz	—	2 (2.2%)	4 (4.3%)	—	**6 (6.5%)**
Others	3 (3.3%)	10 (10.9%)	9 (9.8%)	—	**22 (23.9%)**
Total sample	**10 (10.9%)**	**41 (44.6%)**	**38 (41.3%)**	3 (3.3%)	**92 (100%)**

Note: Most significant groups are bold highlighted for clarity.

TABLE 5: Sample distribution according to the built-up area, occupancy, and occupancy density.

Built-up area* (m^2)	**No. of dwellings**	**No. of persons**	**No. of dwellings**	**No. of minors**	**No. of dwellings**	**Stocking density (m^2/person)**	**No. of dwellings**
30–49	—	1	7 (7.6%)	0	32 (34.8%)		
50–99	23 (25.6%)	2	13 (14.1%)	1	29 (31.5%)	From 15 to 29	26 (28.9%)
100–149	40 (44.4%)	3	27 (29.3%)	2	24 (26.1%)	From 30 to 59	46 (51.1%)
150–199	20 (22.2%)	4	33 (35.9%)	3	7 (7.6%)	From 60 to 89	10 (11.1%)
200–400	7 (7.8%)	From 5 to 8	12 (13.0%)	4	—	From 90 to 159	8 (8.9%)
Total identified	**90 (100%)**	**Total identified**	**92 (100%)**	**Total identified**	**92 (100%)**	**Total identified**	**90 (100%)**
Unidentified	2	Unidentified	—	Unidentified	—	Unidentified	2

Note: Most significant groups are bold highlighted for clarity.
∗According to land registry data.

hold true for cooling, with just over a half of the users reporting using HVAC for cooling purposes (61%).

On the other hand, users report that, in winter, the usual heating setpoint ranges between 19°C and 22°C (even if 9% of cases set it at 24°C), with 20°C (38%) being the most common. The temperatures self-reported as comfortable were 19°C (26%), 20°C (23%), and 21°C (21%). As for their summer counterpart, cooling setpoints oscillate between 24°C and 28°C, with 24°C (33%) and 25°C (29%) being the leading setpoint temperatures.

The analysis further highlighted a daily ventilation habit for most households (79% in winter and 85% in summer), generally for less than 30 min (68%), both those who ventilate daily and those who ventilate every 2 or 3 days. No fixed time was found concerning the ventilation of the dwellings in winter, and in summer, it is done first thing in the morning. With regard to the indoor thermal comfort perception (scale as per ASHRAE 55 [50]), respondents reported feeling "comfortable" more frequently in winter than in summer; specifically, the winter-related perception responses reflected that well-nigh half of the users (47%) felt thermally comfortable, with a tendency towards "occasionally too cold" (32%); conversely, in the heating season, the perception of "occasionally too hot" (44%) abounds, followed by "often too hot" (29%), while solely a quarter of users reported being "comfortable" (21%).

It should be noted that potential cognitive biases associated with both the HVAC parameters [51] and the potential linguistic biases may be encountered in the context of the survey research [52].

5. Multivariate Data Analysis and Discussion of Results

The comfort temperatures yielded were then analysed to characterise the thermal performance of the case studies in different periods, focusing on three main points: envelopes' thermal capacity, the user's adaptation to the state of comfort through their habits, and HVAC systems. Each section of the data analysis includes a discussion of the respective outcomes. Statistical analysis and quality control data are provided in Appendix C.

5.1. Preliminary Considerations. Prior to the analysis, the authors found it necessary to add a few considerations to clarify the aspects of hygrothermal conditions and air quality discussed in this paper.

5.1.1. As Regards Standardised Hygrothermal and Air Quality Ranges. The Spanish Building Code requirements for thermal installation conditions (CTE DB-HE 2) [42] were outlined in the Spanish regulation on thermal installation in buildings (RITE) [53], which establishes indoor design conditions for operative temperature and relative humidity (Technical Instruction IT 1.1.4.1.2). These are set for persons with a sedentary metabolic activity of 1.2 met and a clothing thermal insulation level of 0.5 clo in summer and 1 clo in winter and a PPD (predicted percentage of dissatisfied) of less than 10%, assuming a low air velocity level (< 0.1 m/s). The aforementioned conditions are also bound to the thresholds of 21°C–23°C and 40%–50% relative humidity in winter and 23°C–25°C and 45%–60% humidity in summer.

Furthermore, according to the latest energy saving measures, energy efficiency and reduction of energy dependence on natural gas (art. Twenty nine RD 14/22 regulation [54]), the air temperature during the use and maintenance of air-conditioned living spaces must be modified as follows: In heated spaces, it shall not exceed 19°C, while in cooled ones, it shall not be under 27°C, and the relative humidity must stand between 30% and 70%.

To validate these measures, this research took on a broader scale of analysis based on international standards. The EN 16798-1:2020 regulation [55] indicates that the criteria for thermal environments of heated and cooled buildings should be based on the predicted mean vote (PMV)-PPD thermal comfort indices defined in EN ISO 7730:2006 regulation [56] for the design or evaluation of existing environments. Said analysis focused on the general thermal sensation and degree of discomfort according to the PMV and PPD indexes. Firstly, the metabolic activity, clothing level, and air velocity values were found to be suitable for residential use according to the standard. Moreover, and regarding the aforementioned HVAC thresholds, the 19°C heating limit resulted in a thermal sensation, that is, a PMV of −0.54 and a PPD of 11.2%, which is slightly above 10%. As per the EN ISO 7730, a PPD in the 10%–25% bracket results in a slightly warm or slightly cool PMV, but thermal adaptation through clothing is to be expected. Thus, this situation could easily be solved by slightly increasing the clothing insulation, which could be considered as part of the household's new cost-saving habits, for example, adding a thin jumper which would result in a 1.3°C reduction in the optimum operative temperature.

Furthermore, the lower cooling limit of 27°C corresponds to a PMV of +0.74, that is, slightly warm, and a PPD of 17.2%. The reduction in clothing layers inside the home would result in a 0.4°C decrease in the optimum operative temperature and is considered to be a viable solution to diminish the PPD. What is more, the EN ISO 7730 determines that for cooling seasons, where occupants can operate the opening and closing of windows, higher temperatures than PMV-estimated values could be tolerated.

It was therefore concluded that the operative temperatures, taken in this article as comfort temperatures, would be set between 19°C and 23°C for winter and 23°C and 27°C for summer.

As for the indoor air quality, the CO_2 concentration was examined (Appendix D), which is related to the ventilation in the dwellings (CTE DB-HS 3 [57]). Since current regulations cannot be applied to the whole case study sample from previous construction periods, values established for buildings with a similar use to housing were taken as a reference (RITE [53]), according to which spaces should be at least at the IDA 3 category level, that is, medium quality air. This classification corresponds to 800 ppm (where 400 ppm is the average concentration of outdoor air in a city and 1500 ppm is the upper limit for comfort conditions).

5.1.2. With Regard to Outdoor Temperatures. The outdoor data stemming from sensors were found to differ sharply within the same locality while simultaneously contrasting with the official weather data supplied (AEMET [58]). This may be explained by the possible formation of microclimates in close proximity of the facades as a result of solar absorption, nearby vegetation and water bodies, the shape of the envelope, and urban configuration, among others [59]. For the data analysis carried out in this research, the authors opted to use the outdoor point temperatures from the sensors placed in each dwelling, on the basis that it was more appropriate due to their direct impact on the dwellings' envelope.

5.1.3. Concerning Relative Humidity. The annual monitoring records available were analysed to identify extreme values. The outdoor humidity ranges obtained stood between 80% in winter and 28% in summer, while indoor humidity fluctuates between 59% and 39%. These values are within standard comfort ranges (Section 5.1.1), and hence, further analysis of this variable was considered unnecessary, as there is no discomfort due to humidity in this geographical environment.

5.2. Approach to the Thermal Performance of the Envelope and Comfort Status. The section aims to determine the thermal behaviour of the dwellings' envelope by monitoring temperatures and to investigate its correlation with the two thermal construction periods (regulated by the CT-79 standard and the CTE standard), the building typology (single-family, *U*, and multifamily, *C* or *B*), and the comfort temperature. In addition, the envelope's energy retrofit interventions carried out by users (addition of thermal insulation and change of carpentry) have been taken into account.

For this purpose, the daily average outdoor–indoor thermal gap of representative periods was studied, that is, November 2021 and April 2022, in which there was no continuous window opening or HVAC systems functioning. These requirements allowed excluding any other impacting variables other than the envelope's behaviour on the calculated time lag results.

The smaller outdoor–indoor thermal gap values (closer to 0) reflect indoor temperatures more akin to outdoor ones, which is only appropriate when the latter is close to the comfort limits, in which case there is a reduced need for a thermal barrier. However, when faced with less favourable outdoor conditions, the envelopes should respond with greater attenuation to the thermal waves and have larger outdoor–indoor thermal jumps. Negative gaps (which are common in the months analysed) imply that the outdoor temperature is lower than the indoor temperature and vice versa. A daily pattern of thermal variation similar to the outdoor temperature indicates a constant level of thermal protection and proportional to the outdoor conditions.

In addition, the time lag and the decrement factors [60, 61] have been calculated to assess the heat storage capacity of each group of dwellings in the sample, which characterise the outdoor–indoor heat transfer delay and relate the amplitude of the indoor temperature to the amplitude of the outdoor temperature as an indicator of whether the building is prone to temperature changes (results provided in Appendix E). Efficient envelopes have a high time lag and a low decrement factor, achieving good thermal stability by preventing fluctuations in outdoor temperature from propagating indoors.

5.2.1. Cold Season Without HVAC Systems. The month of November 2021 in Extremadura was characterised as very cold (higher towards the end of the month) with respect to the average temperatures in historical records (10.3°C, with a maximum of 15.5°C and a minimum of 5.1°C) [62].

a. With the CT-79 regulation: Twenty-four case studies have records matching this period. Of these, 16 are multifamily households, and the remainder are single-family households; moreover, one energy efficiency intervention has been conducted in 10 of them. The outdoor–indoor thermal gap ranges from negative extreme values of −3.3°C to −14.8°C, with an average value of −8.2°C (Figure 2). The mean time lag for this group of dwellings is 441 min (standard deviation of 0.18), and the mean decrement factor is 0.35 (standard deviation of 0.17).

b. With the CTE regulation: There are 23 dwellings covered by this period, 15 of them are multifamily dwellings, and the rest are single-family ones. Four have undergone one renovation, and five were submitted to two renovations. The outdoor–indoor thermal gap ranges between the negative values of −1.3°C and −14.7°C, with an average value of −7.7°C (Figure 3). In this sample, the monthly mean time lag is 493 min (standard deviation of 0.18), and the mean decrement factor is 0.38 (standard deviation of 0.19).

5.2.2. Hot Season Without HVAC Systems. The month of April 2022 was cold with respect to historical average temperatures in Extremadura (13.3°C, with a maximum of 19.4°C and a minimum of 7.2°C) [62].

a. With the CT-79 regulation: Seventeen dwellings were considered in reference to this period. Out of these cases, nine are multifamily dwellings, and the rest are single-family dwellings. Twelve have not had any retrofit intervention conducted upon them, while four were retrofitted once and one twice. The outdoor–indoor thermal gap spans between the values of 1.4°C and −13.7°C, with an average value of −4.4°C and remaining negative most of the time (Figure 4). The average time lag is 345 min (standard deviation of 0.19), and the average decrement factor is 0.25 (standard deviation of 0.14).

b. With the CTE regulation: Under this umbrella, 18 dwellings can be found, of which 11 are multifamily dwellings and seven single-family dwellings; amongst these, four had been retrofitted once and one twice, and the remaining 13 were nonrenovated. The outdoor–indoor thermal jump ranges between 3.5°C and −12.8°C, with an average value of −4.0°C. As in the previous case, the gaps are usually negative (Figure 5). In this case, the monthly average time lag is 415 min (standard deviation of 0.19), and the decrement factor is 0.20 (standard deviation of 0.10).

5.2.3. Discussion of Results. The analyses carried out point to an overall homogeneous pattern in terms of the outdoor–indoor gap across all the case studies examined, which provided insight into the thermal wave-damping effect provided by the dwellings' envelope. The sample shows similarities in terms of the number of dwellings, construction typology, and number of renovations during both construction periods within each of the 2 months studied. Additionally, the average indoor–outdoor temperature difference of each subsample is similar in both periods, −8°C and −4°C, which indicates the quality of the data.

Yet the disparity in the results obtained is not conducive of determining a direct correlation between energy performance and the building typologies (data overview in Figure 6) or with the energy retrofit interventions carried out on the envelope of the sample for both construction periods. The dwellings in the sample built under the CTE regulation tend to have a slightly greater time lag (with a maximum of 1°C in November and 2°C in April), which also made it impossible to pinpoint notable discrepancies as far as indoor temperature improvement was concerned and with regard to the implementation of specific thermal standards, regulating the envelopes' construction.

By the same token, and with respect to the comparison between the results obtained for the time lag and the decrement factor, a very similar behaviour was detected in each month (standard deviation less than 0.20 in all cases), pointing to a low discrepancy in the envelope behaviour within the sample for both construction periods.

In the coldest period, a larger jump was determined (−8°C), indicating a more stable envelope performance, and vice versa. In addition, the time lag and stability coefficient mean values were 441–493 min and 0.35–0.38 min for the periods of CT-79 and CTE, respectively. In the warmer period, with a lower jump (−4°C), the time lag and stability coefficient mean values were worse: 345–415 min and 0.25–0.20 min.

The issues outlined in the analysis imply that other determining variables play a significant role in the thermal performance of the building envelope. This is the case of factors directly related to the urban and building configuration, which directly affects energy demand and, therefore, comfort, such as inter alia, the design of the envelope, its orientation, shading, and compactness. The correct execution of the envelope in each period and subsequent energy retrofit interventions, thermal bridges, and air infiltration are additional elements that can tip the scales in thermal behaviour. On the other hand, bearing in mind that dwellings almost

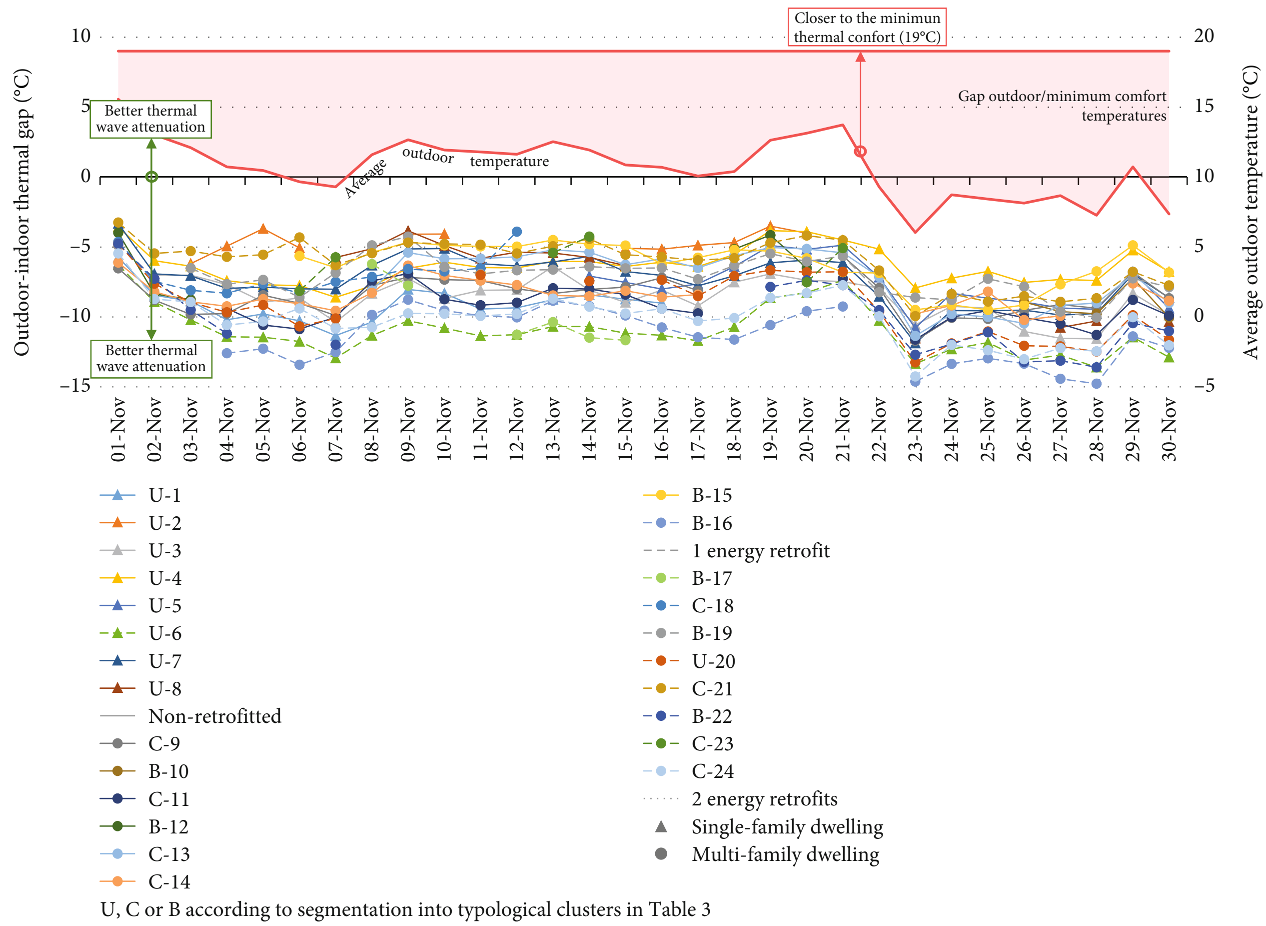


Figure 2: Comparison of the indoor–outdoor thermal gap during November 2021 based on average daily temperatures with respect to the outdoor average, its relationship with the building typology, the number of energy retrofitting actions carried out, and the comfort temperature limit in a sample of dwellings built to CT-79 standards.

always behave in the same way throughout the full period analysed, the occupancy patterns and usage habits of each household should be taken into account, encompassing matters such as ventilation or shading.

5.3. Assessment of the Indoor Thermal Conditions and Comfort Hours. This section aimed to, firstly, investigate the thermal comfort conditions in the case studies and, secondly, to determine which construction period, occupancy, and habit variables could hold influence over the former. The monitoring period chosen encompassed the hottest and coldest annual weeks, and hence, the analysis was based on worst-case scenario, following the methodology of previous research [63, 64]. In this way, the second week of January 2022 (omitting the first week due to lack of occupancy in some of the dwellings during Christmas) and the first week of July 2022 were selected, for both construction periods. HVAC systems were likely activated to achieve comfort in both weeks; however, it is outside the purview of this section to analyse said systems or the users' energy consumption. The three analyses carried out are as follows:

- Firstly, the weekly indoor thermal oscillation of the dwellings was examined, as well as its relationship with the comfort range and outdoor temperature (weekly maximum and minimum averages), differentiating between each construction period. To establish a first approach to the case studies' patterns of use and their thermal comfort conditions, the full 24-h daily range was considered. Additionally, the dwellings' occupancy was verified by means of the indoor CO_2 concentration data, from which indirect conclusions could be inferred such as the presence of air infiltration or ventilation habits, which in turn can impact indoor thermal variations.

- To complement this, the percentage of weekly indoor thermally comfortable hours was computed for each dwelling, contrasting the results with the energy retrofit actions carried out on the envelope, that is, carpentry and insulation, and the HVAC systems. Furthermore, the analysis was limited to the daytime range (from 07:00 to 23:00), since the sleeping temperatures are lower than the comfort temperature (to this end, it was also verified that none of the respondents had placed the indoor sensor in the bedroom). The final objective of this second analysis, in addition to getting a deeper insight into the dwellings' comfortable

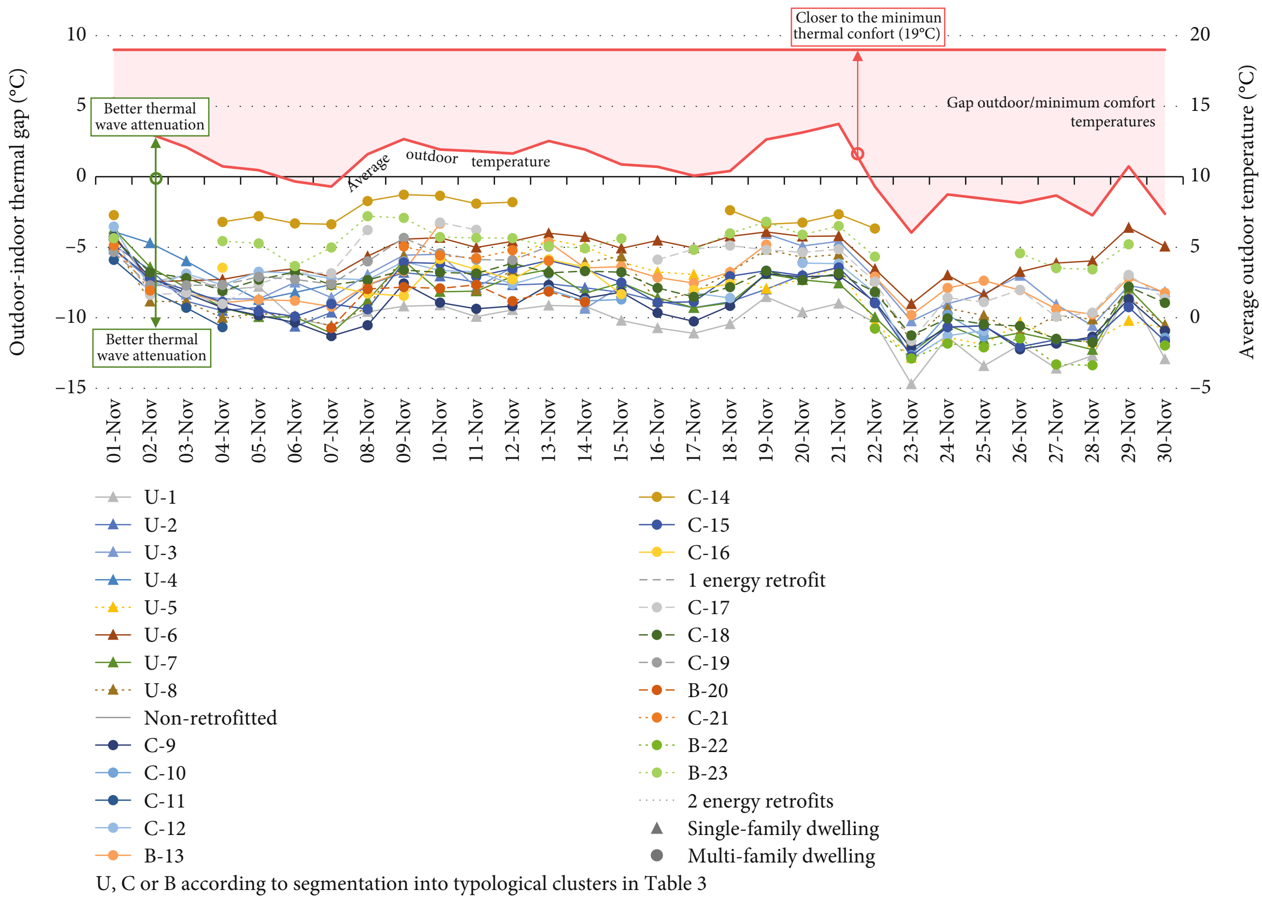


Figure 3: Comparison of the indoor–outdoor thermal gap during November 2021 between the average daily temperatures with respect to the average outdoor temperature, its relationship with the building typology, the number of energy renovations carried out, and the comfort temperature limit in a sample of dwellings built according to the CTE regulation.

hours, was to determine whether there was a correlation between the retrofit actions conducted and improved thermal behaviour.

- Finally, the difference between comfort conditions in the morning (from 07:00 to 15:00) and in the evening (from 16:00 to 23:00) was checked, taking into account that the users work mostly in the morning (some of them remotely) and there is a possibility that the HVAC system was turned on in the evening. With this in mind, the data analysis was limited to working days only, from Monday to Friday, when the dwellings were guaranteed to be occupied. The aim here was to discern the occupancy patterns of this user profile.

5.3.1. Extreme Period of the Cold Season. For this period, data were available for 34 dwellings of the total sample. The weekly average outdoor temperatures for each dwelling ranged from 8.1°C to 13.1°C. With regard to the indoor temperature, it should be noted that almost all dwellings, with the exception of seven, record minimum values below the thermal comfort threshold; in the case of the maximum values, four of them display levels above the maximum comfort temperature, while four do not reach the minimum. Just 41% of the dwellings in the sample have an average weekly indoor temperature within the comfort range. There is a marked oscillation of absolute indoor temperatures, from 1.2°C to 8.7°C. This behaviour is analogous in both construction periods, at around 4°C (Figure 7).

In the second analysis, it was observed that 12 case studies reached the comfort temperature for a substantial part of the time (> 75% of hours), of which, seven dwellings hold a constant state of comfort (five of which are nonrenovated). The remaining six reach comfortable conditions for approximately half of the time (five of them having carried out one or two renovations). The last six remain in discomfort for nearly the entire day (comfort time < 3% of hours). No notable differences were identified as far as performance between the two construction periods, with again analogous average comfort percentages, around 50% (Figure 8).

The third analysis conducted shows that during weekdays, the afternoon is the most thermally comfortable extent of time, which could indicate that they are mostly inhabited during that period. Furthermore, 11 of the 34 dwellings analysed fail to reach the comfort temperature for at least 40% of hours, may that be in the afternoon or the morning (Figure 9).

5.3.2. Extreme Period of the Hot Season. Fifty dwellings were analysed for this extreme period. Regarding indoor temperature values, the minimum temperatures in three of the

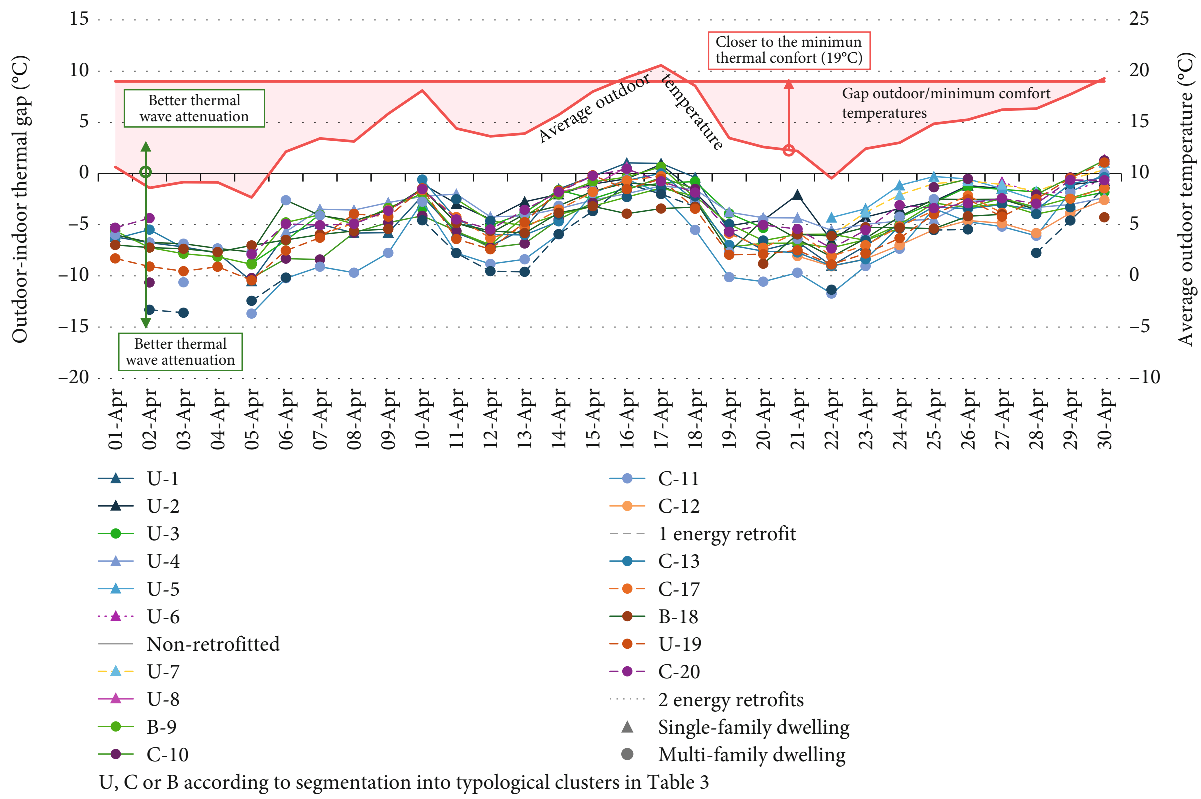


Figure 4: Comparison of the indoor–outdoor thermal gap during the month of April 2022 between the average daily temperatures with respect to the outdoor average, its relationship with the building typology, the number of energy retrofit actions carried out, and the comfort temperature limit in a sample of dwellings built to CT-79 standards.

dwellings slightly fall behind the comfort temperature threshold, while 10 dwellings exhibit higher minimum indoor temperatures at all times. In the case of the maximum indoor temperatures, all dwellings except one exceed the comfort range, spanning from 25.2°C to 32.8°C. The indoor temperature variation oscillates between 1.4°C and 8.6°C from one dwelling to another, making the average very similar in both periods, 4°C. In this week, the indoor averages for each dwelling fluctuate from 24.6°C to 30.5°C, and only 16% of the case studies present a weekly average indoor temperature within the comfort range (Figure 10).

Through the second analysis, it could be seen that the comfort temperature was only reached by four dwellings for an extensive period of time (> 75% of hours) (two were renovated). Two dwellings undertook three renovations, one spent 100% of hours in comfort conditions, and the other one merely spent 15%. Of the remaining dwellings, 22 of them present thermal discomfort at almost all times (comfort < 3% of hours). As happened for the extreme cold week, no notable performance differences were identified between the CTE and the CT-79 construction periods, with a quite similar average comfort percentage, at around 18% (Figure 11).

The third analysis executed highlighted how the comfort time varies from one dwelling to another in the afternoon and morning. Of the 50 dwellings studied, in 11 of them, the percentage of comfort time in the afternoon exceeds that of the morning, which would indicate that the dwellings are inhabited in the afternoon, while 26 of them are occupied in the morning. In addition, 39 dwellings fail to reach the comfort temperature for at least 40% of hours either in the afternoon or in the morning (Figure 12).

5.3.3. Discussion of Results. Kindred results were obtained for the dwellings' comfort and indoor thermal condition in the CT-79 and CTE construction periods and in the three subsequent analyses:

- In the first analysis, it was observed that the sampled dwellings maintain comfort conditions for half of the 24 h-hour day in the extreme winter week but only one-sixth of this time during the summer, despite the much more uncomfortable outdoor winter temperatures warranting heating systems to achieve comfort. In line with this, users reported a more regular activation of the HVAC systems in winter than in summer. On some occasions, these systems are not used within the maximum winter and minimum summer regulated boundaries and exceed them; this is a more frequent occurrence in winter, demonstrating that there are possibly dissatisfied people within the standardised ranges of less than 10%.

The indoor thermal behaviour of the sampled dwellings is very heterogeneous, regardless of their construction period and the outdoor temperature range; both minima and

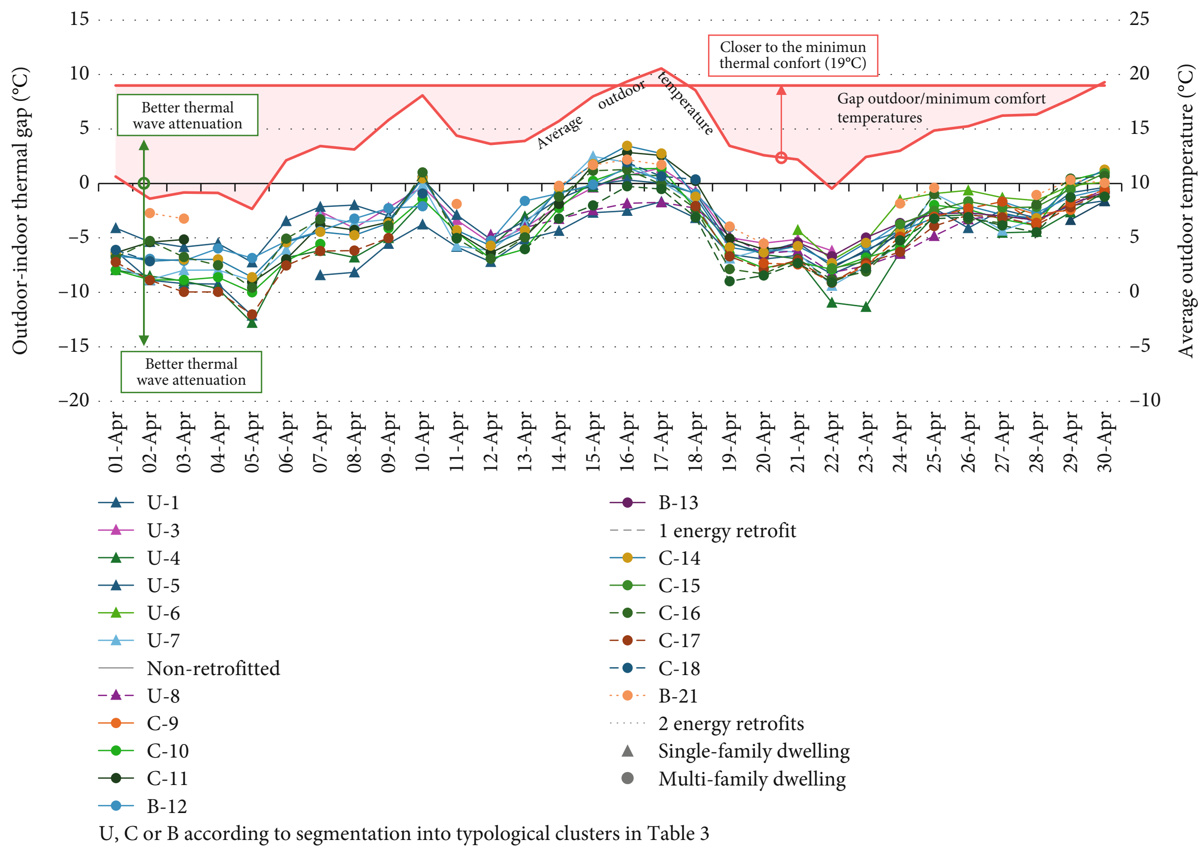


FIGURE 5: Comparison of the indoor–outdoor thermal gap during the month of April 2022 between the average daily temperatures with respect to the average outdoor temperature, its relationship with the building typology, the number of energy renovations carried out, and the comfort temperature limit in a sample of dwellings built according to the CTE regulation.

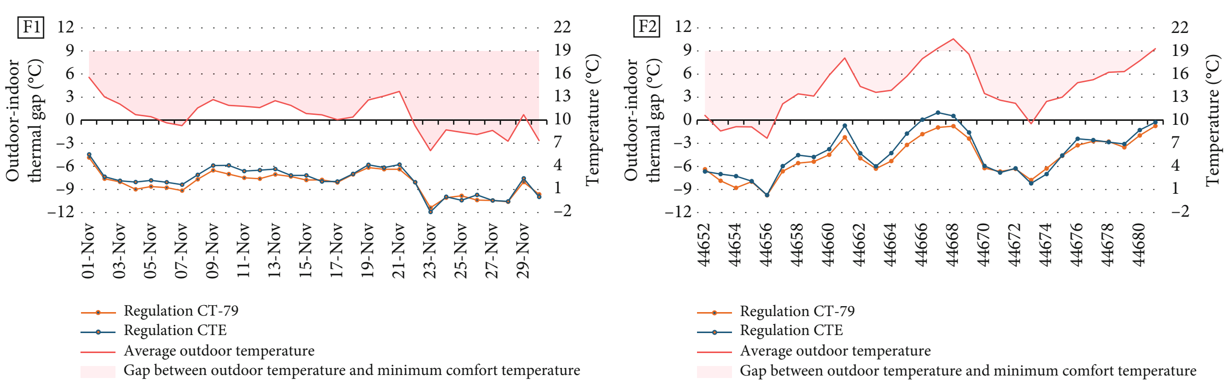


FIGURE 6: Comparison of the average daily outdoor-indoor thermal gap with respect to the outdoor average, at the lower comfort limit between dwellings built to CT-79 standards and those built to CTE standards in the months in November 2021 (F1) and April 2022 (F2).

maxima and the daily oscillations are characterised by a vast array of values that lack common ground. This overlooks the diversity of habits and choices of each user and their weight on the dwellings' thermal performance. Furthermore, numerous dwellings displayed considerable indoor thermal oscillations in both the CT-79 and CTE construction periods, that is, being highly influenced by outdoor temperatures and with little inertia. It can be inferred that the presence of separate HVAC systems facilitates their individual use, and it was found that even when these are turned on up to the comfort setpoints, they quickly move away from these thresholds during the week.

The indoor fluctuating temperatures indicate that many dwellings are strongly influenced by outdoor temperatures and that envelopes have little thermal stability: in winter even when systems are supposed to be activated because

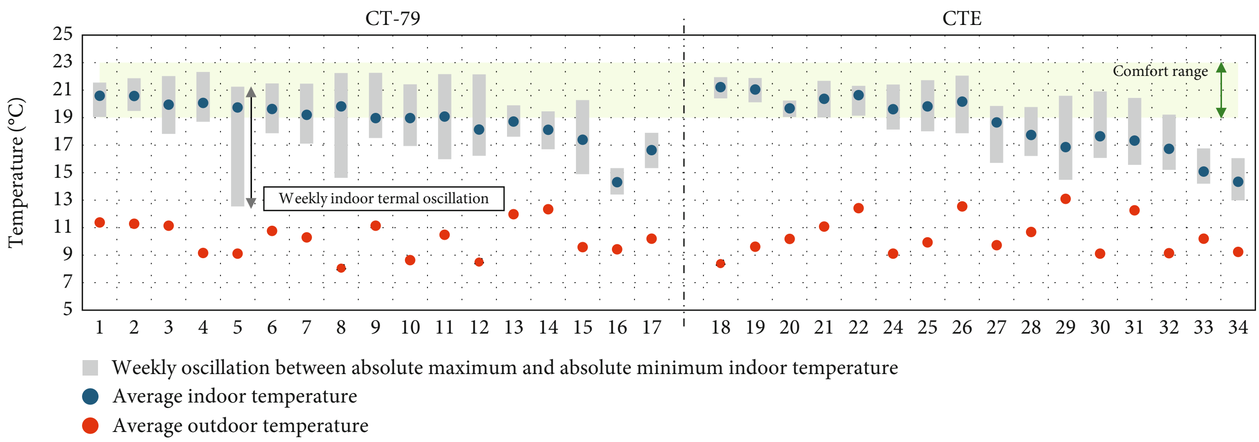
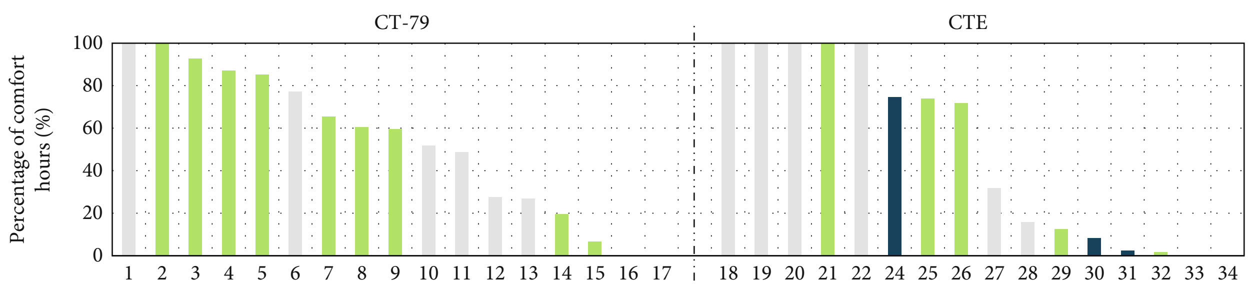


Figure 7: Side-by-side comparative chart illustrating indoor and outdoor temperatures of a sample of dwellings with respect to the comfort temperature in an extreme winter week according to the different construction periods.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	24	25	26	27	28	29	30	31	32	33	34
Insulation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	1	0	0	0
HVAC systems	0	0	1	1	1	0	1	1	1	0	0	0	0	1	1	0	1	0	0	0	1	0	1	0	1	0	0	1	1	1	1	0	0
Carpentries	0	1	0	1	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	0	0
Total of retrofits	0	1	1	2	1	0	1	2	2	0	0	0	0	2	1	0	1	0	0	0	1	0	3	1	1	0	0	1	3	3	1	0	0

0 - retrofit no 1 - retrofit yes Non-retrofitted 1-2 retrofits 3 retrofits

Figure 8: Comparison between the percentage of hours of daytime comfort (from 07:00 to 23:00) of a sample of dwellings with respect to the implementation of energy retrofit actions according to the different construction periods in an extreme winter week.

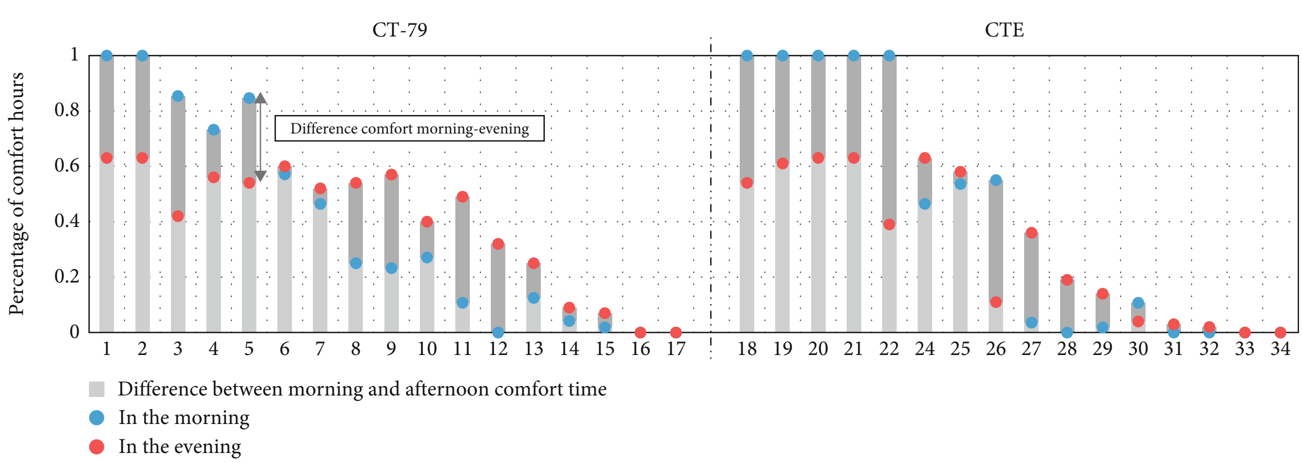


Figure 9: Comparative balance between the time percentage spent within comfort ranges in the morning (from 07:00 to 14:00) and the afternoon (from 15:00 to 23:00) of a case study dwelling during weekdays (Monday to Friday) of an extreme winter week.

average indoor temperatures are far from outdoor ones and in summer when the cooling systems are turned off, which have a fairly short-lived effect by cooling the air alone.

- In the second analysis, which excluded nighttime performance, winter daytime comfort hours were threefold higher than in summer, leading to the reiteration

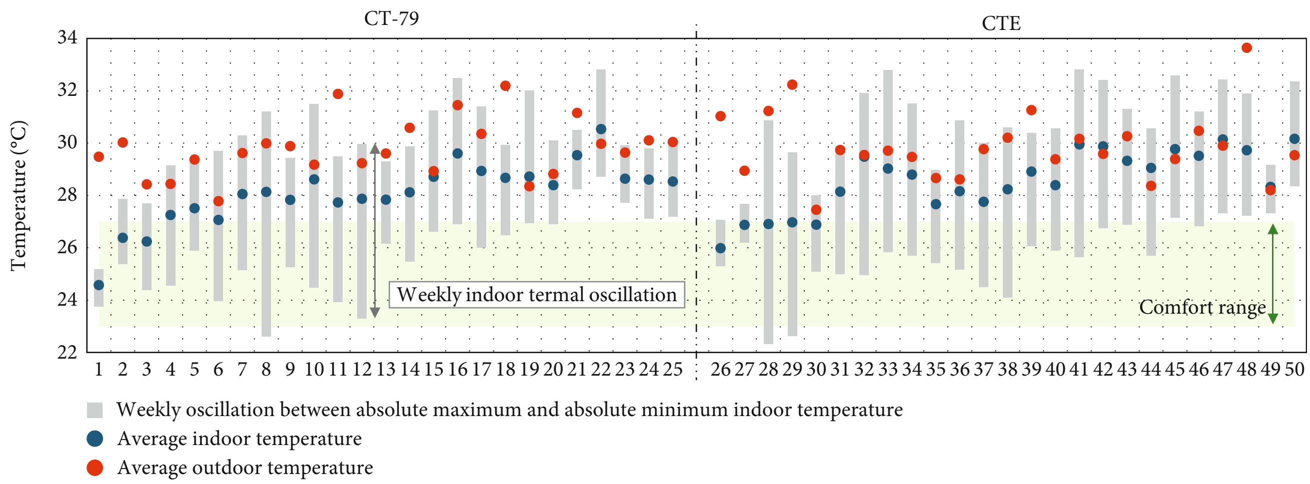
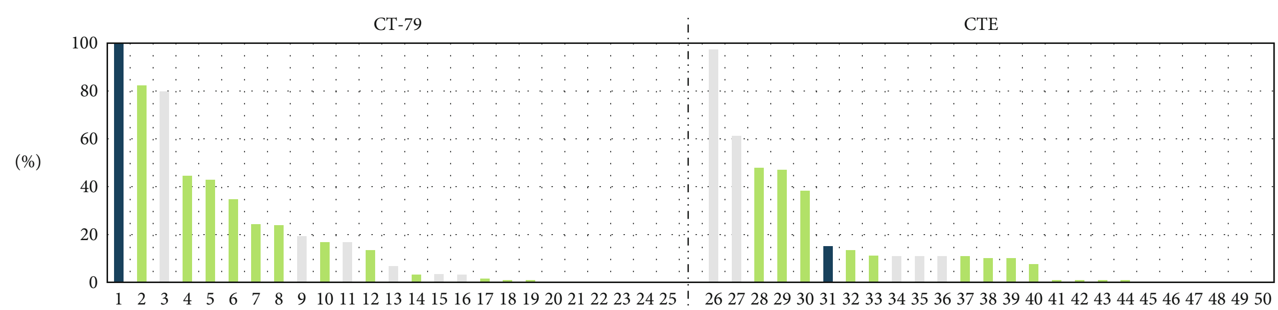


Figure 10: Comparison between indoor and outdoor temperatures of a sample of dwellings with respect to the comfort temperature in an extreme summer week according to the different construction periods.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Insulation	1	1	0	0	0	0	0	0	0		0	0	0	1	0	0		0		0	0	0	0	0	0
HVAC systems	1	1	0	1	1	1	1	1	0	1	0	1	0	1	0	0	1	0	1	1	0	1	1	0	1
Carpentries	1	0	0	1	0	1	0	1	0	1	0	1	0	0	0	0		0	1	0	0	1	0	0	0
Total of retrofits	3	2	0	2	1	2	1	2	0	2	0	2	0	2	0	0	1	0	2	1	0	2	1	0	1

	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
Insulation	0	0	0	0	1	1	0		0	0	0	1	1	0	0	0	0	0	0	0		0	0	0	0
HVAC systems	0	0	1	0	0	1	1	1	0	0	0	0		1	1	0	0	0	0	0	1	0	0	0	0
Carpentries	0	0	0	0	0	1	0	1	0	0	0	1	1	0	0	0	0	0	0	0		0	0	0	0
Total of retrofits	0	0	1	0	1	3	1	2	0	0	0	2	2	1	1	0	0	0	0	0	1	0	0	0	0

0 - retrofit no   1 - retrofit yes   Non-retrofitted   1-2 retrofits   3 retrofits

Figure 11: Comparison between the percentage of hours of daytime comfort (from 07:00 to 23:00) of a sample of dwellings with respect to the implementation of energy retrofit actions according to the different construction periods in an extreme summer week.

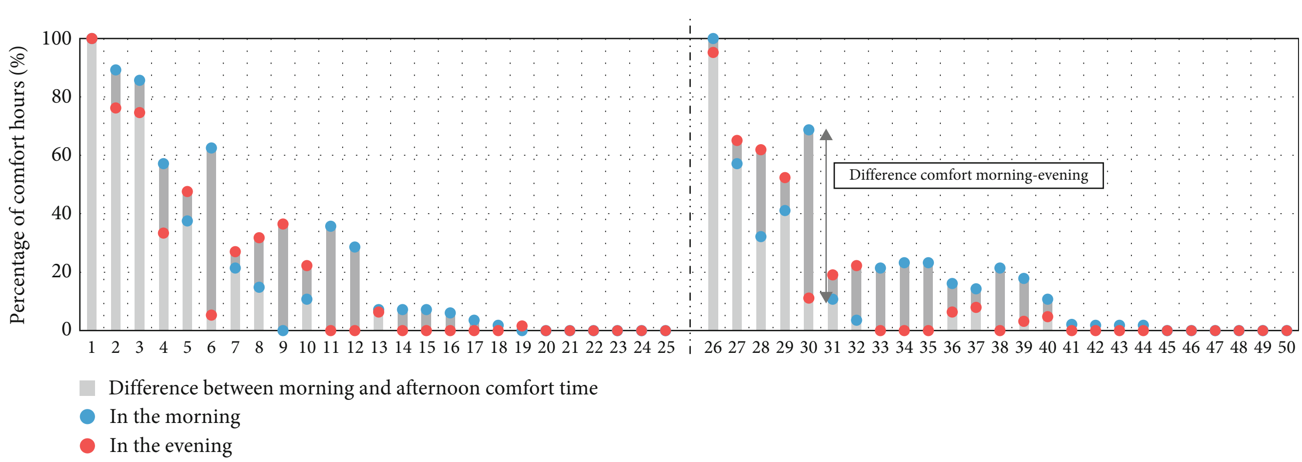


Figure 12: Comparative balance between the percentage of comfort time in the morning (from 07:00 to 14:00) and the afternoon (from 15:00 to 23:00) of a sample dwelling during the weekdays (Monday to Friday) of an extreme summer week.

of the above observations regarding the difference between the two seasons. On the other hand, the renovations performed on the case studies were yielded not to directly contribute towards the improvement of their indoor thermal comfort conditions. It should be pointed out that it is unknown whether the interventions in question were carried out correctly or effectively or whether subsequent renovations could have been carried out without being self-reported.

- Finally, in the third analysis looking at the weekdays, users were observed to occupy their households mostly in the afternoon in the heating season and indistinctly in the cooling season, when children are home on summer break. The HVAC systems were confirmed to be turned on exclusively during occupied times, which is indicative of energy-saving habits. In this case, the time spent at home matches that of indoor comfort conditions, which is not continuous throughout the day. Once again, the percentage of time spent in comfort in winter is greater than that of summer.

5.4. Analysis of the Percentage of Comfort Hours With Respect to Thermal Comfort Sensation. The aim of this section was to check whether the percentage of comfort hours matches the indoor thermal sensation perceived (Section 4.4), excluding the nighttime (from 07:00 to 23:00). The same extreme weather periods were chosen for analysis, that is, the second week of January 2022 and the first week of July 2022. In this case, no differentiation was made between the CT-79 and CTE construction periods or in the number of refurbishments implemented, as these aspects have been previously covered.

In order to carry out the study, we compounded the dynamic thermal data of indoor daily oscillation and its rapport with the comfort range, by the self-reported thermal sensation rating.

5.4.1. Extreme Period of the Cold Season. Survey data was only available for nine dwellings in the extreme winter week, so the results are not conclusive. In any case, there was a mismatch between the comfort perception level perceived by some users and the dwellings' comfort hours. One user reports feeling often too cold, despite spending approximately 80% of the time in comfort conditions, or two other users reported feeling occasionally too cold while spending less than 10% of the time in comfort conditions. Conversely, the only user who reported feeling comfortable exhibited a percentage of daytime comfort hours of 100%, or the two users who occasionally felt too cold had less than 10% of discomfort hours (Figure 10). Also, most of the users who say that they do not turn on the heating system are actually cooler in their homes, and their hours of comfort are shorter, with a few exceptions who report that they do not usually turn on the heating system and yet are comfortable almost all day. The heating system setpoint temperatures are within the comfort range and are akin to the temperatures self-reported as comfortable, although it is noteworthy that several users report feeling comfortable at a lower temperature than the setpoint temperature used in the heating systems. Only one household set the heating setpoint temperature at 19°C, as recommended by the savings measures (Figure 13).

5.4.2. Extreme Period of the Hot Season. In this extreme period, data are available for 26 dwellings. As for the users' thermal sensation, it is worth noting that a mere four report feeling comfortable, although only one presents a percentage of daytime comfortable hours of nearly 50%. Thus, it can be seen that the thermal comfort sensation varies according to each person, for instance, the occupants in three dwellings that only reach the comfort temperature for less than 10% of the time, expresses comfort, or all of the users (ten) less than 40% feeling occasionally too hot (Figure 13).

The analysis emphasized many dissimilarities between the dwellings across all the parameters studied. Nonetheless, and as happened with the extreme cold period, overall, users who state that they do not turn the cooling system on usually feel too hot in their homes, and their comfort hours are diminished. The cooling system operating setpoint temperatures are generally within the comfort range and are quite similar to the temperatures at which users report feeling comfortable. It is noticeable that in most of the cases studied (38%), users set the setpoint temperature of the HVAC systems 1°C–2°C lower than their own comfort temperature, which is energy inefficient in the summer period. Only two households comply with the savings measures and set the air-conditioning setpoint temperature at 27°C and 28°C. The majority of survey respondents reported occasional heat in the summer, despite standing within the comfort ranges set by the regulations (Figure 13).

5.4.3. Discussion of Results. This section of the study evidenced a general mismatch between the percentage of comfort hours and the users' comfort perception. Yet, as in previous sections, there is a large inconsistency in the indoor thermal behaviours within the sample. In addition, dwellings are not usually in a state of comfort, which is more common in winter than in summer. Likewise, the HVAC setpoint temperatures were found to be within regulated limits, as observed in the responses summed up in surveys, but it should be noted that in summer, most users set a lower setpoint temperature than their personal comfort temperature, while in winter, both temperatures tend to converge towards the same value.

6. Conclusions

Merely reducing energy consumption in dwellings, through control of the energy demand of the envelope and more efficient systems, is not sufficient if it is not accompanied by indoor comfort, which is influenced by other factors, linked to occupancy behaviours. The continuous long-term monitoring and the questionnaires of a large sample of dwellings

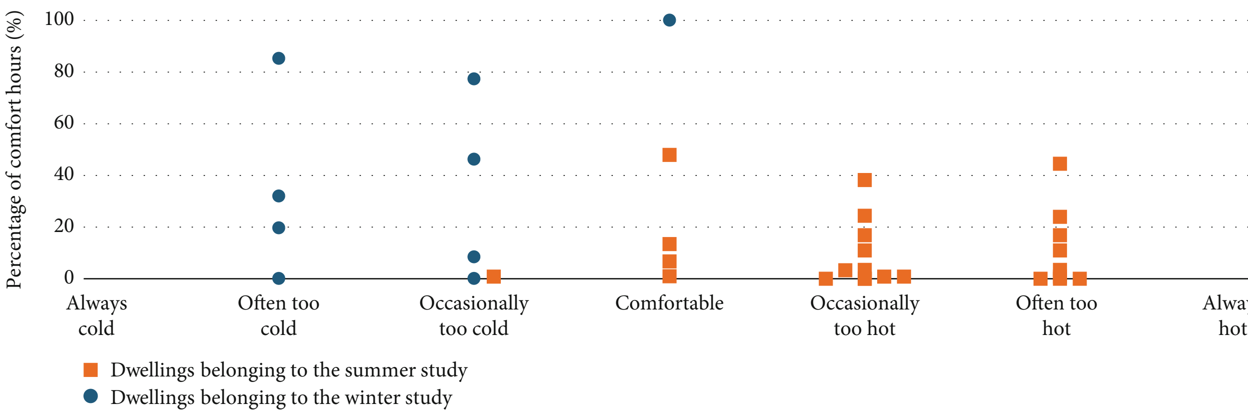


Figure 13: Comparison between the daytime indoor temperatures (from 07:00 to 23:00) of a sample of dwellings, with respect to their percentage of comfort hours and the thermal sensation of the users in the extreme summer and winter weeks.

with a homogeneous user profile collect static and dynamic time series data, making it possible to identify the thermal behaviour patterns. This paper highlights that the latter covers a wide spectrum of actions that, in turn, lead to theoretical uncomfortable conditions prolonged in time, particularly during winter, given the ranges stipulated by regulations that do not align with users' comfort perception.

What is more, no common ground was found among the indoor thermal behaviour patterns of the sampled dwellings, indicating that individual preferences and behaviours play a key role in the user's comfort sensation. This may be due to, inter alia, differences in thermal adaptation and sensitivity to humans' ability, radiation surfaces, and HVAC system features. Therefore, there is an urgent need to develop adaptive thermal comfort models that enhance both comfort requirements and building energy performance [65].

Additional key features from this research could be underlined: On the one hand, the collaboration of the user in placing the sensors in their households and in filling questionnaires allowed for the identification of specific occupancy parameters and use patterns; on the other hand, the use of low-cost monitoring technology allowed for a massive scope of results. Furthermore, this study was conducted within the autonomous community of Extremadura; however, the methodology employed can be applied to any other case study belonging to a geographically delimited area, characterised by climatic, typological, building and construction similarities. The representativeness of the sample is a key factor in ensuring the reliability of the findings.

Finally, the authors acknowledge the following limitations that arose in the course of this research with regard to the methodology applied:

- A large number of dwellings had to be monitored for a long monitoring period to obtain the precise variables for analysis according to the required climatic periods and the above results.

- The availability of both static and dynamic data depends on the continuous involvement of the users, the functioning of the sensors, and the maintenance of the system.

- The placement of the sensors in a room representative of the occupancy of the dwelling must be ensured.

In subsequent studies, other massive and indirect data questions concerning the environment, building configuration, construction, and HVAC systems, as well as energy consumption, should be contemplated. Additional avenues for future research may be identified in external monitoring sources that are not necessarily time-limited in their duration, such as campaigns or research projects. These may include both static sources, which are typically maintained by governmental bodies (e.g., statistical institutes and cadastre services) and dynamic sources and CWS citizens. It is necessary to consider that, currently, in the latter case, open data is only available for external variables linked to a specific location, and only certain users are granted access to the internal data. At last, this data will be capable of facilitating extensive analysis of the building stock.

Moreover, future studies should expand on the survey data linked to the occupancy and user habits via specific comfort perception questions accompanied with point-in-time measurements, the activation of HVAC systems, and possible adaptive behaviours such as ventilation or clothing, including all users of the dwelling rather than a representative occupant and considering age and gender differentiation.

Conversely, the data obtained from building monitoring can be employed in the calibration of digital twin models, which facilitate the prediction of thermal behaviour and the assessment of adaptation strategies for the enhancement of both efficiency and comfort. In order to achieve this, it would be necessary to define representative models of the park that would allow the results obtained to be extended.

In addition to these considerations, it is imperative that more comprehensive policy recommendations be implemented to ensure that the regulations related to energy efficiency and comfort have a tangible impact on the thermal performance of buildings, both in new buildings and in the context of energy renovation actions.

Appendix A: Correspondence Between Each Dwelling's Monitoring KIT Number and Those of the Figures

Information about the monitoring kits is presented in Table A1.

TABLE A1: Correspondence between each dwelling's monitoring KIT number and those of the figures.

	Figure 2	Figure 3	Figure 4	Figure 5	Figures 7, 8, and 9	Figures 10, 11, and 12
KIT-003		C-10			18	
KIT-007		C-21				
KIT-012	B-15					
KIT-014	U-6					14
KIT-021	U-1		U-1		10	
KIT-022		U-1		U-1		28
KIT-023	U-2		U-2		16	15
KIT-024	B-16		B-16			
KIT-026						1
KIT-029		U-5		U-4		38
KIT-030	U-8		U-8		12	3
KIT-033						42
KIT-040						2
KIT-042	C-9				1	
KIT-045		U-2			19	
KIT-046	B-10		B-9		11	18
KIT-047						20
KIT-051						21
KIT-053	C-11		C-10		5	7
KIT-054	B-17				8	
KIT-055	U-3		U-3		3	5
KIT-056		B-22			24	
KIT-057						26
KIT-058				U-3		
KIT-062		C-11				
KIT-063		U-6		U-5	33	43
KIT-064				C-9		
KIT-071						19
KIT-073						45
KIT-075						8
KIT-078	B-12				13	
KIT-080		U-8			30	
KIT-087			C-15			4
KIT-088			C-11			9
KIT-089				U-6		44
KIT-091			C-12			13
KIT-092	C-18		C-17			
KIT-096						16
KIT-099						34
KIT-104						40
KIT-109		C-9		C-10	20	
KIT-115		C-18		C-17	25	
KIT-116		C-12		C-11	21	
KIT-130						46
KIT-152						31

TABLE A1: Continued.

	Figure 2	Figure 3	Figure 4	Figure 5	Figures 7, 8, and 9	Figures 10, 11, and 12
KIT-164						27
KIT-177						32
KIT-182	B-19		B-18		14	10
KIT-183		C-17		C-16		
KIT-185		C-16			26	
KIT-187						35
KIT-189		U-3			32	
KIT-190		B-23		B-21	31	
KIT-191	U-7				17	
KIT-195	U-20		U-19		4	22
KIT-196	C-21		C-20		9	6
KIT-197						36
KIT-198						23
KIT-201	B-22					
KIT-205						24
KIT-206						17
KIT-207						30
KIT-209		U-4				
KIT-210	U-4		U-4			
KIT-214					34	
KIT-217						37
KIT-219	U-5				15	
KIT-222	C-13		C-13		6	11
KIT-223	C-14		C-14			
KIT-226		C-19		C-18		
KIT-227					7	
KIT-228		B-20				
KIT-234				B-13		47
KIT-235				U-2		41
KIT-238						39
KIT-239						29
KIT-241						25
KIT-245			U-7			
KIT-246						48
KIT-247		C-14			29	
KIT-250				C-19		
KIT-251				B-20		
KIT-259			U-6			
KIT-263		C-15		C-14	22	49
KIT-264				U-8		33
KIT-266			U-5			
KIT-267						12
KIT-268				C-15		
KIT-270	C-23					
KIT-272		U-7		U-7	27	50
KIT-275	C-24					
KIT-278		B-13		B-12	28	

Appendix B: Occupant Questionnaire

Questionnaire for the selection of users carried out by the Government of Extremadura before the installation of the equipment was completed by 255 people. Its contents are as follows:

1. User data
   - E-mail address and name
   - Public department work
   - Age and gender
2. Housing data
   - Home address
   - Type of housing: single-family, block
   - Cadastral reference
   - Possible renovations carried out
     - o. Before 1979, 1980–2007, after 2007
     - o. Air conditioning/heating systems, replacement of windows, modification of insulation elements, and other energy efficiency–related work
   - Existence of energy efficiency certificate
   - Existence of Internet connection and permanent Wi-Fi
   - Number of occupants (and also the number of minor and dependents)

Descriptive questionnaire carried out by UEx, with the aim of collecting descriptive data on the dwellings and the habits of the occupants, was answered to by 37 users of the previous ones. Its content are as follows:

1. Situation of Sensors
   - Outdoor sensor location: protected from wind and rain, unprotected from wind and rain, protected from solar radiation, others
   - Indoor sensor
     - o. Number of people usually in the room where the indoor sensor is located: none, one, two, three, four, or more
     - o. Location: living room–dining room, bedroom, kitchen, corridor or hall, bathroom or toilet, office, study room
     - o. Location near: window, computer, two or more computers, TV, appliances, outside wall
2. Hygrothermal comfort and air quality
   - Thermal sensation in summer and in winter: always hot, often too hot, occasionally hot, comfortable, occasionally too cold, often cold, always cold
   - Temperature (°C) of the thermostat on the climatization systems, minimum comfortable temperature, and maximum comfortable temperature: in summer (≤ 24, 25, 26, 27, 28, ≥29, do not know, do not have) and in winter (≤19 ≤ 19, 20, 21, 22, 23, 24, do not know, do not have)
   - Ventilation:
     - o. Frequency: daily, every 2 or 3 days, sporadically
     - o. Duration: less than 30 min, between 30 min and 1 h, or more than 1 h
     - o. Schedule in summer (early in the morning, do not have a fixed time, during the night) and in winter (always at midday, do not have a fixed time)
3. Housing data
   - Type of housing: single-family, residential block (top, first, or middle floor)
   - Relationship to the outdoors: with living space under a sloping roof, with uninhabited space under the sloping roof, with a flat roof
   - Layers of facade walls: one single layer, two layers and air chamber between them, two layers and thermal insulation between them, ventilated façade, do not know
   - Changes since the first questionnaire: insufflation of thermal insulation in the air chamber of envelope, carpentry for better ones, additional windows (double windows), awnings, lamps to led, more efficient climatization systems, photovoltaic panels, better energy rating domestic appliances, number of people living in the house, habits, energy efficiency certificate, location of sensors, others
   - Windows:
     - o. Material: PVC, aluminium with thermal break, standard aluminium, wood
     - o. Opening system: sliding, casement
     - o. Blind: integrated/not integrated in the window, do not have
     - o. Glass: simple, double with chamber, do not know
     - o. Solar protection system in addition to the blind: do not have, awning, lattice, others
     - o. Climatization system
     - o. Usage when uncomfortable in summer and in winter: yes, regardless of consumption; no,

depending on the different sensation among the users; no, due to cost; others

o. Type of energy: electric, solar, city gas, diesel, biomass, others

o. Type: individual, community, do not have

o. Possibility to switch transmitters on or off independently: yes, no

4. Usage habits, mark the actions you usually carry out
   - Set the thermostat 1° lower an hour before going to bed
   - Set the thermostat at a lower temperature at night than during the day, or switch off the system
   - Raise the blinds in winter in areas exposed to solar radiation
   - Lower the blinds in summer in areas exposed to solar radiation
   - Wear seasonally appropriate clothing

Appendix C: Quality Control Data

This section outlines the quality control procedures for identifying erroneous data from the network's sensors of the sample and ensuring the accuracy of the data used for the subsequent analysis. The quality control was designed based on the particularities involved in hourly urban climate database [66, 67] but also taking into account the CWSs [68, 69]. Therefore, a multilevel control approach was used (Table A2):

- Initial data: Once the hourly data has been collected, a single database of static and dynamic data is created, broken down by dwelling, according to the period of analysis (month or week).
- Checking indoor–outdoor data: To begin quality control, the temperature data for each dwelling, both indoor and outdoor, is checked. Dwellings lacking either type of temperature data are then eliminated.
- Existing daily data: The data available for each dwelling is verified on a daily basis. Only days with at least 50% of the data in the analysed period were selected for examination, as a smaller percentage is insufficient to characterise the entire day.
- Outliers: In addition to monitoring indoor thermal oscillation, the average indoor and outdoor temperatures were checked to identify any extreme values that may be outliers. Discordant values due to incorrect sensor placement were eliminated, such as outdoor temperatures that were much higher than expected for that location or anomalous indoor values with improbable PPDs. At the same time, any values that exceeded the climatic absolute physical limits has also been removed, some cases due to high maximum outdoor temperatures that could have caused solar radiation–induced errors. Furthermore, repetitive values over extended periods may be due to recording failures. By considering the typical temperature cycles, it is possible to estimate the number of repetitions for erroneous data. The threshold has been set at 5 repetitions, which is a period during which outdoor temperature should change. In this case a Z-score higher than 1 has been applied to identify records not corresponding with the natural variability of the temperature series. Lower values resulted in numerous false positives, erroneously marking correct values as outliers. However, increasing the threshold was so loose that registration errors went unnoticed and were included in the database

TABLE A2: Number of dwellings or kits obtained at each stage of the multilevel quality control process.

<table>
<tr><th></th><th></th><th>Initial data</th><th>Checking indoor–outdoor data</th><th>Existing daily data</th><th>Outliers</th><th>Final data</th></tr>
<tr><td rowspan="2">November 21</td><td>Indoor sensor</td><td>67/41589</td><td>51/32364</td><td>50/28808</td><td>50/27757</td><td rowspan="2">47/27757</td></tr>
<tr><td>Outdoor sensor</td><td>51/29143</td><td>51/29143</td><td>50/28791</td><td>50/21853</td></tr>
<tr><td rowspan="2">April 22</td><td>Indoor sensor</td><td>76/40559</td><td>58/29631</td><td>56/24287</td><td>55/23477</td><td rowspan="2">41/23477</td></tr>
<tr><td>Outdoor sensor</td><td>58/24958</td><td>58/24958</td><td>56/24001</td><td>56/17680</td></tr>
<tr><td rowspan="2">1st week of July</td><td>Indoor sensor</td><td>96/14767</td><td>62/9536</td><td>57/8612</td><td colspan="2">50/8032</td></tr>
<tr><td>Outdoor sensor</td><td>62/8733</td><td>62/8733</td><td>57/7329</td><td colspan="2">50/6662</td></tr>
<tr><td rowspan="2">2nd week of January</td><td>Indoor sensor</td><td>58/9624</td><td>40/6640</td><td>35/5322</td><td colspan="2">33/5128</td></tr>
<tr><td>Outdoor sensor</td><td>40/6189</td><td>40/6189</td><td>35/4658</td><td colspan="2">33/4608</td></tr>
</table>

Appendix D: Indoor CO_2 Concentration of the Sample of Dwellings According to both Construction Periods

The following figures (Figures A1, A2, A3, and A4) collect the data related to indoor CO_2 concentration.

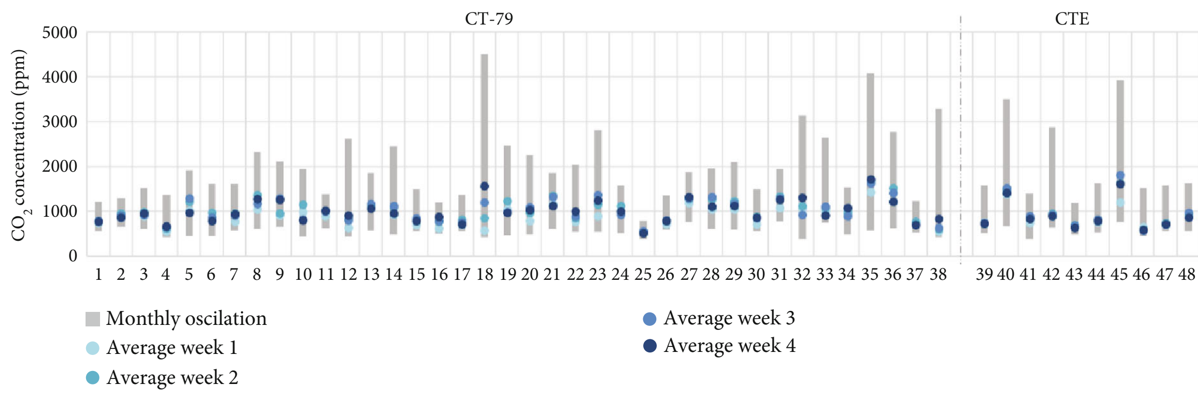


Figure A1: November 2021 data.

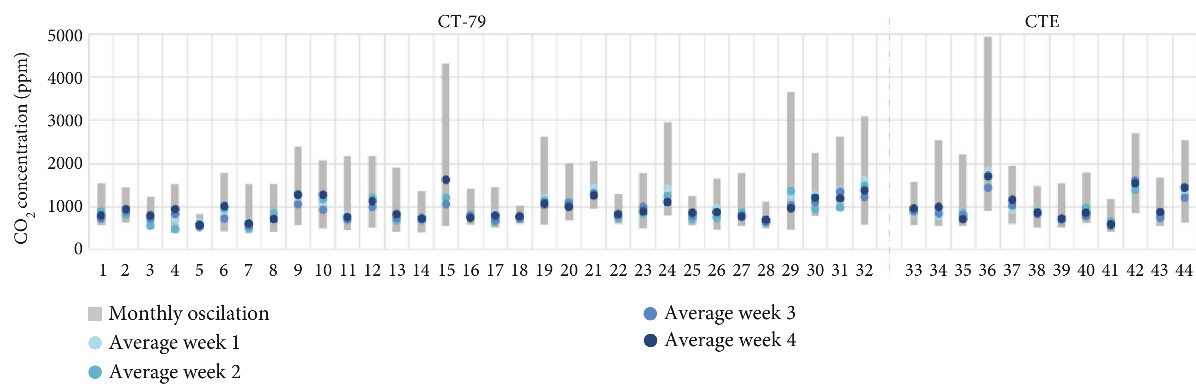


Figure A2: April 2022 data.

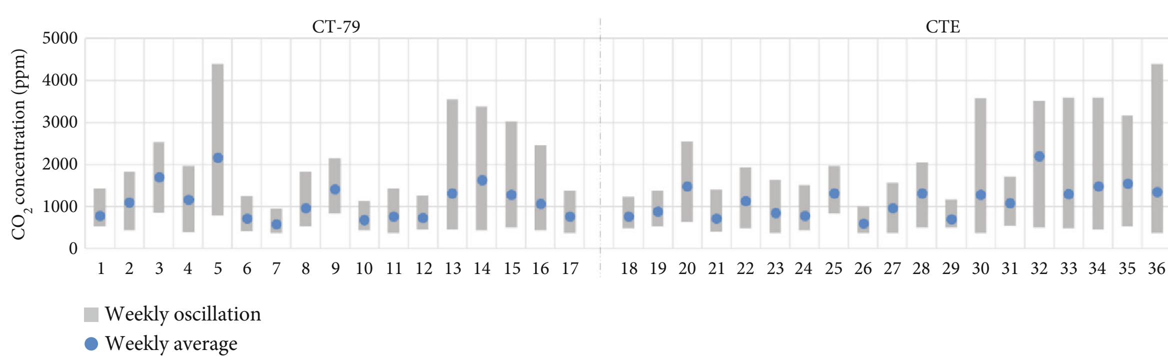


Figure A3: Extreme winter week data.

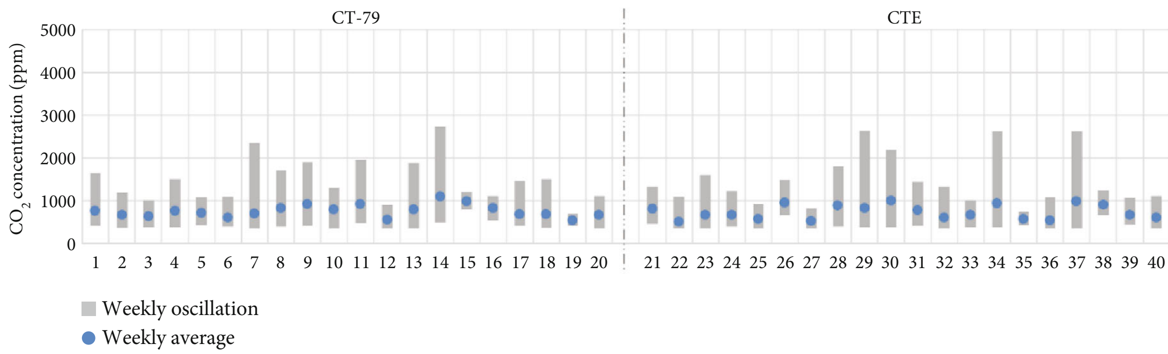


Figure A4: Extreme summer week data.

Appendix E: Average of the Values of the Time Lag and Decrement Factor According to the Analysed Period for Each Case Study

The average of the values of the time lag and decrement factor are presented in Table A3.

TABLE A3: Average of the values of the time lag and decrement factor according to the analysed period for each case study.

November 2021						April 2022					
N° KIT	CT-79 Average decrement factor	Time lag (min)	N° KIT	CTE Average decrement factor	Time lag (min)	N° KIT	CT-79 Average decrement factor	Time lag (min)	N° KIT	CTE Average decrement factor	Time lag (min)
012	0.56	327	003	0.20	648	021	0.11	260	022	0.23	258
014	0.23	260	007	0.45	493	023	0.13	466	029	0.33	326
021	0.41	558	022	0.26	456	024	0.20	422	058	0.13	645
023	0.12	515	029	0.36	347	030	0.24	353	063	0.10	438
024	0.18	534	045	0.23	243	046	0.23	390	064	0.13	220
030	0.37	490	056	0.90	486	053	0.24	424	089	0.15	366
042	0.22	596	062	0.30	594	055	0.64	174	109	0.06	498
046	0.53	432	063	0.10	664	087	0.35	302	115	0.25	482
053	0.32	494	080	0.38	630	088	0.16	152	116	0.15	493
054	0.67	567	109	0.11	448	091	0.15	282	278	0.23	452
055	0.65	150	115	0.49	410	092	0.11	527	183	0.16	520
078	0.19	587	116	0.17	499	182	0.57	375	190	0.44	477
092	0.18	540	278	0.31	431	195	0.16	426	226	0.34	231
182	0.66	519	183	0.29	634	196	0.32	266	234	0.33	354
191	0.20	576	189	0.26	694	210	0.20	175	235	0.22	430
195	0.38	474	190	0.74	614	222	0.16	240	250	0.14	360
196	0.29	134	209	0.80	427	223	0.16	503	251	0.24	357
201	0.58	306	226	0.33	300	245	0.26	386	263	0.11	430
210	0.23	514	228	0.50	372	259	0.18	420	264	0.15	511
219	0.27	289	247	0.45	623	266	0.41	360	268	0.06	340
222	0.24	270	263	0.20	236				272	0.16	538
223	0.26	444	272	0.48	648						
270	0.22	552									
275	0.34	462									
Average	**0.35**	**441**	**Average**	**0.38**	**493**	**Average**	**0.25**	**345**	**Average**	**0.20**	**415**
σ	**0.17**	**0.18**	**σ**	**0.21**	**0.18**	**σ**	**0.14**	**0.08**	**σ**	**0.10**	**0.07**

The time lag (φ) is the time it takes for the heat wave to propagate from the outdoor towards the indoor of the building, and the decreasing ratio of its amplitude during this process is termed as "decrement factor" d_f or coefficient stability [70, 71]. Both were computed based on the following formulas (Equations (A.1) and (A.2)):

$$(\varphi) = t_{\mathrm{Ti\ max}} - t_{\mathrm{To\ max}}, \tag{A.1}$$

$$d_f = \frac{Ti_{\mathrm{MAX}} - Ti_{\mathrm{MIN}}}{Te_{\mathrm{MAX}} - Te_{\mathrm{MIN}}}. \tag{A.2}$$

where $t_{\mathrm{Ti\ max}}$ and $t_{\mathrm{To\ max}}$ are the time when inside and outside temperature are maximum, Ti_{MAX} and Ti_{MIN} are the maximum and the minimum indoor temperature, and Te_{MAX} and Te_{MIN} are the maximum and minimum outdoor temperature.

Data Availability Statement

The data presented in this study can be obtained from the corresponding author upon request.

Disclosure

A preprint of this work has previously been made available [72].

Conflicts of Interest

The authors declare no conflicts of interest.

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