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A STUDY ON HYGROTHERMAL CONDITIONS IN INTERMITTENTLY HEATED OR UNHEATED BEDROOMS IN SOUTHERN EUROPE

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Abstract

Indoor hygrothermal parameters have an important role in the assessment of indoor air quality (IAQ) and comfort. In fact, the perception of air quality is strongly influenced by temperature (T) and relative humidity (RH). In Northern Europe, due to the severe climate conditions during winter, it is common to adopt continuous heating to guarantee sufficient thermal comfort in residential buildings. On the contrary, in Southern European countries, due to the specific climate, economy and culture, a permanent heating practice in winter is generally not adopted. Consequently, the indoor climate in Northern and Southern Europe is expected to be quite different, and this discrepancy should be taken into account when designing retrofit interventions aimed at improving indoor comfort and lowering energy demands. In particular, when studying the properties of interior coating materials, T is commonly set between 20-25 °C and RH in the range 33-75%. These are considered acceptable and common indoor conditions for continuously heated buildings, but they might be not representative of Southern European reality.

For the present study, four residential buildings were chosen in the city of Lisbon. The indoor air T and RH were continuously recorded for one bedroom in each building during wintertime. The bedrooms are characterized by a floor surface of 7.5-10 m^2, the occupancy of one person during an average of eight hours, natural ventilation and the presence of one window North/Northwest oriented and with manually-regulated shading. All rooms were monitored under operational conditions, with users adopting intermittent heating (room heaters) or no heating at all. The main differences between the case studies concern the floor where the apartments are located and the constructive characteristics of the buildings. The indoor hygrothermal conditions obtained in the monitoring campaign are discussed in this paper and indoor thermal comfort is evaluated. Finally, despite the differences between the case studies, an approximation of the overall indoor T and RH fluctuations is provided.

1.1 INTRODUCTION

The importance of indoor environmental quality (IEQ) is nowadays largely acknowledged due to the extended amount of time people spend indoor [1]. Consequently, the study of parameters as indoor thermal comfort [2, 3, 4], indoor air quality [5], perceived quality [6] and the correlation with human health [7] gained importance in research. In this context, the adoption of building materials that help passive regulation of indoor humidity has got increasing attention during the 21st century [8] mostly by the use of hygroscopic coating systems [9, 10]. In this case, the idea is to exploit the moisture buffering ability of the materials to improve indoor hygrometric conditions. Indeed, hygroscopic materials tend to absorb moisture when RH rises and then release it when the air gets drier [11], thus moderating the peaks in indoor RH and reducing the need of operational energy [12, 13] while passively improving indoor comfort.

In order to evaluate and compare the moisture buffering ability of materials, the most commonly adopted method is the NORDTEST [14, 15]. This test procedure was defined by a research group working on the specific scenario of North European countries [16] and it is based on the hypothesis of continuously heated buildings (e.g. indoor set-point T at 23°C [17]). The methodology was defined considering an occupancy of about 8 h per day, which is typical of several spaces, e.g. offices and bedrooms [18]. Three possible ranges of RH were proposed, and the one normally adopted spans 33%-75%. Even though some other procedures do exist, for instance ISO 24353 [19], the NORDTEST method is the most largely adopted because it allows for a quantitative evaluation of the moisture buffering capacity [16] of materials through one parameter only: the practical Moisture Buffering Value (MBV). Hence, this test procedure is very valuable and it allows to compare the potential effectiveness of different hygroscopic materials and coating systems through their MBVs. Nonetheless, although the great contribution provided by the introduction of the NORDTEST procedure, some doubts might arise when it is adopted in the context of Southern European countries. Indeed, in Southern Europe a permanent heating practice is generally not adopted, especially in residential buildings [20]. On one hand, this is a consequence of the milder winter conditions. On the other, the combination of low incomes and high energy costs leads to a general 'Lack of Motivation to Heat', which is extremely high in Portugal, Romania and Greece, and lower but still relevant in other Southern European countries like Spain, Croatia and Italy [20]. Therefore, despite the moderate winter T, Southern European countries are often found to offer uncomfortable indoor hygrothermal conditions for most wintertime, because of the intentionally low use of heating devices [21]. For this reason, lower indoor T and consequently higher RH are expected for Southern countries and this specific situation may require a complementary approach that differs from the standard test conditions of the NORDTEST.

Hence, this study analyses the hygrothermal data obtained through an indoor monitoring campaign performed in 4 different buildings located in Lisbon, Portugal. In each case study, the data was recorded in one bedroom, for the sake of creating a symmetry with the type of space (occupation for 1/3 of the day) considered in the NORDTEST. The monitoring was performed during winter, as it is the period when the benefit of hygroscopic coatings can be best exploited because windows are kept closed most of the time. It is indeed clear that the higher the ventilation rate, the minor the benefit of hygroscopic materials gets [10]. The dataset thus obtained is examined to evaluate the fluctuation of indoor RH and compare it to the scenario adopted in the NORDTEST, while considering possible alternative approaches. Furthermore, indoor hygrothermal comfort is assessed to evaluate if the case studies considered do align with the considerations raised in literature concerning the lack of motivation to heat, the energy poverty and the very low comfort conditions generally affecting residential buildings located in Southern Europe, during winter.

1.2 METHODOLOGY

Case studies and indoor microclimate monitoring

Four case studies were selected for the experimental monitoring campaign. The four buildings are located in the core of the city of Lisbon, as displayed in Figure 1, and the T and the RH were continuously measured in one bedroom for each case study.

Figure 1. Localization of the case studies in the map of Lisbon.

For each case study, a picture of a facade of the building and a plant of the bedroom under study are provided in Figure 2. The selected twentieth-century buildings were built before 1990, when the first Portuguese regulation of thermal requirements for buildings has been published [22]. Therefore, except for one case study that was refurbished and thermally insulated in recent years, they are not expected to comply with it. The bedrooms considered are subjected to one-person occupancy and they are intermittently heated by the users with electric-heating devices or not heated at all.

Case study A (Figure 2.A) is a three-floor building whose envelope was recently refurbished. The bedroom considered is located on the 1th floor and it has an area of about 7.5 m^2. It has one external wall only, which is North-oriented and hosts a balcony. Case study B (Figure 2.B) is a building that does not appear to have been subjected to any relevant modification from the original state and it looks like the result of a social housing project of the second half of the 20th century. The bedroom chosen for the monitoring is on the upper ground floor and it has an area of about 8.4 m^2. It has one external wall, North-oriented, with one window.

Differently from all the others, case study C (Figure 2.C) is a detached house with an individual owner. The bedroom analysed is on the upper ground floor and it has an area of about 7.5 m^2. The bedroom has one external wall, West-oriented, with a window. Case study D (Figure 2.D) is an apartment building and the bedroom monitored is located on the 3rd and last floor. It has a floor area of about 11 m^2 and one external wall, West-oriented, with a balcony.

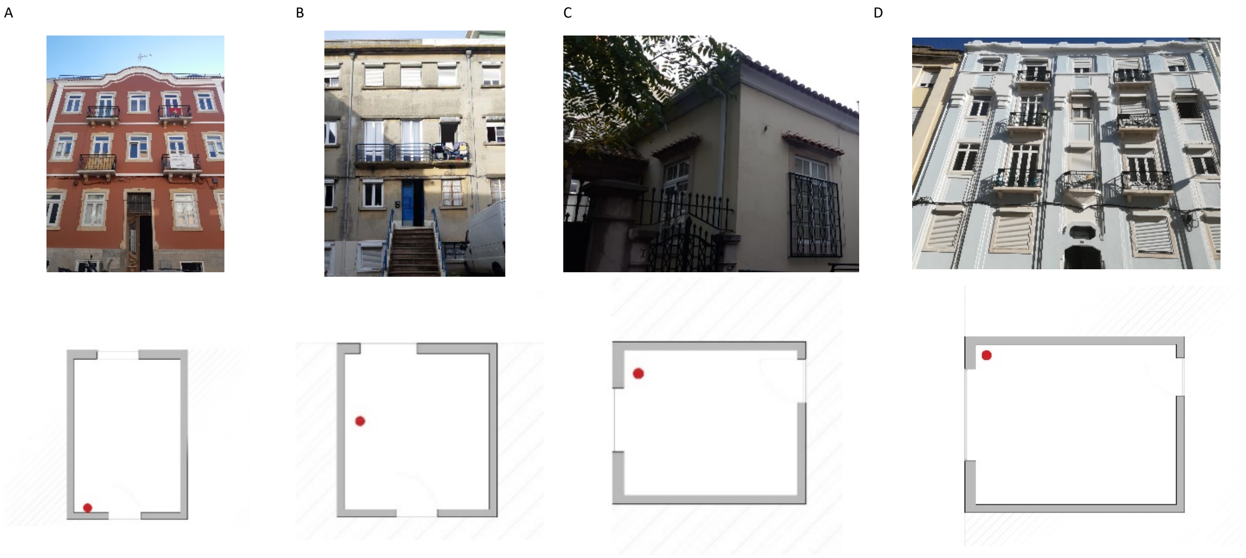

Figure 2. Selected case studies and plans of the monitored bedroom with a red dot indicating the position of the dataloggers adopted for recording environmental conditions.

The indoor monitoring campaign was performed by means of two dataloggers HOBO UX100-003 (accuracy: ±0.21°C, ±3.5% for 25- 85% RH and 5% out of this range) and two HOBO U12-013 (accuracy: ±0.35°C, ±2.5% for 10- 90% RH and 5% out of this range). The sampling interval adopted was 10 minutes and the final hygrothermal data were defined as the hourly average values of T and RH obtained from the recordings, as already done in previous studies [23, 24]. The dataloggers were positioned inside paper boxes (opened at the top) to avoid the interference of drafts and solar radiation on the measurements. Furthermore, they were located on the top of furniture, at 70 –180 cm from the floor, to reduce the possibility of direct interactions between the occupants and the sensors. Finally, a minimum distance of 10 cm was kept between the walls and the position of the dataloggers. The outdoor climate dataset was provided by the Portuguese Institute of Sea and Atmosphere (IPMA) [25], from a weather station located in Lisbon (GAGO COUTINHO STATION - Lat: 38.76620278; Long: -9.12749444; Altitude: 120m).

Period of measurements

The winter period considered in this study is 15th November-31st March 2021 and it was determined following the definition of heating season based on the degree days' calculations. Given that the Portuguese legislation [26] that defines degree days does not include a specific identification for the start and end date for the heating period, the Italian classification of climatic zones and heating season was adopted [27]. This choice was considered suitable for the scope as both Portugal and Italy are South-European countries and, what is more, the results obtained appeared representative for the Portuguese climate.

The classification refers to the heating degree-days calculated by eq. (1) according to [28]:

$$DD = \sum_{e=1}^{n} (T_i - T_e) \qquad (1)$$

In eq. (1) n is the number of days considered in the evaluation, T_i is the indoor air T, fixed at 20°C [29] and T_e is the outdoor average air T on the e-day. In this calculation, the days that have a T_e higher than 20°C are excluded as they are not considered to require the use of indoor heating devices. The heating degree days obtained for the city of Lisbon, based on data recorded during the year 2019-2020 by IPMA, were 1307, which correspond to a climatic zone C. This result indicates a heating period lasting from 15th November-31st March 2021, according to Italian standard [27].

1.3 RESULTS AND DISCUSSION

Climatic data and statistical evaluation

Figure 3 shows the hourly data of T and RH obtained in the indoor environmental monitoring, versus the ones recorded by IPMA for the outdoor climate conditions, in winter. According to the collected data, during winter the outdoor T ranged 1-26°C and the RH around 40-100%, with the T being lower than 16 °C for most of the time and RH being generally above 75%. Regarding indoor climates, hygrothermal conditions stayed between 10-28°C and 21-90% RH.

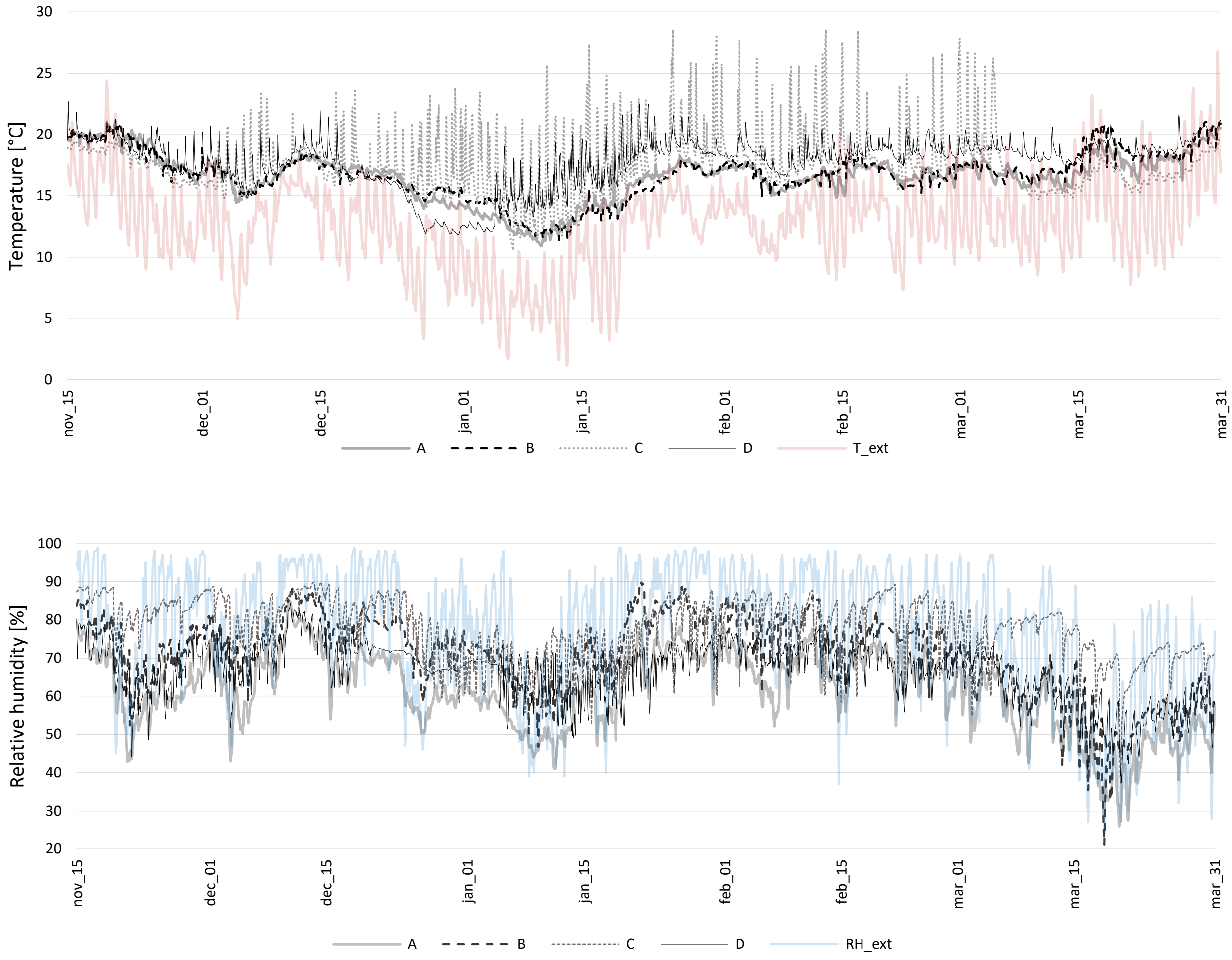

Figure 3. Hourly average air temperature (°C) and relative humidity (%) data recorded by IPMA for the city of Lisbon and the same parameters recorded indoor the four bedrooms (A, B, C and D) for the period 15th November – 31th March.

To analyse the typical range of variation of indoor T and RH in the residential buildings in Lisbon, a statistical evaluation was applied, and the results are shown in Figure 4. The curve of accumulated frequency reported in Figure 4 clearly shows that the lower threshold value considered in the NORDTEST is not very representative of the indoor hygrometric conditions analysed. Indeed, this condition was never reached in case studies C and D, while such low levels of RH, namely under 35%, are obtained for less than 5% of the time in the other 2 case studies. This result indicates that a RH level around 33% is not representative of a typical daily peak of low humidity but it is more of an exceptional condition in the case studies considered. This outcome is definitely coherent with the heating strategy adopted in the case studies: while continuous heating may lead to low levels of RH, intermittent or absent heating leads to lower T which entail higher RH levels. As far as the upper limit value of the NORDTEST is concerned, i.e. 75% RH, it seems quite representative of a typical condition of high RH for case studies A and D, as indoor hygrometric conditions are below this value for 80% of the time or more. On the contrary, much higher RH levels can be found in case studies B and C, where a RH higher than 75% is detected during 60% and 40% of wintertime, respectively. Even for T, the range considered (23°C ± 0.5°C) does not appear to represent typical indoor conditions in the analysed bedrooms. Indeed, lower T than 22.5°C are found for more than 90% of the time in all the case studies taken into analysis.

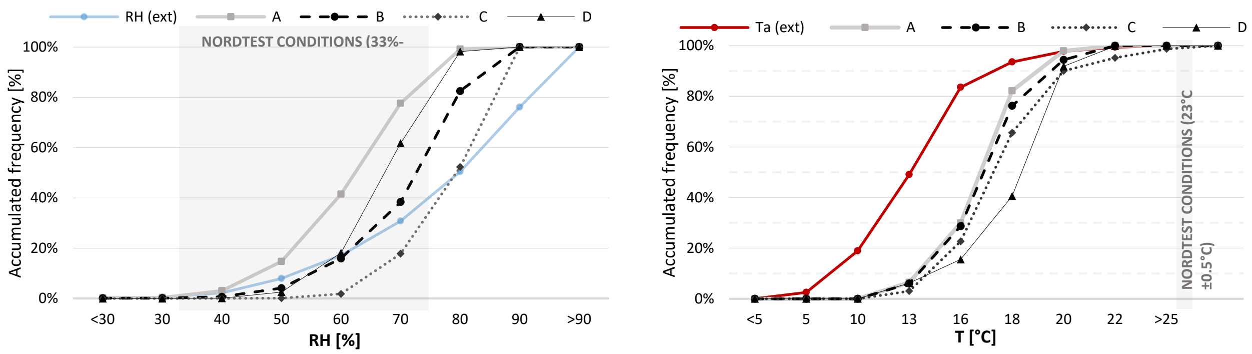

Figure 4. Relative humidity and temperature distribution in winter period 15th November – 31th March in each of the four bedrooms and outdoors.

In order to have a representation of a typical range for indoor RH and T fluctuations, two intervals are hereby considered: the 90th – 10th percentile (P90% – P10%), excluding the values that are only recorded 10% of the wintertime for being very high or low, and the more restrictive interval 75th – 25th percentile (P75%, P25%). Considering all case studies, the average values of P75% and P25% are 63% - 16°C and 76% - 18.5°C, whereas the average values obtained for P10% and P90% are 56% - 14.5°C and 82% - 19.5°C, as reported in Figure 5. According to this analysis, a typical range of fluctuation would be 63-76% RH and 16-18.5°C (considering 25th – 75th percentiles) or 56%-82% for RH and 14.5-19.5°C (accounting for 10h – 90th percentiles). The proposed ranges are hereby assumed as representative of the indoor climates considered, and they are compared to the indications provided for RH by ISO 24353 [19] and NORDTEST [16], as well as the dataset measured in situ. From the qualitative comparison provided in Figure 5, the step 50-75% RH suggested by ISO 24353 [19] for a “middle humidity level” appears to better estimate the indoor data-set and it is closer to the ranges hereby proposed than the NORDTEST. In the latter, the minimum RH appears extremely lower than the values of indoor RH registered, and it is relevantly minor than the lower limits estimated with P10% and P25%. This difference between typical testing conditions and real climates might potentially result in an overestimation of the potential benefits of hygroscopic materials applied in the Southern European context. In fact, the conditions of the NORDTEST have a greater range of RH and a much lower minimum value, which would probably result in higher desorption values than at “more realistic conditions”. For this reason, it could be valuable to have further studies aimed at evaluating the scenario of Southern European countries and a possible complementary approach to adopt for applications of hygroscopic materials within this context. Regarding T, both the methods (ISO and NORDTEST) account for a T of 23±0.5°C, which is quite far from the ranges hereby observed (16-18.5°C and 14.5-19.5°C). Even though the effect of T on the moisture buffering in building materials is hardly ever investigated, according to Mazhoud et al. [30] a linear correlation between T and MBV exists, probably for the effect of T on saturation vapour pressure [31], and the possibility of considering a specific T for Southern European climate may be an option to consider in future investigations.

Indoor comfort

The standards ISO7730 and ASHRAE55 [32, 33] for the evaluation of indoor comfort, refer to calculation of predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD), taking into account metabolic rate, clothing insulation, air T, radiant T, air speed and RH. Nevertheless, for residential spaces some of these parameters are of difficult representation, due to the uncertainty on the activities performed, the variability of clothing, the use of the windows, etc. Thus, an adaptive model would better represent comfort conditions for the residential case studies. As referred by Peeters et al. [34] for bedrooms, winter T should be higher than 16°C to guarantee neutral or comfort sensation for the occupants. Furthermore, a RH range of 30-70% is recommended by ISO 7730 [32] for indoor air quality reasons. Comparing the datasets obtained via indoor monitoring with the mentioned ranges of acceptable hygrothermal winter conditions (T≥16°C, 30%≥RH≥70%), it emerges that all case studies are unable to provide comfortable indoor conditions for at least 50% of wintertime (i.e. above 70% for case studies B and C and around 51% for the other two). Furthermore, it is evident that the global discomfort in all the monitored bedrooms is caused by low T and high RH, which is consistent with the complains made by the bedrooms’ users, who claimed the environmental conditions to be quite cold and very moist.

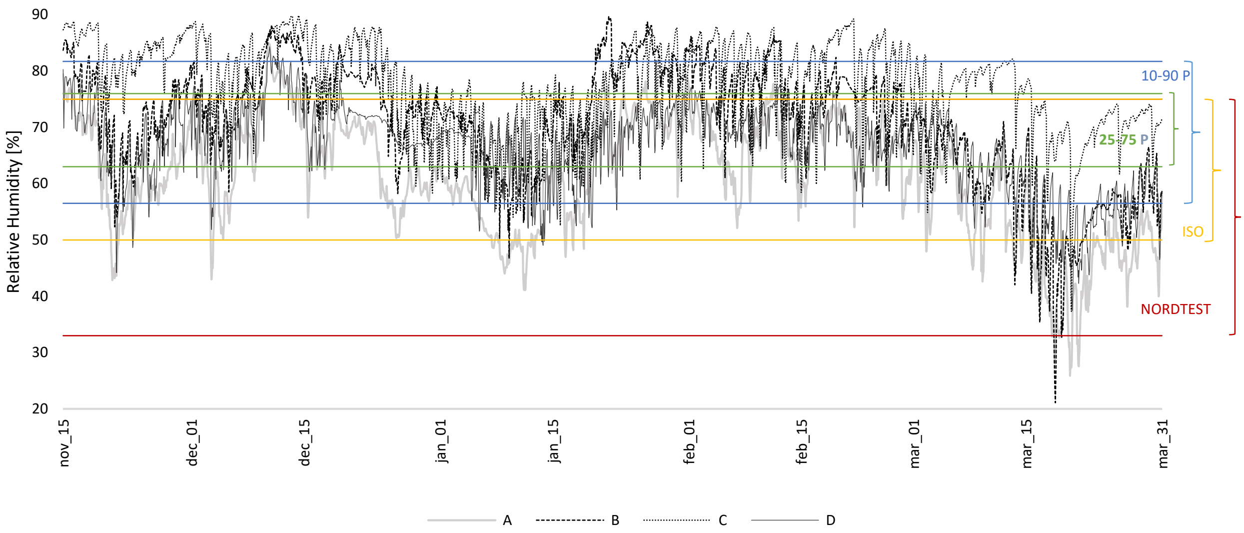

Figure 5. Indoor RH in each of the four bedrooms with 10th, 25th, 75th and 90th percentile and comparison with limits of the steps recommended by the standards [16] and [19].

1.4 CONCLUSIONS

From the collected data, a realistic representation of indoor environmental conditions was defined through the use of the 25th and 75th percentiles (63-76% RH and 17.5±1.5°C) and with 10th and 90th percentiles (55-80% RH and 17±2.5°C). The ISO 24353 sets the closest values with its step 50-75% RH, while the conditions commonly adopted for the NORDTEST procedure (33-75%) have a lower limit that does not seem representative for the indoor climates considered. Indeed, such low levels of RH are reached for less than 5% of the time in two case studies and never in the other two. Furthermore, the temperature adopted in both ISO 24353 and NORDTEST appeared to be much higher than the average conditions found in the experimental campaign. Overall, these outcomes suggest that the typical hygrothermal conditions adopted for determining the Moisture Buffering Value with the NORDTEST method might be not adequate for representing the moisture buffering capacity of materials when Southern European intermittently heated or unheated residential spaces are considered. Concerning indoor comfort, conditions out of the considered boundaries are observed for all case studies for at least 50% of wintertime, namely global discomfort is observed above 70% of the time for case studies B and C and around 51% of the time for the other two cases.

The present investigation represents a preliminary study and it is part of a wider research, which includes more case studies and longer monitoring periods. Further results will be soon provided for the sake of better evaluating the suitability of adopting different standard methods for testing the moisture buffering ability of building materials and products and their adaptability to the Southern European context.

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