Thermal comfort assessment of the first residential Passivhaus in Latin America

Abstract

New approaches to building design, such as the Passivhaus standard, aim to minimise energy consumption and improve indoor environmental comfort. In 2014, the first Passivhaus dwelling in Latin America was built, and since then, other buildings have followed this approach. However, there is little published data on thermal comfort in Passivhaus certified dwellings in non-European countries. No previous study has evaluated the thermal comfort in Passivhaus buildings in Latin America. This work aims to assess the annual overheating of the first Passivhaus dwelling in Mexico City following the Passivhaus, static (CIBSE Guide A, Passivhaus, Mexican standards) and dynamic (Adaptive approach – CIBSE TM52) methodologies to assess overheating.

Indoor temperature and relative humidity were measured over one-year at 5-minutes intervals. Temperatures above 25°C were observed in the bedroom during 7.53% of the year, the living room (8.03%) and the kitchen (8.20%). There was a significant daily temperature variation in the kitchen (4.15°C) and living room (6°C). Overheating was observed through the CIBSE Guide A static criteria in the bedroom and kitchen. The Adaptive and Passivhaus criteria suggested no overheating. Passivhaus overheating criteria sets indoor temperatures as acceptable. Occupant perception of thermal comfort matched the Adaptive and Passivhaus criteria results. While the results presented here cannot be generalised, they could be used to help improve the design and performance of Passivhaus certified dwellings in similar climates'. The results highlight the potential for Passivhaus dwellings to provide comfortable indoor environments while minimising energy consumption in Latin American countries.

Keywords: The Thermal comfort; Passivhaus; Building performance evaluation; Adaptive comfort; Mexico.

1. Introduction

The way homes are designed and built has evolved in the past few years, driven in part by "*…rising energy prices, increased resource competition and a moral imperative to create a sustainable built environment* (Hopfe and McLeod, 2015, p. 3)". The built environment is estimated to be responsible for over 40% of global energy consumption (Anderson, Wulfhorst and Lang, 2015). Indoor environmental comfort plays a critical role in building energy consumption. Heating and cooling loads account for as much as 60-70% of the total energy consumption in homes (Pérez-Lombard, Ortiz and Pout, 2008). New approaches for low-energy homes – such as Passivhaus standard, LEED (Leadership in Energy & Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Methodology) – were introduced to minimise CO_2 emissions and energy consumption.

However, adopting a low-energy standard or regulation does not guarantee the desired results. Buildings can still exhibit performance gaps (Miguez *et al.*, 2006), such as overheating, poor indoor air quality (IAQ) and poor energy performance. For example, Australian (Kang *et al.*, 2021), French (Cayre *et al.*, 2011), Belgian (Hens, Parijs and Deurinck, 2010), Dutch (Tigchelaar and Daniëls, 2011), British (Kelly, 2011), and German (Sunikka-Blank and Galvin, 2012; Bauer *et al.*, 2021) low-energy homes often consume more energy than expected. Occupant behaviour in terms of heating expectations, lighting use and window opening, amongst others, could explain these gaps (Masoso and Grobler, 2010).

The Passivhaus concept evolved from Swedish passive solar architecture and super-insulated homes to reduce the heating demand and improve the thermal transmittance (U-Values) of building fabric, windows and doors, as evidenced on the Swedish SBN1975 Building Code. Passivhaus are "*…building[s], for which thermal comfort (ISO 7730) can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality conditions – without the need for additional recirculation of air* (PHI, 2017)." The Passivhaus concept is based on five fundamental principles: super-insulation, thermal bridge-free construction, airtight building envelope, use of mechanical ventilation with heat recovery (MVHR) and high-performance windows and doors (Moreno-Rangel, 2021). The most critical factor in Passivhaus design is to meet the heating load (≤15 kWh/m^{2}a) and heating demands (≤10 kWh/m^2) while maintaining thermal comfort levels (Schnieders and Hermelink, 2006). Indeed, thermal comfort is the centre from which Passivhaus develops, as it is taken into account in line with the peak supply air heating load considering supplied flow rates (30m^3/h per person), indoor temperatures (between 20-25°C) and treated floor area in the project (Feist *et al.*, 2015). The genesis of the Passivhaus approach was the reduction of energy consumption in colder climates. However, due to the robustness of the design approach and verification of construction, it is now being adopted across a variety of locations with varying climatic conditions. Given the emphasis on energy savings, a key question is what impacts this may have in warmer climates, and this case study provides new insights into a Passivhaus dwelling in Mexico.

Passivhaus dwelling design aims to reduce the heat exchange and indoor sources of heat that could cause overheating. In fact, due to the effectiveness of the envelope performance, overheating is the most critical concern for thermal comfort in Passivhaus buildings. Recent research suggests that to mitigate overheating, additional design practices such as avoiding solar radiation, providing shading, as well as the configuration, orientation and size of windows need to be considered (McLeod, Hopfe and Kwan, 2013; Lomas and Porritt, 2017). Nonetheless, overheating has been documented in Passivhaus dwellings (Ridley *et al.*, 2013; Foster *et al.*, 2016; Fletcher *et al.*, 2017). Grudzińska (2021) suggest that passive techniques could be used to improve their thermal performance. These techniques are: i) orientation of balconies, ii) external shading, iii) external partitions, iv) internal shading, v) allowing natural ventilation vi) minimising the internal gains.

A recent study also showed discrepancies between measured overheating with those simulated with the Passivhaus Planning Package (PHPP) (Finegan, Kelly and O'Sullivan, 2020). They found that the measured overheating was higher than the one simulated with the PHPP. Therefore, a more robust methodology could simulate overheating to bridge the simulated and post-occupancy building performance gap. Goncalves, Ogunjimi and Heo, (2021) found that the current model could undervalue overheating hours by 33.33% due to design infiltration and ventilation rate overestimation. Moreover, it is particularly sensitive to internal heat gains, solar absorptance and opaque conductivity. Indoor temperatures in dwellings are essential as thermal comfort diminishes with high temperatures, causing reduced productivity, sleep disturbance, impaired judgment, and diminished attentiveness (Peacock, Jenkins and Kane, 2010).

One of the most accepted definitions of overheating is "*[…] the phenomenon of excessive or prolonged high temperatures in the home, resulting from internal or external heat gains, which may have adverse effects on the comfort, health or productivity of the occupants*" (Zero Carbon Hub, 2015, p. 11). Different criteria are utilised to assess the risk of overheating, either through static or dynamic values, as explained below. Although numerous criteria define temperatures at which overheating can occur, there is not a universal definition (Zero Carbon Hub, 2012). Neither has an accepted standard for the domestic sector been established (Zero Carbon Hub, 2012, 2015). The CIBSE Technical Memorandum TM59 (2017) 'Methodology for the assessment of overheating in homes' attempted to address this by providing a consistent framework for evaluating overheating risk in new homes (Mourkos *et al.*, 2020). The TM59 is broken down into criteria for predominantly naturally ventilated homes, those that are predominantly mechanically ventilated, and communal corridors. Therefore, when assessing the risk of overheating, it is essential to address different criteria to understand the indoor temperatures better.

This work presents the thermal comfort assessment results of the first certified Passivhaus dwelling in Latin America. Temperatures were measured using a low-cost monitor that allowed remote monitoring. Thermal comfort was assessed using the Passivhaus criteria, the CIBSE Guide A, the Mexican Standard and the Adaptive approach. Additionally, the relative humidity and occupant perception were also assessed. Finally, this work also discusses further work for the development of the Passivhaus in Latin America.

2. Method

This work presents results from the Passivhaus dwelling monitoring conducted between the 1st of June 2016 and the 31st of May 2017. According to the Koppen climate classification, Mexico City has an Oceanic Subtropical Highland Climate (Cwb). These locations experience dry and warmer winters, with warm and wet summers (Kottek *et al.*, 2006). The Foobot, a low-cost monitor, was used to monitor air temperature [-40-125°C; ±0.4°C] and relative humidity [0-100%RH; ±4%RH] simultaneously at five-minute intervals in the bedroom, kitchen and living room. A total of three Foobot devices were used in each room; this allowed a higher degree of data quality, allowing for data comparison and corroboration. The Foobot was tested before this work and deemed to be reasonably accurate with minor variation in air temperature (-0.24°C, BCa 95% CI, -0.25°C to -0.23°C) and relative humidity (-0.01%RH, BCa 95 CI, -0.78%RH to 1.08%RH) (Moreno-Rangel *et al.*, 2018). The system was used as it could be deployed remotely, with remote collection of data and was acceptable to the building owners and occupants. The calibration equations are described in our previous work (Moreno-Rangel *et al.*, 2018). They were applied to every single data point to reduce the bias that low-cost sensors could suppose. The mean of each parameter at each time interval from the three Foobots was calculated. It was this score that was used to perform the analysis. As this was a long-term study, using the low-cost monitors would be highly difficult and add challenges for building occupants to install a different set of sensors. Hence, outdoor temperature and relative humidity were collected from the local atmospheric monitoring program's official website in Mexico City (http://aire.cdmx.gob.mx/).

Occupant perceptions of thermal comfort were collected using a certified survey as described by Raw (1995). This questionnaire was adapted from an online version. Participants were asked to complete the thermal comfort perception section once at the end of the study taking into account their perception for the complete seasons. Participants were asked to rate the temperature comfort, temperature cold/hot feeling, variations during the day and their overall satisfaction during summer and winter. Raw's survey is based on a seven-option unipolar (one extreme is good and the other is bad) and bipolar (neither end of the scale is ideal) scales, which were assessed as described by Raw (1995):

i. Unipolar scale:
   a) Ideal score: 1
   b) A score higher than 3 requires further investigation
   c) A score above 5 is cause for concern,
   d) Any score higher than the mean should be investigated further and ratings above one standard deviation above the mean should be a cause for concern.
ii. Bipolar scale:
   a) Ideal score: 4
   b) A score outside of the range 3 to 5 requires further investigation
   c) A score outside of the range 2 to 6 is cause for concern,
   d) Any score above one standard deviation above the mean should be a cause for concern.

As this was a long-term study, occupants were asked to provide a general weekly pattern use of the dwelling on which the occupancy patterns are based.

2.1. Thermal comfort assessment criteria

2.1.1.Dynamic criteria (Adaptive approach)

Overheating is not just a function of extreme temperature. Other factors are involved (Nicol, 2004), especially in buildings without mechanical cooling (Nicol and Humphreys, 2002). As explained in the CIBSE TM52, the adaptive approach considers indoor and outdoor temperatures from previous days and is considered a dynamic benchmark. The criterion calculated according to the maximum and minimum acceptable temperatures and daily mean outdoor air temperature from the CIBSE TM52 category II (normal expectation for new buildings or renovations):

Equation 1: $Upper\ limit{:}\ T_{max} = 0.33T_{tm} + 18.8 + 3$

Equation 2: $Lower\ limit{:}\ T_{min} = 0.33T_{tm} + 18.8 - 3$

where T_{min} and T_{max} represent the acceptable temperature and T_{rm} the outdoor running mean temperature calculated as follows:

Equation 3: $T_{rm} = (T_{od-1} + T_{od-2} + T_{od-3} + T_{od-4} + T_{od-5} + T_{od-6} + T_{od-7})/3.8$

Equation 4: $T_{rm} = (1 - a)T_{od-1} + \alpha T_{rm-1}$

where T_{od-2} represents the outdoor temperature daily mean for the previous day, T_{od-2} for the day before and so on; T_{rm-1} is the exponentially weighted running mean for the previous day and α is 0.8.

The adaptive method defines overheating in a building or room when it fails any two of the following criteria:

- **Hours of exceedance** limits the number of hours that the temperature can exceed the threshold comfort temperature. The temperature difference (ΔT) between the measured temperature (T) and the T_{max} should not be greater or equal than 1.0°C during the non-heating season (May to September) for any more than 3% of the occupied hours of this period.
- **Daily weighted exceedance** represents the severity of overheating in any one day. The criterion is passed when the daily limit for weighted exceedance (W_e) during occupied hours is less than or equal to 6. W_e is calculated using the following equations:

  Equation 5: $W_e = \sum(h_e + WF)$

  Equation 6: $\therefore W_e = (h_e \times 0) + (h_e \times 1) + (h_e \times 2) + (h_e \times 3)$
- **Upper temperature limit** refers to the maximum indoor temperature for a room or building. Hence, ΔT should never exceed 4°C.

Previous studies have used the TM52 methodology to assess overheating in warm tropical climates (Gamero-Salinas, Monge-Barrio and Sánchez-Ostiz, 2020). The climate in Mexico City is mild, and it is not common to use heating in Mexico. In this work, the non-heating season is defined as the period between May to September. The monitoring phase showed that the outdoor temperatures were the warmest in the year. Hence, we included the month of April as an extended period.

As stated earlier, in 2017, CIBSE published the 'TM59: Design methodology for the assessment of overheating risk in homes (2017).' This guideline is based on the principles of the TM52. However, it adds building simulation to help designers to predict the risk of overheating. Since the Passivhaus is already built, simulation is unnecessary as the overheating assessment is carried through physical measurements.

2.1.2. Static criteria

2.1.2.1. Passivhaus criteria

The Passivhaus defines thermal comfort in five different categories based on the percentage of annual hours of temperature above the 25°C thresholds at any point, as expressed in Table 1 (Feist *et al.*, 2015). Therefore, the benchmark described as Passivhaus criteria used in this work is 25°C during 10% of the annual hours.

Table 1: Frequency of overheating criteria in Passivhaus dwellings. Source (Feist et al., 2015).

% of time of temperature above 25°C	Assessment
≥15%	Catastrophic
10-15%	Poor
5-10%	Acceptable
2-5%	Good
<2%	Excellent

2.1.2.2. CIBSE Guide A

The CIBSE Guide A sets the overheating criteria based on a temperature threshold. The first criterion sets temperatures at 25°C in living rooms and 23°C in bedrooms at no more than 5% of the occupied hours and the second at 28°C in living rooms and 26°C in bedrooms at no more than 1% of the occupied hours.

2.1.2.3. Mexican standard

Mexico's national regulation (NMX-AA-164-SCFI-2013) establishes thermal comfort limits between 18°C to 25°C. However, it does not set a percentage of time on which the criteria may fail.

2.2. Relative humidity and absolute humidity

The Chartered Institution of Building Services Engineers (CIBSE) recommends levels of 40-60%RH for home spaces or optimally 65%RH for a comfortable temperature (CIBSE, 2006). The United States Environmental Protection Agency (EPA) advises home users to keep relative humidity levels below 60%RH, ideally 30-50%RH (EPA, 2012). For this study's purpose, a benchmark of 40-60%RH is used, as this is considered the most appropriate to fit with both CIBSE and EPA recommendations.

When assessing the indoor environment, psychrometric charts can be used to investigate the air's behaviour, showing the properties of the air temperature, relative humidity and moisture content on which one can define a comfort area. The CIBSE KS20 states that the psychrometric conditions for comfort are based on air temperature and relative humidity (CIBSE, 2012). Therefore, this study uses ideal (20°C-25°C and 40%RH-60%RH) and extended (18°C-28°C and 30%RH-70%RH) psychrometric conditions for comfort for living rooms and ideal (18°C-23°C and 40%RH-60%RH) and extended (16°C-25°C and 30%RH-70%RH) for bedrooms. The calculations for the psychrometric charts in this work were developed using the calculations described in the CIBSE Guide C (CIBSE, 2007).

2.3. Household characteristics

The Passivhaus is located west of Mexico City's historic centre with an orientation north to south, facing the predominant north and north-west winds. The layout is a multipurpose room (living room, kitchen and dining area) connected to a hall and from this to the bedroom and toilet (Figure 1 and 2). Two adults and one baby occupied the flat. The occupancy patterns and the frequency of window opening as described in the occupancy diaries are shown in Table 2. Figure 3 and Table 3 shows a summary of the building characteristics and construction details.

Table 2: Household characteristics.

Household characteristic	
Household occupancy	2 Adults, 1 child (>16).
Age range (years)	40-50, <15
Smoking	No
Daily occupancy pattern (bedroom)	00:00-06:30; 22:30-24:00
Daily occupancy pattern (kitchen)	07:30-09:00; 14:00-16:00*; 20:30- 21:30
Daily occupancy pattern (living room)	09:00-09:30; 14:00-16:00*; 21:30-22:30
Frequency of window opening (morning)	Rarely
Frequency of window opening (afternoon)	Occasionally
Frequency of window opening (evening)	Regularly
Frequency of window opening (night)	Constantly
* Only during weekends	

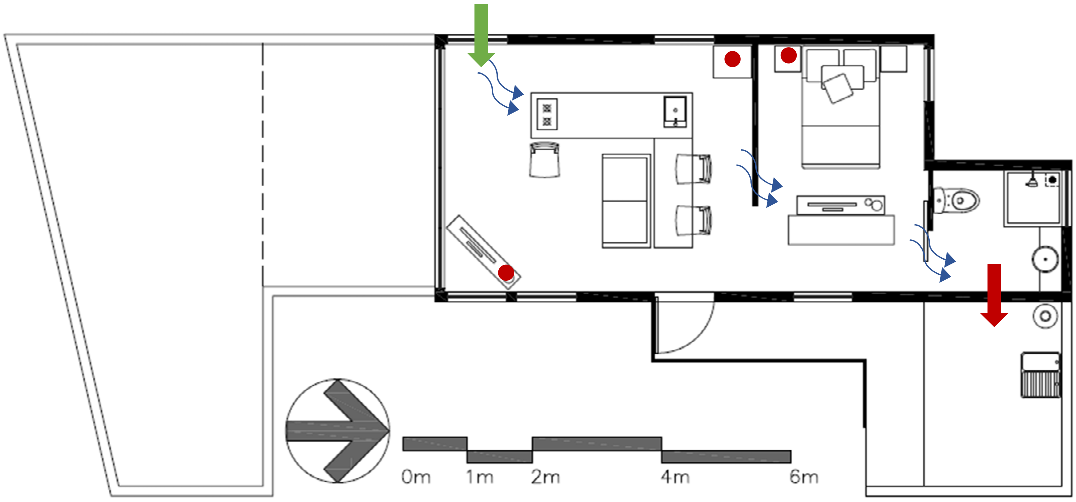

Figure 1: Passivhaus layout. The red dots indicate the placement of the sensors. The blue arrows indicate the ventilation flow. The green and red arrows represent the inlet openings and extraction fan, respectively.

Figure 2: External views from the Passivhaus flat in Mexico City.

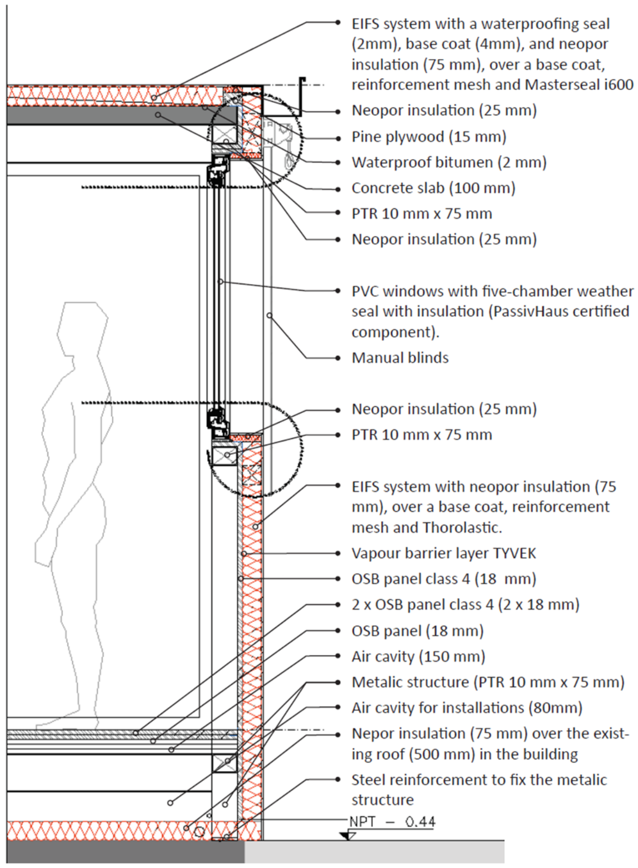

Figure 3: Construction details of the Passivhaus in Mexico City. Courtesy of INHAB.

Table 3: Main building characteristics of the Passivhaus.

Building characteristic	**Value**
Airtightness (n_{50})	0.59 h^{-1}
Floor area	42 m^2
Main door	PVC (Passivhaus certified)
U_g-value (window)	1.64 W/(m^2K)
U-value (floor slab)	0.33 W/(m^2K)
U-value (roof)	0.36 W/(m^2K)
U-value (wall)	0.37 W/(m^2K)
Ventilation	Mechanical extraction & cross natural ventilation

	Due to the mild climate, no MVHR was needed. An extraction fan ran intermittently to provide 42 m^3/h as calculated by the PHPP calculations—no kitchen hood.
Window type	Double-glazing 6 mm/ 12 mm air, 4 mm low-e-clear-claro (Passivhaus certified)
Building Standard	Passivhaus (certified)

Unlike most Passivhaus dwellings in Europe, the ventilation system in warmer climates can be hybrid, relying upon mechanical and natural ventilation instead of mechanical ventilation with a heat recovery (MVHR) system. This home used mechanical extraction ventilation—in the toilet—and three openings equivalent to 0.05 m^2—in the living room, the other end of the house. Although these openings were initially fitted with a filter as required by the Passivhaus standard (grade F7 – capable of filtering fine dust and $PM_{1\text{-}10}$), they were removed after six months due to maintenance issues. Figure 1 shows the location of the inlet openings and extraction fan. Before this study, the ventilation system was recommissioned to comply with the PHPP air flows (42 m^3/h). The extraction fan had a higher capacity (95 m^3/h), even after being installed (74.30 m^3/h), than those required by the PHPP. To compensate for those differences, a timer regulated the fan to work for 34 minutes per hour, with the option of being manually activated/deactivated.

3. Results

3.1. Prevalence of overheating accordingly to the dynamic criteria

The Adaptative method suggests that the overheating assessment should be carried between 1 May to 30 September. In this period, only the bedroom of the Passivhaus room failed the criteria. April was also assessed as it is considered a warm month in Mexico City. One may argue that the dynamic overheating criteria from the Adaptive approach could have been challenging to fail in locations with warm outdoor temperatures. For instance, the upper limit (T_{max}) annual mean was 27.67°C allowing for indoor temperatures up to 29.55°C (Figure 4).

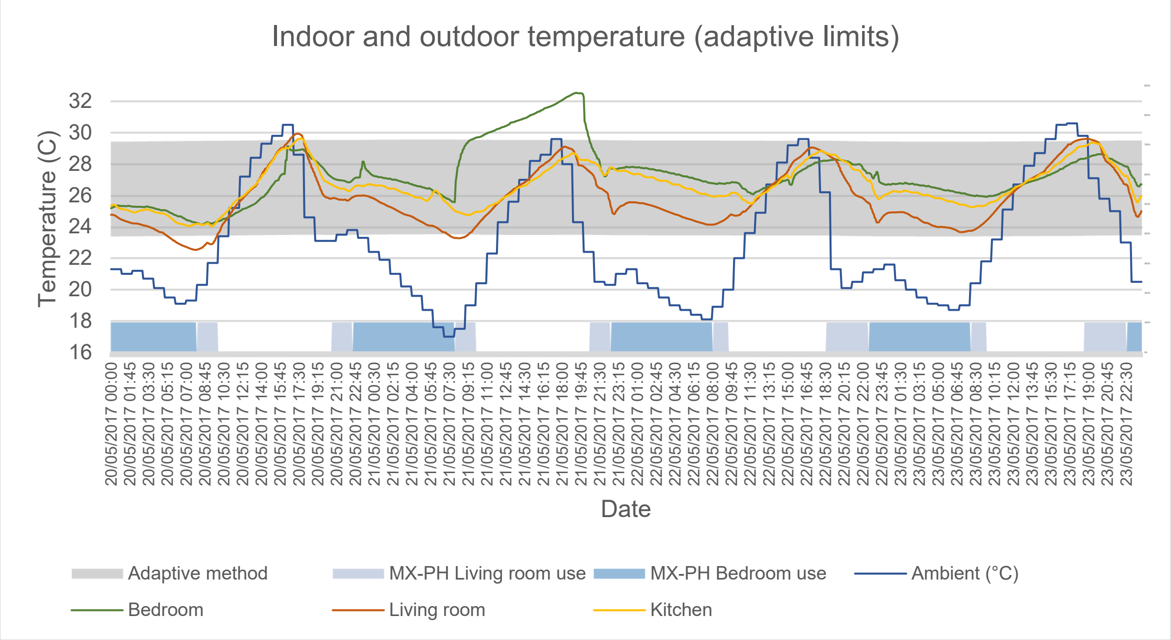

Figure 4: Indoor (bedroom, kitchen and living room) and outdoor measured temperatures between May 20th and 23rd, 2017.

3.1.1. Criterion 1 – Hours of exceedance

The bedroom was the only room that experienced several hours of exceedances where the operative temperature exceeded the maximum acceptable temperature by 1°C. Although this threshold was exceeded, this was not enough to fail the threshold. This period only represented 0.5% of the time between May and September. May was the month where all the overheating was recorded. In April, a similar number of hours failing the criteria were recorded in the bedroom. Nonetheless, extending the non-heating season to include April, this criterion would failover only 1%. Consequently, the Passivhaus dwelling fulfilled criterion 1.

3.1.2.Criterion 2 – Daily weighted exceedance

The daily weighted exceedance criterion failed in three days during May—8th, 21st, 24th, with scores of 7.16, 16.58 and 6.5 respectively in the bedroom, the only room where it failed. Additionally, April measurements showed that it failed in three additional days—16th, 25th, 26th, with scores of 14.91, 6.75, 10.91 and 6.5, respectively. These days were characterised by high outdoor temperatures, with peaks above 28°C. According to the National Metrological Service (SMN), 2017 has been the hottest year since records started in 1953, followed by 2019 and 2016. As such, criterion 2 failed.

3.1.3. Criterion 3 – Upper temperature limit

The upper temperate limit was not reached during the measurements, as the highest temperature difference (ΔT)—even expanding the non-heating seasons to start from April—was 3.02°C. Consequently, the Passivhaus dwelling fulfilled this criterion.

3.2. Prevalence of overheating accordingly to static criteria

Figure 5 shows the percentage of time exceeding the Passivhaus and CIBSE Guide A overheating thresholds. According to the Passivhaus criteria, the bedroom and kitchen thermal comfort was rated acceptable, as temperatures above the 25°C thresholds were 7.52% and 5.49% of the monitored time. While indoor temperatures were usually between the desired 20°C to 25°C, as suggested by the Passivhaus, the results also show that temperatures below 20°C were more common than overheating temperatures. Temperatures below 20°C were measured between 46.04% to 29.3% of the time, as shown in Figure 6.

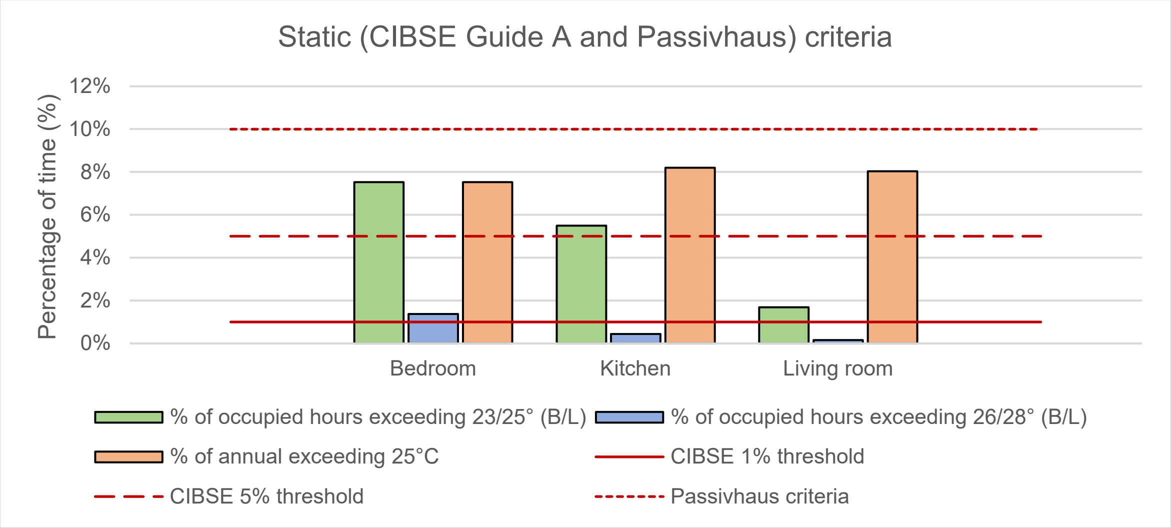

Figure 5: Percentage of time with temperatures exceeding the CIBSE TM52 and Passivhaus thresholds

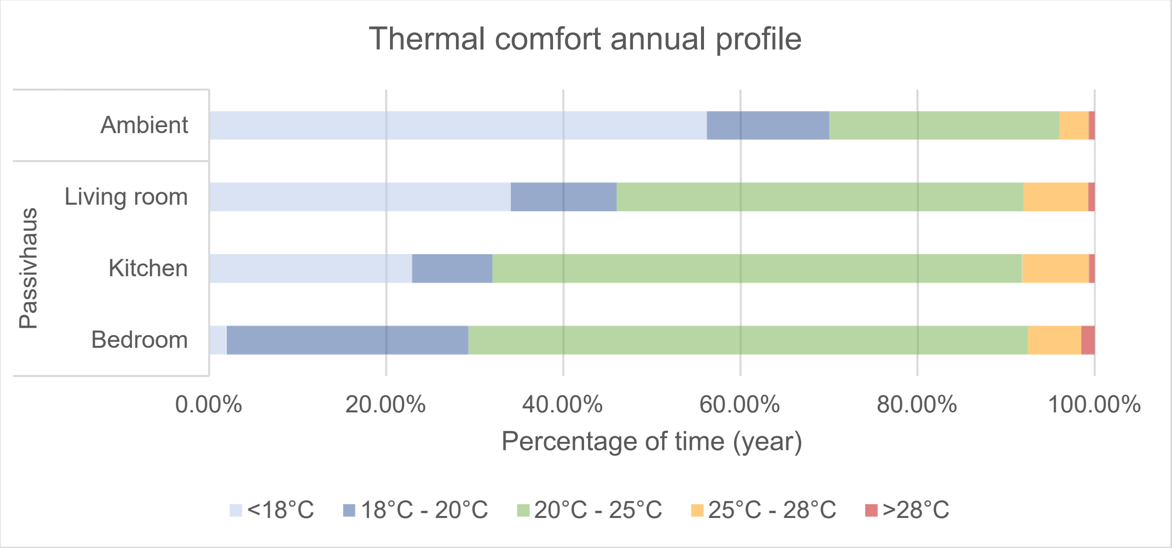

Figure 6: Annual thermal levels by ranges.

The CIBSE Gide A threshold of 5% of occupied hours at 23°C for the bedroom and 25°C for the kitchen and living room were exceeded by only in the bedroom and kitchen by 2.52% and 0.69%, respectively. Therefore, accordingly to the CIBSE Guide A, measured temperatures in the bedroom and the kitchen were associated with overheating. The Bedroom was the only space to exceed the 1% threshold of occupied hours at 26°C during as it exceeded this threshold by 0.37%.

3.3. Seasonal temperature variation

Analysis of the temperatures revealed that May and April are the most critical months during which outdoor temperatures could lead to overheating. Maximum indoor temperatures in the bedroom were 32.55°C in May and 30.82°C in April. The monthly temperature variations are shown in Figure 7. Overall, mean temperatures during May were the highest (25.52°C, 24.78°C, 24.31°C in the bedroom (B), kitchen (K) and living room (L) respectively) and January the lowest (B: 19.22°C, K: 19.17°C, L: 17.81°C).

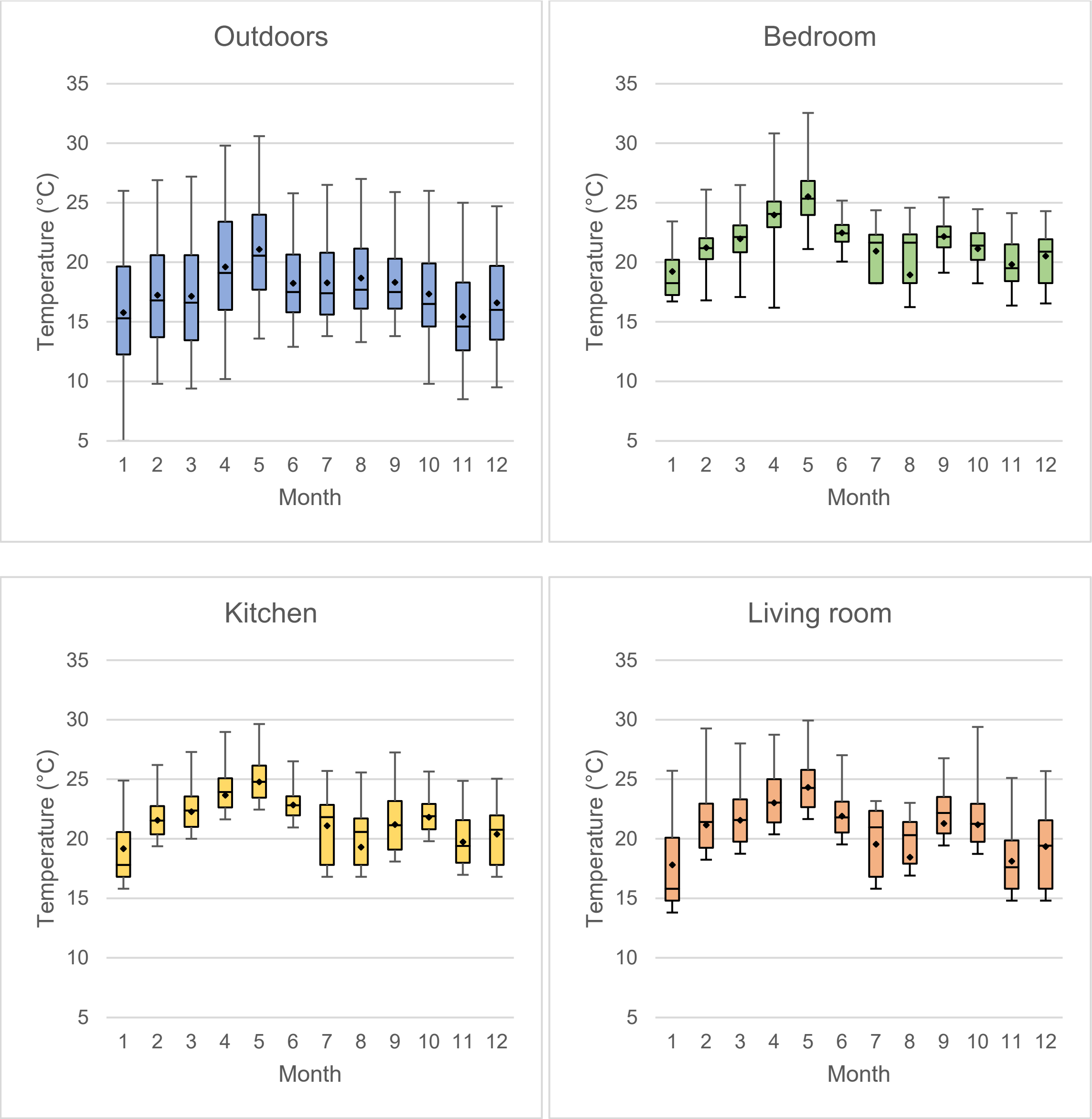

Figure 7: Indoor (bedroom, kitchen and living room) and outdoor temperature variations by month.

3.4. Daily temperature variation

The Passivhaus presented significant daily indoor temperature variations throughout the year (Table 4), which were correlated (*r*=0.521, p<.01) to outdoor temperatures, as shown in Figure 8. Nonetheless, winter temperatures in the living room had a considerable variation compared to the other spaces. It is important to note that there did not appear to be a considerable temperature difference between the bedroom, kitchen and living room throughout the year. This suggests a homogeneous temperature condition throughout the Passivhaus regardless of whether the temperatures were cold or warm.

Table 4: Daily temperature variations indoors and outdoors by season.

		Mean of the daily temperature variation (°C)	Extreme daily temperature variation	
			Min (°C)	Max (°C)
Summer	Bedroom	2.01	0.90	4.73
	Kitchen	3.10	1.35	5.93
	Living room	5.04	3.00	7.36
	Outdoors	9.05	5.40	12.20
Autumn	Bedroom	2.43	1.09	6.22
	Kitchen	4.07	1.09	7.5
	Living room	5.02	1.84	10.26
	Outdoors	8.83	2.90	13.20
Winter	Bedroom	3.28	1.07	6.58
	Kitchen	4.67	2.08	8.67
	Living room	7.23	3.27	14.38
	Outdoors	11.69	6.30	15.10
Spring	Bedroom	3.95	1.01	9.80
	Kitchen	4.43	1.68	10.82
	Living room	6.29	3.35	6.64
	Outdoors	11.17	7.00	14.80

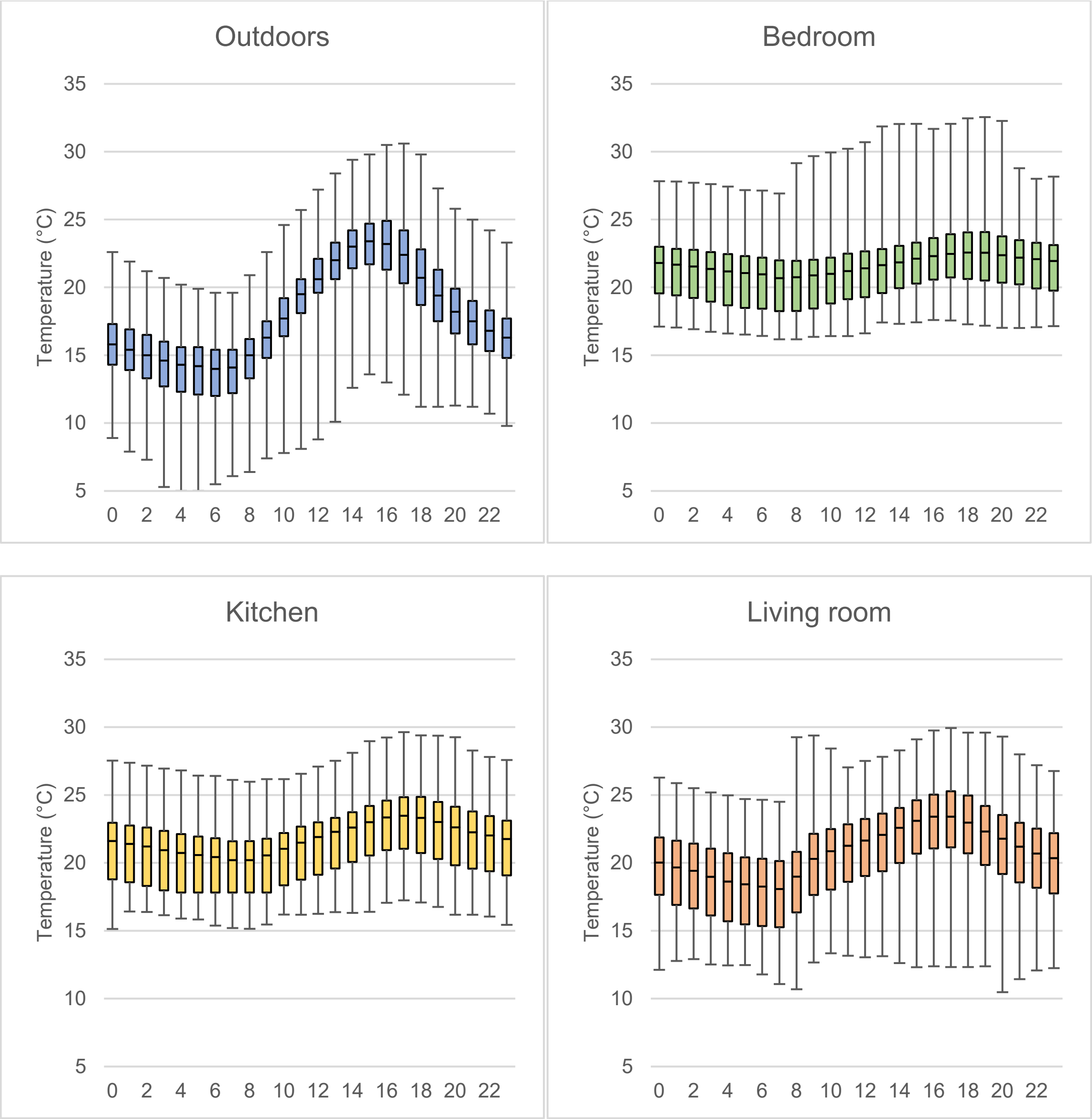

Figure 8: Indoor (bedroom, kitchen and living room) and outdoor daily temperature variations.

3.5. Humidity

Relative humidity thresholds were assessed and related to air temperature using psychrometric charts. Relative humidity above the recommended 60%RH was measured between 7% to 8% of the time. Similarly, relative humidity levels below 40%RH were 35% to 44% in the Passivhaus (Figure 9). Indoor relative humidity levels reached a minimum of 20.07%RH, 17.821%RH and 18.04%RH in the bedroom, kitchen and living room, respectively. The psychrometric evaluation showed that spring levels were the most critical. They have a higher occurrence of warm and dry conditions (Figure 10).

In contrast, summer was the most comfortable (Figure 11). Actual moisture levels could be masked to a degree by higher indoor temperatures. Therefore, analyses of vapour pressure were also carried out.

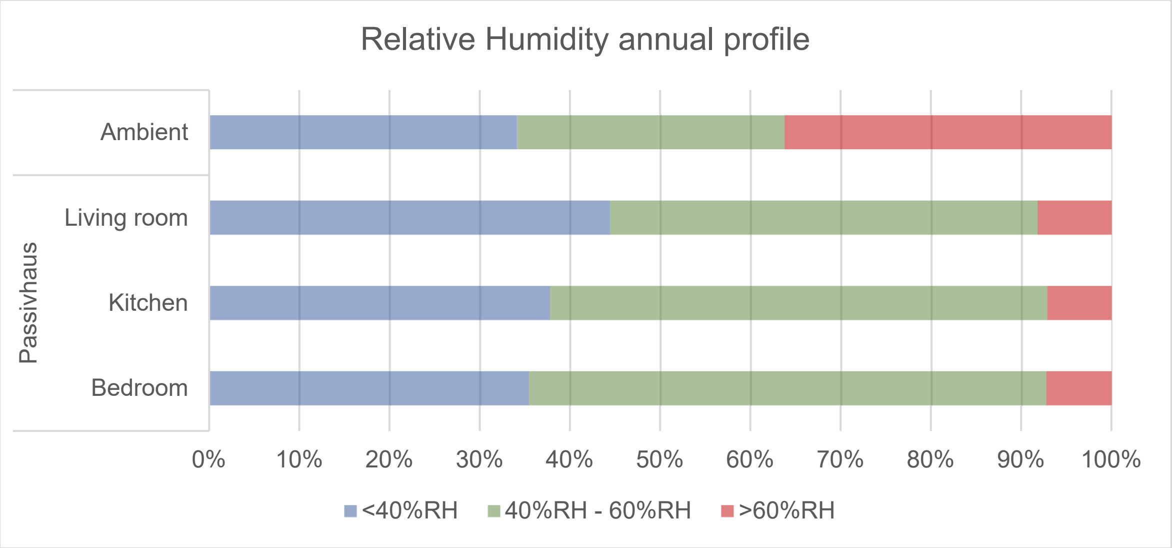

Figure 9: Annual relative humidity levels by ranges.

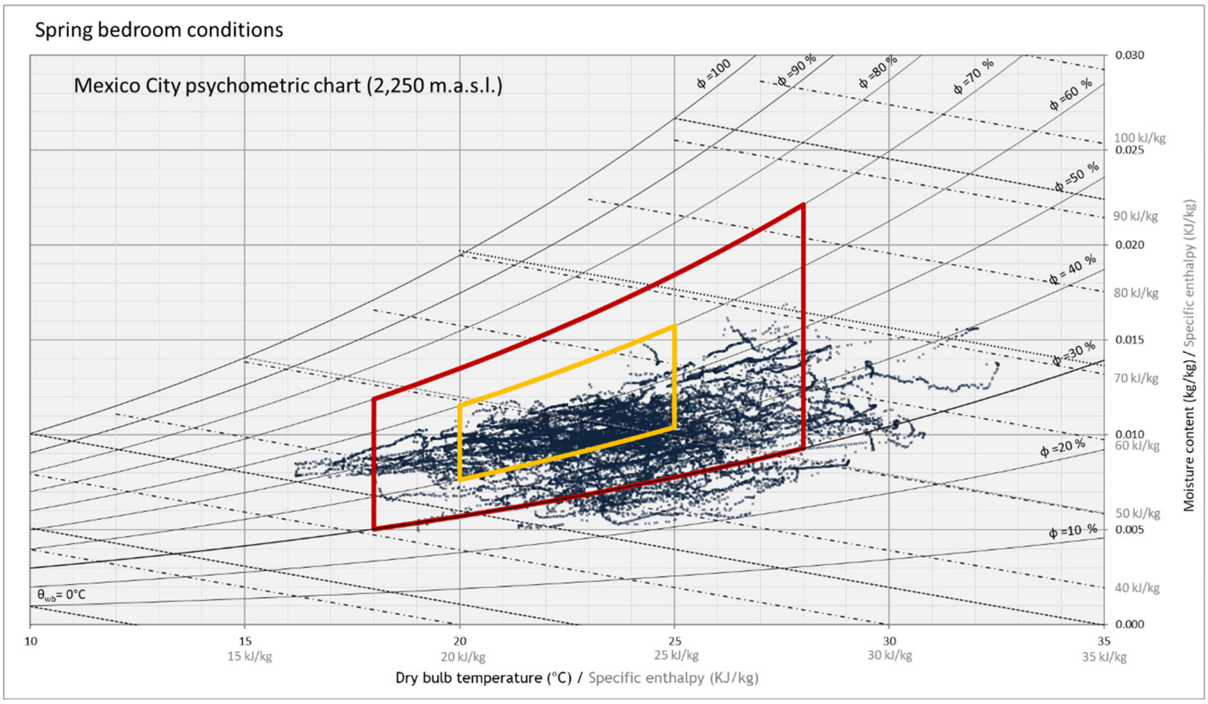

Figure 10: Spring psychrometric evaluation of the bedroom conditions during spring. The yellow rectangle delimitates the ideal comfort range and the red the extended comfort range.

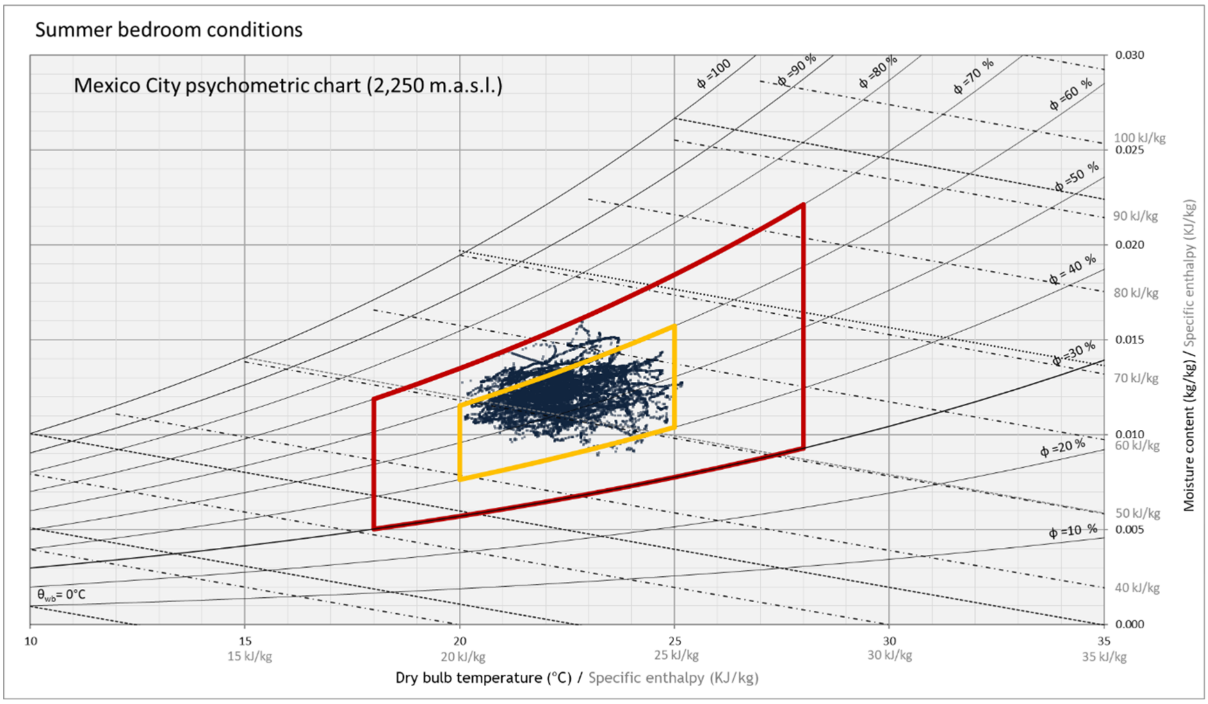

Figure 11: Summer psychrometric evaluation of the bedroom conditions during spring. The yellow rectangle delimitates the ideal comfort range and the red the extended comfort range.

Table 5: Annual vapour excess from the Passivhaus. A positive vapour excess means that the indoor concentration is higher than the ambient. In contrast, the negative value indicates it is lower than the ambient.

	Summer		Autumn		Winter		Spring		Annual	
	Vapour excess (%)		Vapour excess (%)		Vapour excess (%)		Vapour excess (%)		Vapour excess (%)	
	>7 g/kg	>12 g/kg	>7 g/kg	>12 g/kg	>7 g/kg	>12 g/kg	>7 g/kg	>12 g/kg	>7 g/kg	>12 g/kg
Bedroom	-33.2	4.7	15.4	7.9	35.0	0.0	47.8	2.8	-2.7	0.0
Kitchen	-38.0	3.0	12.3	9.0	34.4	0.0	45.5	2.9	2.4	-0.1
Living room	-60.8	1.0	5.2	9.0	30.7	0.0	45.8	2.3	-12.0	0.0

The humidity threshold as defined by the Passivhaus standard, 12g/kg for 20% of the occupied time, were never exceeded in any of the spaces. The results indicated that 12 g/kg were observed during

4.34%, 3.56% and 3.65% in the bedroom, kitchen and living room, respectively. Vapour excess, the difference between indoor and outdoor, was calculated for each room, as illustrated in Table 5. The low frequency of relative humidity levels above 60%RH was masked by higher indoor temperatures as vapour pressure above 7g/kg was significant.

3.6. Thermal perceptions

The survey analysis results were derived from the participants' views (N=3) assessed as Raw (1995) suggested and complemented with the occupants' answers to open-ended questions. Summer results are shown in Table 6 and winter in Table 7.

Participants were generally satisfied with the thermal conditions during summer. The comfortable – uncomfortable (M=2), too hot-too cold (M=3.67) and satisfactory overall (M=2) scales were close to the ideal score. Although daily variations during summer (mean summer daily temperature variations in bedroom 2.01°C, kitchen 3.10°C and living-room 5.04°C) occurred in the Passivhaus, participants perception mean score (M=2.66) does not reflect this fact.

Table 6: Statistical analysis of thermal comfort perceptions during summer.

Thermal perception	**Resident**	**Score**	**Mean**	**SD**	**Mean + SD**	**Mean - SD**	**Min**	**Max**
Comfortable (1) - uncomfortable (7) scale	R1	1	2.0	1.0	3.0	1.0	1.0	3.0
	R2	2						
	R3	3						
Too hot (1) - too cold (7) scale	R1	4	3.7	0.6	4.2	3.1	3.0	4.0
	R2	4						
	R3	3						
Stable (1) - varies during the day (7) scale	R1	2	2.7	1.2	3.8	1.5	2.0	4.0
	R2	2						
	R3	4						
Satisfactory overall (1) - unsatisfactory overall (7) scale	R1	1	2.0	1.0	3.0	1.0	1.0	3.0
	R2	2						
	R3	3						

Similarly, participants stated that they felt overall satisfied (M=1.66) with the thermal comfort. Temperatures below CIBSE suggested thresholds (below 18°C in living rooms and 21°C min bedrooms), correspond to the occupants' perception of the too hot – too cold scale (M=4.33), which suggests that they did not weigh this factor significantly when rating the overall satisfaction. Daily variations during winter (mean winter daily temperature variations: bedroom=3.28°C, kitchen=4.67°C and living-room=7.23°C) were higher than those during summer. Nonetheless, participants perception mean score (M=2.33) does not reflect this fact, and in fact, was rated better than their summer perception (M=2.66).

Table 7: Statistical analysis of thermal comfort perceptions during winter.

Thermal perception	Resident	Score	Mean	SD	Mean + SD	Mean - SD	Min	Max
Comfortable (1) - uncomfortable (7) scale	R1	1	1.7	0.6	2.2	1.1	1.0	2.0
	R2	2						
	R3	2						
Too hot (1) - too cold (7) scale	R1	4	4.3	0.6	4.1	3.8	4.0	5.0
	R2	4						
	R3	5						
Stable (1) - varies during the day (7) scale	R1	1	2.3	1.5	3.9	0.9	1.0	4.0
	R2	2						
	R3	4						
Satisfactory overall (1) - unsatisfactory overall (7) scale	R1	1	1.7	0.5	2.2	1.1	1.0	2.0
	R2	2						
	R3	2						

The surveys suggested that the Passivhaus occupants were generally satisfied in both summer and winter, reflecting the physical measurements. Nonetheless, the daily variations observed in the Passivhaus did not reflect on the thermal perception. The occupants mentioned having external shading over the windows to the south and the patio most of the time. This reduced the indoor temperatures drastically. They also were bothered by draughts from opening the windows, particularly during winter. Finally, they also stated that on some days, the house was too cold. This relates to measured temperatures below 20°C in the living room (~40% of the time) and in the bedroom and kitchen (~30% of the time), suggesting that heating may be needed, particularly in the winter months. Additionally, occupants also reported complaints of dry eyes and dry, itching or irritated skin. They stated that the latter would be better when away from home.

4. Discussion

The aim was to assess the overheating in a Passivhaus dwelling in a warm climate to better understand overheating risk for future Passivhaus dwellings in Latin America. Although the Passivhaus standard was initially developed for cold climates, it has spread to warmer climates such as Mexico. Whilst there is evidence of overheating in Passivhaus dwellings in cold European climates (McLeod, Hopfe and Kwan, 2013; Ridley *et al.*, 2013, 2014; Tabatabaei Sameni *et al.*, 2015; Figueiredo *et al.*, 2016; Fokaides *et al.*, 2016; Rojas *et al.*, 2016) even during winter (Fletcher *et al.*, 2017) there is little evidence of their performance in warmer climates, such as those in Latin American countries. Hence the need to collect evidence about the thermal comfort performance of Passivhaus beyond cold climates. Additionally, there is a difference in the risk of overheating between flats and non-flatted dwellings, as flats are more likely to suffer from higher risks of overheating (Mitchell and Natarajan, 2019).

This paper addressed this issue with the building performance evaluation and thermal comfort assessment of the first Passivhaus certified dwelling in Mexico. When this work was carried out in 2017, this was the only Passivhaus certified dwelling in Latin America. Nowadays, a few more have been built and certified in Chile and other countries. There is an estimate of the fast-growing demand for low-energy dwellings in this region. In 2019, the Latin American Passivhaus Institute was created to promote and support the development of Passivhaus dwellings in Latin America and adapt it to the Latin American context.

It is difficult to determine the frequency of overheating, as each guideline suggests different overheating criteria. Many of these guidelines are based on European guidelines, where heating or cooling through MVHR systems or other active methods is more common. In addition, weather conditions may vary. As such, the upper limit of the temperature range for thermal comfort is higher in warmer climates. For instance, in this work, we found that the risk of overheating is likely to occur in April, although May to September are also warm months. The upper limit reached 29.55°C accordingly to the Adaptive method.

A vital issue for assessing overheating in this study was the way the occupancy criteria were defined. As this was a long-term study, asking the participants to record a detailed occupancy pattern was onerous. Hence, they were only asked to provide a general weekly use pattern. This could introduce a variation gap between real and reported occupancy patterns. While the bedroom activities could be related to a weekly routine or schedule (i.e. around a job or school, night-time), the living room is challenging to forecast. It depends on more comprehensive activities and factors.

Another decisive factor in thermal comfort is the definition of comfortable temperatures in bedrooms and living rooms. As explained in CIBSE et al. (2006), bedroom temperatures above 24°C may cause sleep deprivation. So, it is recommended that temperatures never exceed 26°C, whereas these thresholds in living rooms are 25°C and 28°C. The CIBSE static criteria take this into account; however, neither the Passivhaus nor the Mexican standard takes this into account. One could also argue that the Adaptive approach is more appropriate as it considers the impact of outdoor temperatures on indoor thermal comfort. Nonetheless, temperatures up to 29.55°C were considered to be under the acceptable upper limits. These issues are also reported within UK homes (McGill *et al.*, 2016). They found a high risk of overheating in new-built homes, including Passivhaus. The percentage of the Passivhaus dwellings with overheating was lower compared to the non-Passivhaus.

Indoor temperatures were higher than outdoors, particularly during spring and autumn. This is an interesting finding, as the house does not have any dedicated cooling or heating system. Therefore, if not adequately addressed in future Passivhaus dwellings, they could have an increased risk of overheating. This issue has become more prevalent in North America (Dentz, Varshney and Henderson, 2014), which could be related to improved building envelope with low ventilation provision (Sharpe *et al.*, 2014), with higher expectations of the indoor comfort in high-performance dwellings (Herring and Roy, 2007) or dependence and automation of building mechanical systems. However, temperatures during winter were consistently below 20°C.

Overheating in Passivhaus dwellings is also exacerbated by poor design decision-making when calculating the thickness of insulation. Mitchell and Natarajan (2019) suggests that the overheating risk in Passivhaus buildings is exacerbated by increases in insulation levels and airtightness in new build homes, contrary to retrofits where the lack of insulation and the added thermal mass are the main issues for overheating. These factors have an impact on the U-values from the building elements. For instance, Gamero-Salinas, Monge-Barrio and Sánchez-Ostiz (2020) suggest that in tropical climates, a U-value of 0.62 W/(m^2K) in the façade and 0.50 W/(m^2K) in roofs may be enough for warm tropical climates. In contrast, Mexico City's Passivhaus has walls with 0.37 W/(m^2K) and 0.36 W/(m^2K) in the roof. This suggests that Passivhaus designers should look for the optimum U-values components, including the level of insulation, informed by the different overheating criteria.

Finally, there was evidence of significant daily temperature variation, which could be related to the lightweight construction, ventilation system, architectural design and occupant behaviour. The use of thermal mass could help maintain the temperature stable. Night purge ventilation would be needed to prevent overheating problems during the warmer seasons. While Passivhaus occupants expect temperature stability throughout the house (Zhao and Carter, 2015), there is an emergent body of research that suggests that temperature fluctuations could be beneficial for health (Parkinson and Dear, 2015; Schrauwen and Lichtenbelt, 2016) and are desirable in buildings (Lichtenbelt *et al.*, 2017).

Further work should focus on developing guidelines to improve the thermal comfort of Passivhaus dwellings in warmer climates. Suggestions for further exploration are incorporating additional passive strategies—i.e. ventilation and shading—and studies to determine the appropriate insulation level, U-values, and thermal mass of building components.

This study has distinguishable limitations. First of all, this work presents the monitoring results of only one house. At the time of this research, there was no other Passivhaus dwelling in Latin America. Secondly, the use of low-cost monitors could represent a trade in accuracy; to overcome this problem, we tested the accuracy (by comparison) of monitors used in this research, produced calibration equations, and used three monitors per room as described in (Moreno-Rangel *et al.*, 2018). Finally, the difference between indoor and outdoor monitoring instruments could suppose a small difference in how these are calculated.

5. Conclusion

This study analysed the occurrence of overheating in the first Passivhaus certified dwelling in Latin America to gain a better understanding of thermal comfort in Passivhaus dwellings in these countries. Whilst the results presented here cannot be generalised at a National level; they could serve to develop other Passivhaus buildings within similar weather conditions. Additionally, the results provide much-needed evidence on the indoor thermal comfort performance of a Passivhaus certified home.

Several criteria were used to assess the risk of overheating. The CIBSE TM52 (Adaptive approach) suggests that there is no overheating, although temperatures above 28°C were measured during short periods in May and April. The CIBSE Guide A analysis suggests that overheating occurred in the bedroom. Indoor temperatures in the Passivhaus dwelling were significantly correlated to outdoor temperatures, perhaps due to the lack of MVHR system, which is also reflected on indoor daily temperature variations of 4.29°C (average). Regardless of the evaluation criteria, the April and May months were the most critical when a dryer and warmer indoor environment was measured. As expected in Passivhaus buildings, the relative humidity levels were within the recommended threshold (40%RH – 60%RH). The Passivhaus occupants' perceptions generally match with the measured results.

The results highlight the need for research to improve and inform the adoption of the Passivhaus buildings in Latin America. Further research is needed to inform the use of passive strategies, such as shading, ventilation and thermal mass, as well as the correct levels of insulation.

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8. Declaration of competing interests

None of the authors of this paper has a financial or personal relationship with other people or organisations that could inappropriately influence or bias the content of this article.

9. Author contributions

[Section deleted for reviewing process]

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