Thermal comfort in naturally ventilated dwellings in the Central Mexican Plateau.

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Abstract

A third of Mexico's population (35M people) lacks decent housing. Current efforts to improve housing focus on structural strength and security rather than thermal comfort. However, as 59% of the population earns less than the median income, the building itself must provide adequate internal temperatures, i.e., the range between the minimum temperature suggested by WHO of 18 °C, and the maximum temperatures suggested by the CIBSE TM59:2017 criteria. Despite the perception of being a "warm" country, 38% of the Mexican population lives in places where the external temperatures often drop to 0 °C in winter falling to -6 °C during seasonal cold fronts. This is worrying, as a lack of adequate protection from low indoor temperatures is associated with high excess winter mortality rates. Hence, we undertake one of the first Class-II thermal comfort studies in a cold climate in Mexican homes. For eleven months, hourly indoor environmental and occupancy data, complemented with language-localised bi-monthly thermal comfort surveys, were matched against the Adaptive and PMV thermal comfort models. We find that only 42% of the living room occupied hours were within acceptability ranges, dropping to 22% in winter. Finally, we find that current strategies for achieving homeostatic heat balance are garment based (i.e., extra blankets or clothing), in addition to electric heaters to a lesser extent. Hence, we find that Mexican houses are presently not capable of providing adequate internal thermal environments during cold periods, suggesting the need for an extensive insulation programme.

Keywords

Thermal Comfort, Mexico, Housing, adaptive model, PMV, Overheating

1 Introduction

1.1 Background

In Mexico, 52.4M people (41% of the population) have poor-quality homes, often associated with poverty. Of these, 36M (32%) are in moderate poverty, typically occupying a 2-bedroom house with a total floor area (TFA) of 60m^2 built of solid brick walls and reinforced concrete roofs, and 11M (9%) are in extreme poverty, typically occupying a 1-bedroom house with TFA < 60m^2 built of reed, wood, or steel panels [1]. These are often located in marginalised areas, usually poverty-stricken with high crime rates [2]. Moreover, both moderate and severe poverty houses in Mexico lack adequate and healthy internal environments that endanger the health of the occupant [3].

To address this housing deficit, 264B of Mexican pesos (£ 9.4B) have been invested in mortgages to purchase new homes (59.9%), second-hand (27.4%), as well as for refurbishing their own (6.8%). These investments come from public organisations such as INFONAVIT (36.7%), FOVISSTE (11.3%), and private organisations such as banks (51%). The average amount of money granted in loans in 2020 was MXN600K (s.d.=245K), (£20.5K) [4]. This amount only allows to purchase low cost, and hence, low-quality housing built by private developers. Developers tend to ignore the issue of indoor environmental quality (IEQ) in general and thermal comfort in particular, as aspects related to having a sense of security, or adequate public services, dominate over having a comfortable internal temperature [5]. However, it is well known that health and well-being are strongly affected by IEQ and exposure length [6]. Since a significant proportion of time is spent at home – e.g. about 65% (15.7 h per day) in the US and Canada [7] – the quality of the indoor environment, particularly the thermal environment, is critical in ensuring population health and well-being. Further, the amount of time spent indoors may increase disproportionately due to changing working patterns or health crises such as COVID-19. Therefore, internal environments must provide adequate temperatures at most times.

Unfortunately, little is known about the indoor thermal conditions in Mexican homes, especially in the colder regions. The focus has been on places with hot temperatures in the few extant studies on thermal comfort in Mexico [5, 8-10]. The paucity of thermal comfort studies in Mexico's cold areas is worrying, as 34M (30%) of the Mexican population lives in the '*Meseta Central* (Southern Mexican Plateau, average altitude 2,240 m) with cold Winter temperatures. For instance, the average minimum temperature during Winter 2018-2019 was 1.5 °C (s.d. = 3 °C), but falling to -2.5 °C (s.d. = 2.6 °C), during the seasonal cold front observed over eight days in December 2018 [11]. Given the significant need to provide high quality "low cost" housing that at least guarantees the minimum indoor temperature of 18 °C suggested by the World Health Organization (WHO) [12], the overheating criterion by CIBSE, and the significant resource investment already underway through institutions such as INFONAVIT, we raise the following research questions (RQ):

RQ1: Is the existing housing typology (materials, openings, layouts) in Mexican houses within the '*Meseta Central'* area capable of producing indoor environments that meet the WHO minimum temperature requirement of 18 °C, as well as the maximum temperature requirement set by the CIBSE TM59 Standard?

RQ2: Are the achieved temperatures seen as comfortable by the occupants throughout the year? If not, what temperatures might be seen as being comfortable?

RQ3: What factors influence the thermal sensations and adaptations in the population of central Mexico?

Hence, our overall goal is to research thermal conditions in the homes of the Meseta Central, their compliance with international comfort standards and the minimum temperature standard prescribed by the WHO, and to what extent these conditions are seen as comfortable by the occupants.

2.0 Literature Review

Thermal comfort is a widely studied subject in the literature. Hence, in this section, we briefly define the term and state key considerations prior to reviewing selected works in the literature relevant to our study.

Thermal comfort is defined as *"the condition of mind that expresses satisfaction with the thermal environment, and it is assessed by subjective evaluation*" [13]. Thus, it describes and assesses the balance of personal and environmental factors, leading to a feeling of satisfaction and comfort within an environment. There are two widely accepted methods to evaluate thermal comfort: steady-state [14] and adaptive [15]. Both approaches are included in the international standards ISO 7730 [16] and ASHRAE 55 [13]. Both capture the user's thermal sensation through the same 7-point scale ranging from hot to cold, through the terminology "cold" (-3), "cool" (-2), "slightly cool" (-1), "neutral" (0), "slightly warm" (+1), "warm" (+2), "hot" (+3).

The steady-state model aims to predict the mean thermal sensation vote in (mainly) mechanically ventilated buildings. It results in two indices, the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD). The adaptive model is based on the idea that humans can adapt to different temperatures and that comfort preferences evolve over the seasons [9]. An adaptation in the adaptive model is defined as a response to a change in temperature within a space and classified into psychological, physiological, and behavioural [9]. The adaptive method does not aim to find a fixed temperature band but rather a range of temperatures where the user can be thermally comfortable within their adaptive possibilities due to the external climate. The classical adaptive model is a simple linear function between acceptable indoor operative temperature and the mean weighted external temperature. However, recent studies have shown that relative humidity has a more substantial influence than thought on this traditional adaptive model [17, 18].

The ASHRAE 55 standard classifies buildings into A, B, and C, according to the percentage of people dissatisfied and PMV values, as seen in Table 1. This model requires six variables that must be recorded on-site for its calculation. Four environmental: dry bulb Air temperature ta, Radiant Temperature tr, Air Velocity V, Relative Humidity Rh; and two personal variables: Metabolic rate Met (amount of heat released by a person, depending on their physical activity), and Clothing insulation Clo (thermal resistance of the material from which the garment is made).

Table 1 – Thermal Comfort categories provided by the ASHRAE 55 Standard, where PPD stands for the Percentage of People Dissatisfied and PMV for the Predicted Mean Vote.

Category	**PPD**	**PMV**	**Explanation**

A	< 6%	*-0.2 < PMV < 0.2	Used for buildings where the occupants are vulnerable or fragile, e.g., children, the elderly, and people with disabilities.
B	<10%	*-0.5 < PMV < 0.5	For new and refurbished buildings, e.g., offices, with 90% acceptability.
C	<15%	*-0.7 < PMV < 0.7	Usually for existing buildings, with 85% acceptability.

2.1 Field studies

There is a rising worldwide interest in identifying the thermal conditions prevalent in low- and middle-income households, particularly in emerging economies, reviewed in Table 2. We find that while there exist data on thermal comfort in Mexican homes collected for Master and PhD theses [19-21], there are only three studies from peer-reviewed journals that study thermal comfort in residential dwellings. These are primarily focused on the warmer regions of the country. Gomez-Azpeitia et al. [22] undertook a systematic study of thermal comfort in four hot cities of Mexico, two with high relative humidity. It was found that the acceptable upper limit of comfortable operative temperatures of about 30 °C is significantly above those suggested in international standards.

Interestingly, the study suggests that the neutral temperature in at least one humid location is 1-2 °C lower than in the hot and dry climate, consistent with the recently proposed humidity-adapted model [17]. Griego's study [23] included one city from the Meseta central (Toluca) arrived at very similar conclusions, albeit with a much smaller sample size. This study has a dwelling sample size of three households covered by a single visit and thermal comfort estimated using models rather than directly measured. Therefore, a systematic study is necessary for this colder region, ideally with larger samples and extended periods.

It is noteworthy that the results from the warmer climates in Mexico are consistent with other thermal comfort studies from warm regions, where the neutral temperature is typically above 26°C [23, 24]. This pushes the threshold of thermal discomfort to around 31°C, up to which threshold 91.3% of the respondents were thermally uncomfortable in Mérida [22]. As these studies examine the typical housing typology and construction prevalent throughout Mexico (see Section 3.2), we infer that the building fabric of houses in Mexico's hot areas allow significant heat gains, resulting in thermal discomfort without air-conditioning systems. As expected for poorly insulated buildings, this suggests that dwellings built to the same standards in the colder areas of Mexico are also likely experiencing cold thermal discomfort. Hence, the critical unknown then becomes the *extent* of cold thermal discomfort prevalent in typical homes in the region.

In Latin America, locations with a similar climate to the *Meseta* [24, 25] show most comfort votes below the comfort band suggested by the ASHRAE 55 standard [13]. Similarities in culture and building practices with Mexico and the *Meseta* suggest a similar performance. Furthermore, studies from other newly industrialised countries that focus on a low- and middle-income demographic suggest that the lack of adaptation strategies resulted in significant thermal dissatisfaction in naturally ventilated households at extreme temperatures [23, 24, 26, 29]. Finally, selected studies from other countries commonly perceived as "hot" but report cold temperatures in winter and significant diurnal variations [26, 27, 31, 32] indicate that households do not usually meet minimum temperature standards. In fact, winter excess deaths were higher in these places than in ones with more severe winters [26]. One cause of this could be that building fabric regulations tend to be weaker in countries with mild winters than in extreme ones [27].

Given the approximately 30M people living in the cold temperate region of Mexico's *Meseta Central* and the lack of peer-reviewed thermal comfort data, we conclude that there is a clear need to investigate thermal comfort conditions in this region.

Table 2 – Literature review on thermal comfort studies in Mexico and other developing / newly industrialised countries with similar climates. All the studies target social housing or others provided by the state. The operational mode can either be NV (Naturally ventilated) or AC (Air Conditioned / Mechanically ventilated). T_n °C stands for the calculated neutral temperature. A dash (-) is used where data were not available. M = Mexicali, H = Hermosillo, C = Colima, Me = Merida.

Study	**Period**	**n of buildings**	**n of participants**	**Type of population**	**Location**	**Köppen classification**	**Type of Sensor**	**Model**	**Type of field study**	**Operational mode**	**Tn [°C]**
[23]	26/04/2011 to 11/05/2011	5	-	Middle-class	Salamanca and Toluca, Mexico	Cwb – Oceanic subtropical highland	-	PMV	Class III	NV	-
[22]	May 2006 to July 2007	-	679	Middle-class	M, H, C and Me, Mexico	BWh – Hot desert (M and H), Aw – Tropical Savana (C and M)	QUESTemp° 3	Adaptive	Class I	NV	M – 25.3, H – 27.2, C – 25.9, Me – 22.2

[28]	July 2015 and December 2015	74	74	Middle-class	Across Mexico	-	-	Adaptive	Class III	NV / AC	-
[29]	May to July 2008	45 flats	100	Social Housing	Khairatabad, India	Cwa – Monsoon influenced subhumid tropical	Sisedo" Hygro therm / Eurolab thermometer	Adaptive	Class II	NV	29.2
[30]	April to November 2005	-	-	Army living headquarters	Coimbra, Brazil	Aw – Tropical savanna	Microclimatic station	PMV	-	2 x NV 1 x AC	27.4
[24]	January to November 2016	40	40	Social Housing	Ciudad Concepción, Chile	Csb – Mediterranean warm/cool Summer	Pt100 / Capacitive sensor	Adaptive	Class II	NV	24.4

[31]	May to November 2016	43	43	Social Housing	Tianjin, China	Dwa – Hot Summer continental climates	-	PMV	Class II	AC	24
[32]	June 2017	30	30	Low-income households	Crete, Greece	Csa – Mediterranean hot Summer climates	-	PMV	Class II	AC	-
[25]	NS	44	44	Social Housing	Bogotá, Colombia	Cfb – Oceanic	HOBO U12 data loggers	Adaptive / PMV	Class II	NV	23-31
[33]	June to September 2000	4 (housing estates)	257	Social Housing	Singapore City, Singapore	Af – Tropical rainforest	Not specified	PMV	Class III	NV / AC	-
[34]	July to August 2017, and	19	19	-	Adelaide, Australia	Csb – Mediterranean	HOBO U12-013 data logger	Adaptive	Class II	NV	22.8

	September to October 2017					warm/cool Summer					
[35]	December 2012 and April 2013	43	74	Social Housing	Athens, Greece	Csa – Mediterranean hot Summer climates	-	-	-	-	-

3.0 Methods

The literature review has suggested a clear need for a study that answers the research questions set out in Section 1.1. Here, we present the methods utilised to help answer them. This section includes the careful selection of a suitable site and a sample of homes, the development of a survey instrument and the co-incident longitudinal measurement of indoor conditions.

3.1 Site

Our location of choice within *the Meseta Central* is the Greater Toluca urban area (19 ° 14 ‘N 99 ° 35’ W), the capital city of the State of Mexico (Estado de México) and 50km away from Mexico City. The city is located in Mexico’s central valley on the Mexican plateau and is limited by the Cordillera Neovolcánica (Neo volcanic mountain range), 30km from the Xinantecatl volcano (4700m altitude). It has an approximate 800 km^2 and 900,000 inhabitants and an altitude of 2,635 meters above sea level. Figure 1 shows its geographic location at a national and regional level. Thus, the climate in Toluca is representative of the climate in the plateau.

The Köppen climate classification of the urban area of Toluca is oceanic weather type Cwc likewise certain regions of Western Europe and the United Kingdom. The site has a contrasting climate, as temperatures can range from 0° C to 27 °C, during a typical Winter day, and from -5 °C to 25 °C during seasonal cold fronts [11]. The region’s average temperature is 13.1 °C (std 5.8) [36] due to the significant diurnal temperature variations. Its annual relative humidity is 65%

(std 5.5). It has 2026 hours of annual sunshine, and its yearly average rainfall averages 63mm (std 58mm), from which 90% of these rains happen during the 'rainy season' period from May to October [37].

Figure 1 – Site location at a national level (left) where the United States borders north, and at regional level (left) where the Greater Toluca area is marked in black, and Mexico City is located on its right

3.2 Participants

The sampling strategy was based on the two-step adaptive cluster sampling [38] as it was necessary to assure that: i) our sample would not be biased, ii) our recruitment methods were adequate, and iii) that all the homes would be comparable amongst each other. We did this through two recruitment stages, in September 2017 for our pilot study (7 homes) and in January 2018 (23 homes). Both recruitments were made through a targeted sampling [39], allowing for control of the specific characteristics of the sought homes while having the single requirement that all homes had to be naturally ventilated. The study was promoted through poster sheets in universities, local markets, and churches in neighbourhoods where the type of housing we were looking for predominated. Figure 2 shows a cross-section of these types of homes, and Table 3 shows the properties of these materials, which can be considered medium to high thermal mass due to the use of solid wall construction of brick or concrete. In the country, this type of construction is used in 74% of the total housing stock. The vast majority of the remaining (22%) are built with weaker materials as seen in Table 4.

The recruitment process was as unbiased as possible. For instance, coverage bias [40] was avoided as we assured to include houses inhabited by people from all socioeconomic statuses, ages, occupations, level of studies and gender (Table 5). In addition, this variety within the sample also prevented self-selection bias, as there was not any ignored sector of the population [41]. Non-response bias [42] was counteracted as all our participants were told that they could leave the study at any point. Further, all respondents showed a willingness to cooperate throughout all visits.

Our sampling process left us with a total of 30 homes. However, we had three dropouts, and one sensor malfunctioned, leaving us with a total sample of 26 homes. While this is a small sample, and hence exposed to the risk noted by others [15], the extensive period of time of the data collection stage, coupled to the high level of uniformity in house building practice in Mexico across socioeconomic status, allows us to shed light on thermal conditions within such homes, as seen in. In addition, two homes stated that they use external means of heating during winter, one ethanol chimney (id7) and one electric heater (id27). Nevertheless, they explained in the surveys that these are only used “rarely” and in isolated situations. As all homes were naturally ventilated, none have insulation nor double glazing, and none are solely oriented to the north (one home had a northeast orientation, and two had two facades facing both north and east), the temperatures captured amongst our sample are comparable to each other. The full description of the characteristics of the homes (e.g., occupancy, location, house type, and orientation) is seen below in Table 6.

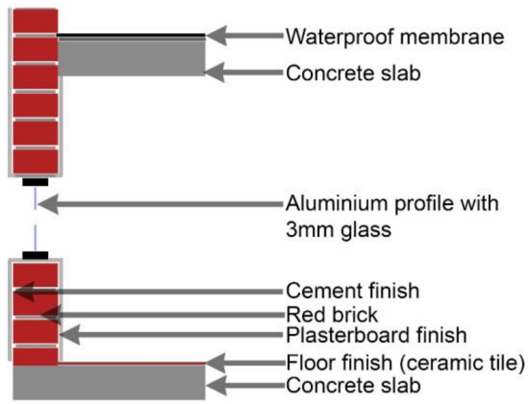

Figure 2 – Construction detail of a typical home from Mexico.

Table 3- Properties of the most commonly used construction materials in Mexico source [43]

Envelope element	Material	Thickness (m)	Density (kg/m^3)	Thermal ~~Conductivity~~ Transmittance (~~W/m^2 K~~ $Wm^{-2}K^{-1}$)
Walls	Redbrick	0.13	2000	2.1
Roof	Reinforced Concrete	0.16	2300	4.4
Window	Single glazing	0.003	2200	5.9

Table 4 – Different types of materials of the building envelope of the total housing stock in Mexico. Source: [1]

Wall Materials	
Solid wall (brick, block, concrete)	88%
Adobe	6%
Wood	3%
Others (asbestos, bamboo, waste)	3%
Roof Materials	
Concrete	74%
Metal	14%
Asbestos	5%
Wood	2%
Others (waste, cardboard, palm leaves)	5%
Floors (finish)	
Concrete plus a finish (wood or ceramic tiles)	49%
Only concrete	48%
Earth	2%

Table 5 – Characteristics of the sample

Demographic Characteristic

Sex	Male	14
	Female	12
Age	20 or less	2
	20-30	5
	30-40	9
	40-50	8
	50 or more	8
Qualifications	No higher education	2
	Undergraduate	9
	Postgraduate	7
	High School	4
	Preferred not to answer	10
Occupation	High Skilled Job	13
	Housewife	5
	Own Business	4
	Retired	2
	Student	1
	Preferred not to answer	7
Socioeconomic Characteristics		
Room Numbers	0-5	17

	5-10	15
Reported Fuel Poverty	No	74
	Yes	15
Heating Used (in days)	0	62
	0-5	7
	Ten or more	20
House Age	Five or less	15
	5-10	4
	10-15	4
	15 or more	9
Income	Less than 9000	17
	More than 9000	15

Table 6 - Description of the houses monitored. All the cities mentioned in the Locality column belong to the Toluca Urban Area.' The number to the right of "Family" corresponds to the number of members of said family.

ID.	**Locality**	**Floors**	**House Type**	**Occupancy**	**Orientation uncovered**			
					North	East	South	West
2	Metepec	2	3 Bedrooms, kitchen, living & dining	Family-3			x	
3	Metepec	1	1 Bedroom studio	Single			x	

4	Metepec	2	2 Bedrooms, kitchen, living & dining	Family-4			x	
6	Toluca	2	3 Bedrooms, kitchen, living & dining	Family-4		x		
7	Toluca	1	1 Bedroom studio	Single		x		
9	Metepec	2	2 Bedrooms, kitchen, living & dining	Family-4		x		
11	Lerma	1	3 Bedrooms, kitchen, living & dining	Family-4	x	x		
14	San Mateo Atenco	2	2 Bedrooms, kitchen, living & dining	Couple			x	
16	Toluca	2	2 Bedrooms, kitchen, living & dining	Family-3	x	x		
17	Metepec	2	5 Bedrooms, kitchen, living & dining	Family-4			x	
18	Metepec	1	2 Bedrooms, kitchen, living & dining	Couple		x		
20	Metepec	2	2 Bedrooms, kitchen, living & dining	Single				x
22	Metepec	2	4 Bedrooms, kitchen, living & dining	Family-3		x		
24	Toluca	1	1 Bedroom studio	Couple				x

26	San Mateo Atenco / Lerma	2	2 Bedrooms, kitchen, living & dining	Couple				x
27	Metepec	2	4 Bedrooms, kitchen, living & dining	Family-4				x
28	Toluca	2	3 Bedrooms, kitchen, living & dining	Couple			x	
29	Metepec	1	2 Bedrooms, kitchen, living & dining	Family-4		x		
30	Metepec	1	2 Bedrooms, kitchen, living & dining	Family-3			x	
31	San Mateo Atenco / Lerma	2	3 Bedrooms, kitchen, living & dining	Single				x
33	Metepec	1	2 Bedrooms, kitchen, living & dining	Family-3				x
36	Toluca	2	3 Bedrooms, kitchen, living & dining	Family-4			x	
37	Toluca	1	1 Bedroom studio	Single	x	x		
38	Toluca	2	3 Bedrooms, kitchen, living & dining	Couple				x

39	Toluca	2	3 Bedrooms, kitchen, living & dining	Family-4		x
40	San Mateo Atenco	2	2 Bedrooms, kitchen, living & dining	Family-4	x	

3.3 Surveys

Fieldwork was undertaken over eleven months, from March 2018 to February 2019. Due to availability, we visited 14 homes every four weeks, six once every six weeks, and six once every eight weeks. This resulted in a total of 159 survey visits. The surveys were completed between 9:00 a.m. and 8:00 p.m. The first survey was longer than all others as it included the following information:

1. **Dwelling context:** overall aspect, orientation of the windows and doors.

2. **Personal information**: gender, highest level of studies, income, occupation, weight, and height.

The rest of the survey collects data on the following:

1. **Fuel poverty:** Any difficulties in paying energy bills and auxiliary heating were used to determine if they could modify their internal environment when it became too cold.
2. **Thermal comfort:** We used the 7-point ASHRAE-55 scale in our thermal comfort surveys. It was carefully modified to suit Mexico (see Section 3.6). The surveys also included questions essential for PMV and PPD calculations, as described in section 2.1.

3. **Thermal Adaptations:** Questions about their different adaptation strategies and the circumstances in which these were made.
4. **Data monitoring:** We installed the sensors (described in section 3.5) on the first visit. Subsequent visits were used as an opportunity to retrieve and check data collection and obtain air velocity measurements.

3.4 Ethics

A consent form had to be signed by the volunteers. It explained the nature of the research, the frequency of site visits, and a detailed explanation of the sensors' recording. It explained that all participation was voluntary and could leave the study whenever they wished. It also stated that their private data was managed according to the recommendations set by the University of Bath, the UK "Data Protection Act 2018" [44], and the Mexican regulation "Ley Federal de Protección de Datos Personales en Posesión de los Particulares" [45].

3.5 Sensors

Complementing the site visits and thermal comfort surveys described in section 3.3, we placed one temperature and relative humidity sensor (Figure 3) per home during eleven continuous months to prevent "anchored effects" caused by undertaking longitudinal surveys only [46]. The bedroom and the living room are the spaces where a typical household spends 90% of their time at home [47]. However, our participants were concerned about privacy and security and only allowed us to place the sensors in living rooms. This is consistent with other studies in residential settings [48-51]. As a person sleeps on average 7.5 hours (n=7095, s.d.=1.8 hours) per night after the COVID-19 confinements [52], one can assume that a household spends 60% of their day in living areas. Nevertheless, this is relevant because the confinements due to the

COVID-19 pandemic forced part of the world to convert these spaces into work/study areas, particularly in the case of 92% of our sample, whose homes have equal or more family members than rooms. Hence, living rooms must provide comfortable temperatures in the region as a basic need and so people can undertake their studies/work adequately.

Sensors were placed away from heat sources (i.e., away from direct solar radiation and electronic appliances) with the temperature probe, not in direct contact with any surface. When the participants raised aesthetic concerns, sensors were suitably shielded from view, provided the measurement requirements were not compromised. In some cases, the participant allowed us to photograph the sensors after installation, as shown in Figure 4.

The sensors were set to record air temperature and relative humidity every five minutes. These were averaged to an hourly resolution to match external weather data sourced from the weather station: “15266, Metepec-CODAGEM” at a mean distance of 4.5 km (std = 3.1 km) to the studied homes. Although the occupancy was measured through passive infrared sensors (PIR), it was impossible to obtain the occupancy in all the monitored spaces accurately. At times, these did not work correctly, and in other cases, the PIR sensor was covered. So, in coherence with other residential temperature monitoring studies [53, 54], the occupancy in the rooms is assumed from 9:00 a.m. to 10:00 p.m., as suggested for one, two, and three bedroom dwellings in the TM59 standard [55]. The characteristics of the sensors can be seen in Table 6. Figure 3 shows a photograph of the sensor layout. A hand-held Extech HT30 Heat Stress thermometer was used to record the operative temperature at the time of the study, and a calibrated anemometer ATP AVM-8880 to measure wind speed. Both are slightly short of standards compliance but have been used effectively in the past to undertake field surveys in other studies [56, 57].

Table 6 - Characteristics of the Temperature and Relative Humidity sensors

Parameter	Range	Accuracy
DS18B20 temperature sensor	−10 to +85 ℃	>±0.5 °C
RHT03 humidity sensor	0 to 100%	>±2%

Figure 3 - The temperature, relative humidity, and a Passive Infrared Sensor (PIR) used in this study

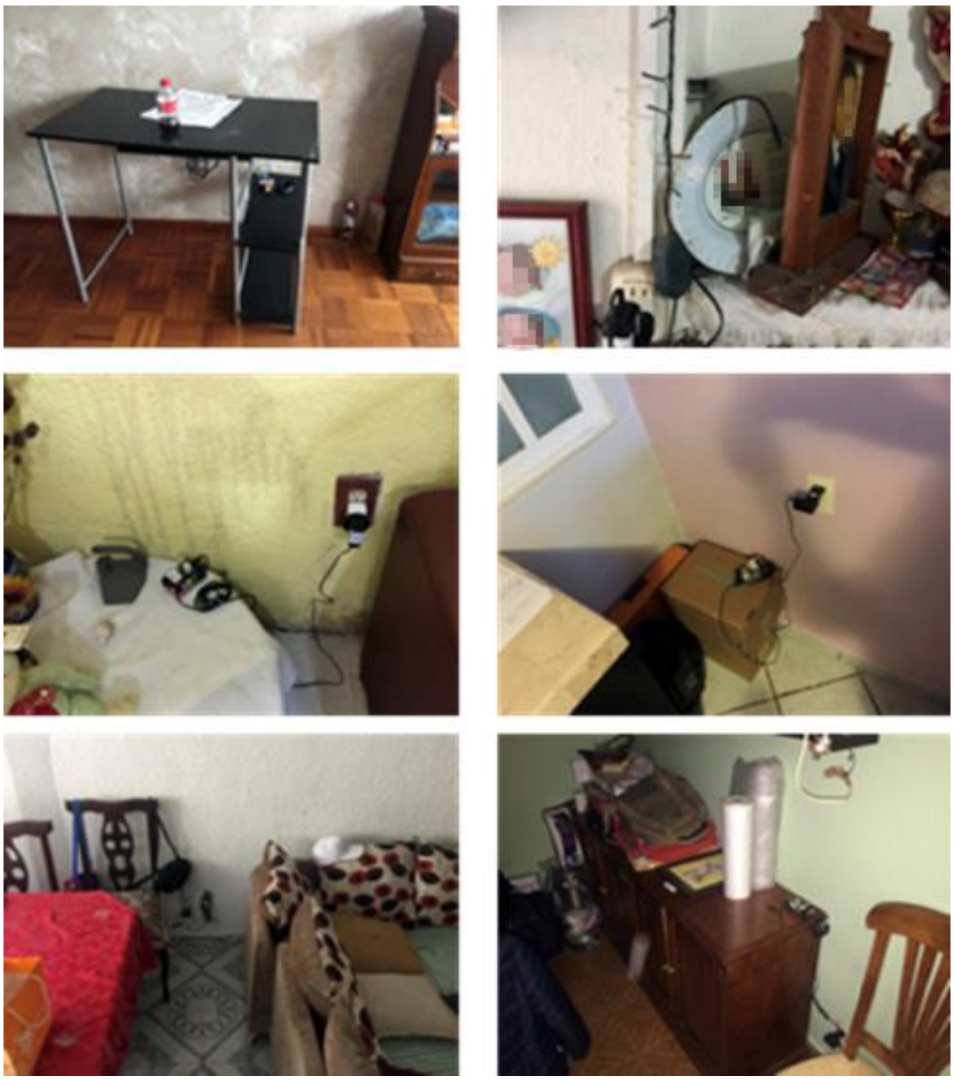

Figure 4 - Photos of some of the houses where the sensors were placed in this study

3.6 Scales and terminology

For the thermal comfort portion of the survey, we use the standard survey recommended in ASHRAE 55 [58]. The official translation of the 7-point scale to Spanish contained in UNE-EN 16798-1:2020 uses the words "*mucho*" (+-3), "*bastante*" (+-2), and “*algo* (+-1)" as severity modifiers for the experienced thermal sensation. This scale was considered potentially problematic due to known linguistic differences between Spanish from Mexico and Spanish from Spain. For example, in Mexican Spanish, "*mucho*" and "*bastante*" can be considered synonyms. Similar concerns resulted in language-localisations of the scale in other studies in Nepal [59], Jordan [60], Qatar & Saudi Arabia [61], or Japan [62].

To address this, we undertook a survey using the CONACYT- UK Mexican students network, asking scholars undertaking PhD studies in the UK their best translation to Mexican Spanish for the ASHRAE TSV scale to verify our hypothesis. A clear majority of agreed terms for each point of the scale (see Figure 21 in Annex 1) from over 180 responses to the survey resulted in the modified translation in Table 7.

Table 7 - Comparative table of the 7-point thermal scale from the ASHRAE 55 Standard, that includes the original terminology in English, the official Spanish translation, and the adopted terminology in Mexican Spanish

Scale	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**
ASHRAE 55	Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot

UNE EN 15251:2008	Mucho frío	Bastante frío	Algo de frío	Neutral	Algo de Calor	Bastante Calor	Mucho Calor
Survey Mexican Spanish	Frío	Fresco	Ligeramente fresco	Neutral	Tibio	Caliente	Muy Caliente

3.7 Indices and standards

Regarding thermal comfort, our analyses were done under the requirements established in the international standards ASHRAE 55 and ISO 7730. Both standards use operative temperature (T_{op}), which combines mean radiant temperature (Tm) and air temperature (Ta), whereas our sensor only recorded air temperature. Differences between air and radiant temperatures are usually minor in typical indoor environments [63] or when the air velocity is < 0.1 ms^{-1} [64]. For example, in a recent domestic study [48], a strong correlation (R^2 = 0.96) was found between T_{op} and Ta suggesting that Ta is a good substitute for To [48]. While radiant asymmetries are more likely in our sample due to the presence of uninsulated walls and windows, the lack of centralised heating systems will likely have resulted in colder than usual indoor surfaces, counteracting the effect of the lack of insulation. The metabolic rate (Met) was calculated with the tables provided in the ASHRAE 55 Standard [13]. We ensured that subjects had either been standing or sitting for 20 minutes before starting the survey. Clothing insulation (Clo) was calculated following Tables 5.2.2.2A and 5.2.2.2B of the ASHRAE 55 Standard, as clothing customs in Mexico are similar to those in the United States.

3.8 Overheating

Consistent with our RQ1, it was essential to study the risk of overheating. The British Standard CIBSE TM59 [55] was used as a benchmark because, to date, there is no Mexican regulation that addresses this issue. This standard provides well-accepted criteria to evaluate overheating in naturally ventilated buildings and has been used in other similar studies [65, 66]. The standard defines the 1st of May to the 30th of September as the summer period. The CIBSE TM59 derives its basic methodology from CIBSE TM52 [67], whose criteria are evaluated against *ΔT*, defined as:

$$\Delta T = t_{op} - t_{max} \qquad (1)$$

Where t_{op} is the hourly indoor operative temperature [°C] and t_{max} is the maximum accepted temperature [°C] set by the European adaptive standard in EN 16798-1:2019 [68]. Here we replace the European adaptive standard with the ASHRAE 55 adaptive standard, such that t_{max} is defined as:

$$T_{max} = 0.31\, T_{a,out} + 21.3 \text{ [69]} \qquad (2)$$

Where $T_{a,out}$ is the mean outdoor air temperature [°C].

The TM59 standard contains criteria that must be met to demonstrate the lack of overheating risk in residential dwellings.

$$H_e = \sum h \,\forall\, \Delta T \geq 1\,°C \qquad (3)$$

The TM59 standard also considers Criterion 2 and 3 from the CIBSE TM52 as optional. Criterion 2 addresses the severity of overheating in any one day through the Daily weighted exceedance W_e where:

$$W_e = (\sum h_e) \times WF \quad (4)$$

$$= (h_{e0} \times 0) + (h_{e0} \times 1) + (h_{e0} \times 2) + (h_{e0} \times 3)$$

Where the weighting factor $WF = 0$ if $\Delta T \leq 0$, otherwise $WF = \Delta T$, and h_{ey} is the number of hours when $WF = y$ [67]. For a space to pass this criterion, W_e must be ≤6 per day. Criterion 3 sets an absolute maximum daily limit temperature, that if exceeded, the level of overheating is not acceptable $\Delta T \leq 4K$.

3.9 Weather

The yearly external temperature average is 13.2 °C, comparable to the annual mean in cold climates such as the UK. However, seasonal average temperatures in Table 8 show large diurnal swings, especially in winter. Figure 5 shows each season's mean hourly temperature and wherein, on average, the temperature fluctuates 13.7 °C per day.

Table 8 -- Mean, Maximum and Minimum temperatures in °C of the four-yearly seasons in Greater Toluca from March 2018 to February 2019. Average diurnal temperature fluctuation ($\bar{x}$) and standard deviation (s) were computed over the corresponding season. Seasons considered as follows: Spring = the 21st of March to the 20th of June; Summer =

the 21st of June to the 20th of September; Autumn = the 21st of September to the 20th of December; Winter = the 21st of December to the 20th of March. Data source: Weather Station:15266 Metepec – CODAGEM.

	Spring	Diurnal range	Summer	Diurnal range	Autumn	Diurnal range	Winter	Diurnal range
Mean	15.3	$\bar{x}$ = 14.4	14.8	$\bar{x}$ = 13.2	12.23	$\bar{x}$=14.9	10.4	$\bar{x}$ = 19.7
Min	6.6	*s* = 3.4	4.1	*s* = 3.2	-4.7	*s* = 4.3	-3.9	*s* = 3.5
Max	26.9		30.0		24.8		25.0	

Note: all data in °C

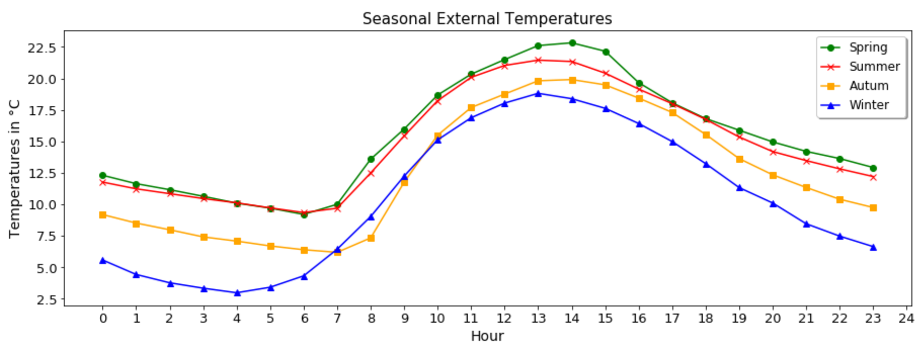

Figure 5 - External mean temperatures by the hour in Toluca (source: Weather station Metepec CODAGEM)

4.0 Results and discussion

4.1 Internal environmental conditions

Table 9 shows the mean temperatures recorded with the minimum and maximum across all the monitored homes.

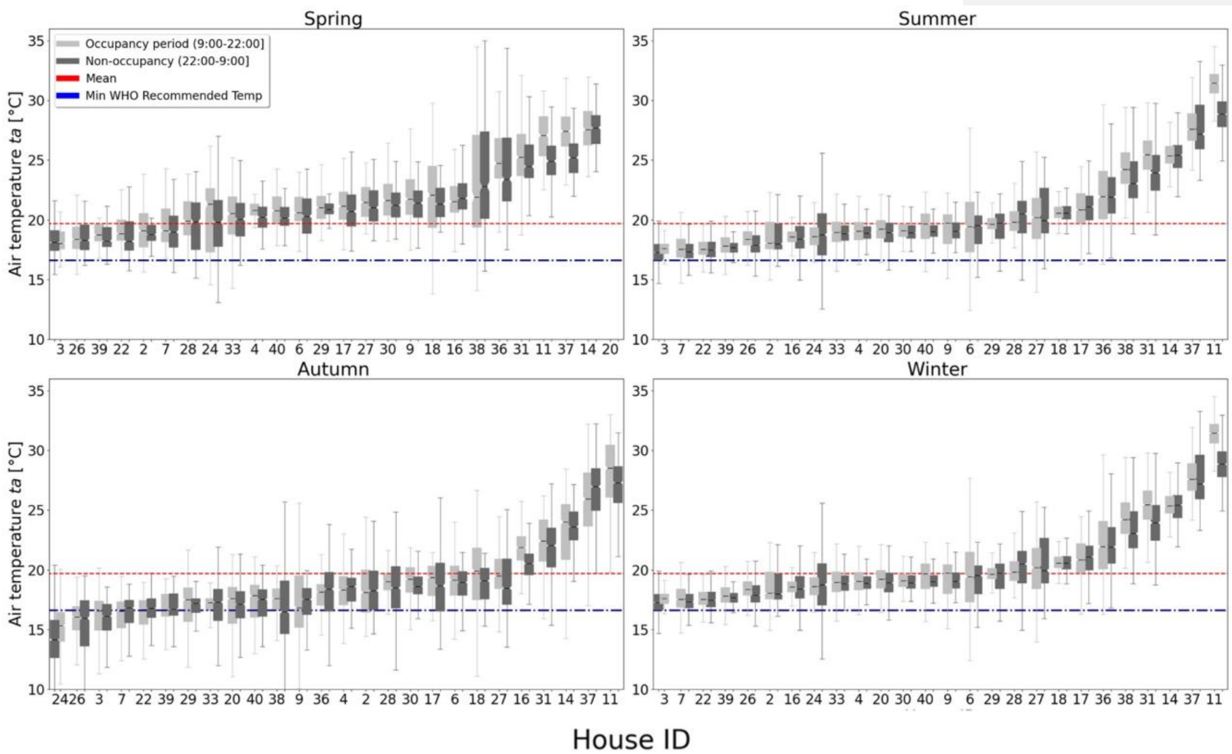

Figure 6 - Ranked box plots of mean living room air temperatures for all recorded seasons Light grey boxes are occupied (daytime) data (9:00am to 10:00 pm], and the dark grey boxes are non-occupied (night-time) data (10:00pm to 9:00 am] shown for reference. The dark blue lines represent the WHO minimum [70], and the red dotted the seasonal mean.

shows the box plots for hourly living room temperatures from the different homes throughout the year. The mean living room temperature was 19.6 °C (std = 2.3 °C), and it stayed within the range of +/- 2 °C depending on the season. Worryingly, the mean indoor temperature in winter was 17.6 °C, i.e., below WHO recommendations. The detailed temperatures for each of the monitored homes are seen in Annex 2. We could also observe that during the colder months, temperature variations are more extensive. We measured the air velocity with a calibrated anemometer during our survey visits, with observations being consistently below 0.1 ms^{-1}. As stated in Section 3.7, Ta is a good proxy to T_{op} under low air velocities and hence, the results of our analysis should be read under the assumption that $T_{op} = Ta$.

Table 9 – Mean, maximum, and minimum Operative Temperatures T_{op} was recorded with the temperature sensors presented in the four seasons. $\bar{X}$ stands for "mean", and sd for "Standard deviation".

	Indoor air temperature [°C]							
	Spring	Diurnal Variation	Summer	Diurnal Variation	Autumn	Diurnal Variation	Winter	Diurnal Variation
Mean	21.5	$\bar{x}$=2.6	20.5	$\bar{x}$=2.6	18.7	$\bar{x}$=2.8	17.6	$\bar{x}$=3.0
STD	2.5	(sd=	3.2	(sd =	3.1	(sd =	3.2	(sd =
Min	13.1	1.6)	10.8	1.6)	4.3	1.6)	4.5	1.9)
Max	35.4		37.5		33		34.9	

We observed that the range of daytime indoor temperatures was more comprehensive during the 'colder' seasons of autumn and winter than the 'warmer' seasons.

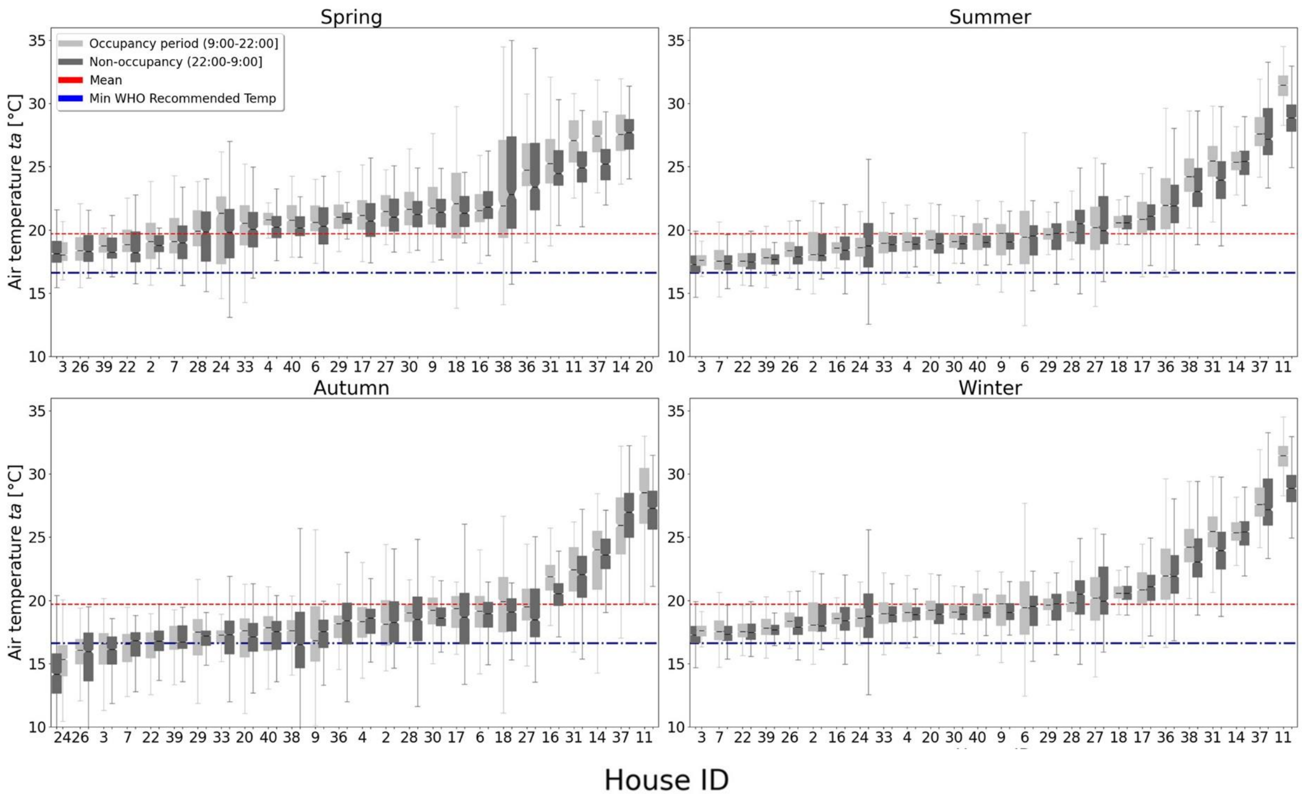

Figure 6 - Ranked box plots of mean living room air temperatures for all recorded seasons Light grey boxes are occupied (daytime) data (9:00am to 10:00 pm], and the dark grey boxes are non-occupied (night-time) data (10:00pm to 9:00 am] shown for reference. The dark blue lines represent the WHO minimum [70], and the red dotted the seasonal mean.

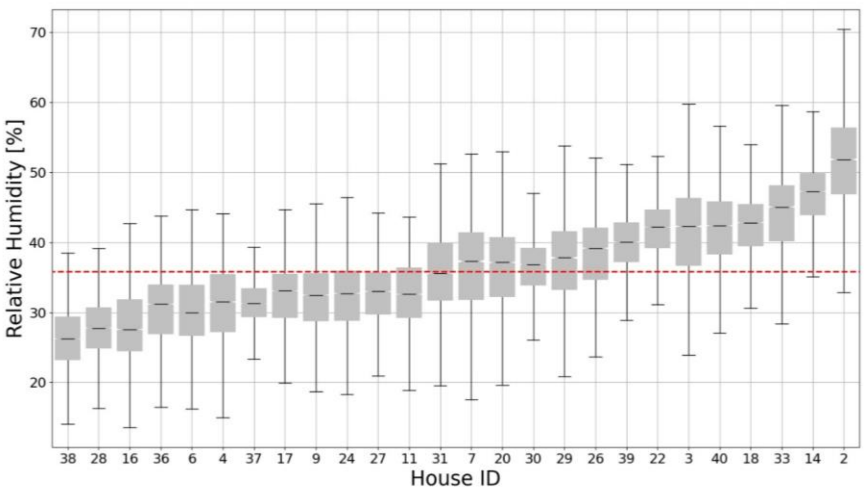

Figure 7 shows the annual relative humidity boxplots for each dwelling monitored. The average relative humidity throughout the whole period was 35.9% (s.d. = 5.5%). The average seasonal data such as minimum, maximum, and mean can be seen in Annex 3.

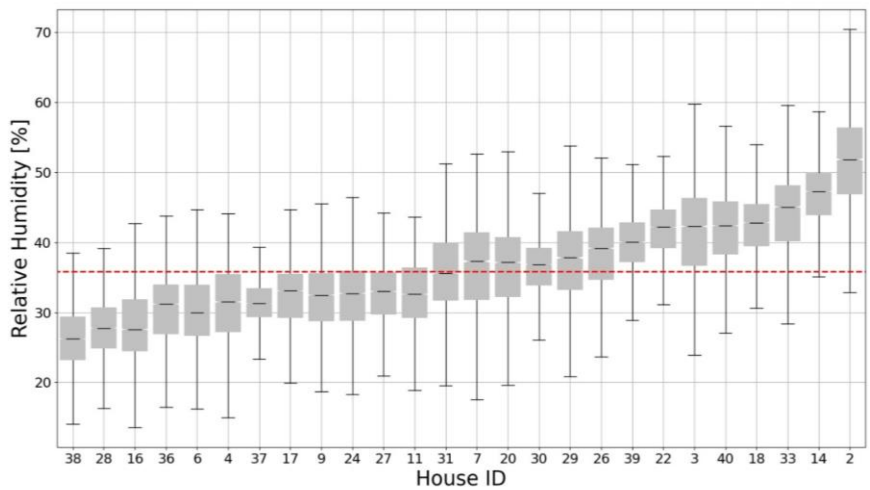

Figure 7 – Box plot of ranked mean internal relative humidity. The red dotted line is the mean.

4.2 Thermal Comfort

4.2.1 Predicted Mean Vote

Figure 8 shows the seasonally normalised density plots for the recorded Thermal Sensation Votes (TSV) against the calculated Predicted Mean Votes (PMV) for the same conditions throughout the different visits. A total of 159 votes were recorded across the various visits throughout all the houses. Many people found themselves more comfortable during the warm seasons of Spring and Summer, as 83.3% of the votes fell within [-1, +1] in both seasons.

However, this percentage decreases in colder seasons, as only 60.2% and, more worryingly, only 47.5% are within the [-1, +1] range for autumn and winter, respectively. The latter is where the most significant thermal discomfort is observed. This behaviour may be explained because even in Summer, warm temperatures do not prevail all day but are only present from 11 a.m. to 6 p.m. However, many homes showed signs of overheating (Section 4.2), which was not reflected on the surveyed TSV's. In contrast, autumn and winter votes were more scattered towards 'colder' votes. This suggests that the people from the *Meseta* may be better adapted to high temperatures. A Spearman correlation analysis between the surveyed TSV's and the calculated PMV showed a strong correlation ($\rho = 0.62$) for Summer. In contrast, Spring and Winter showed a weak correlation ($\rho = 0.35$ and $\rho = 0.45$ respectively), while in Autumn was "very weak" ($p = 0.23$). This suggests that the PMV model may not be the best fit for Mexico during cold seasons.

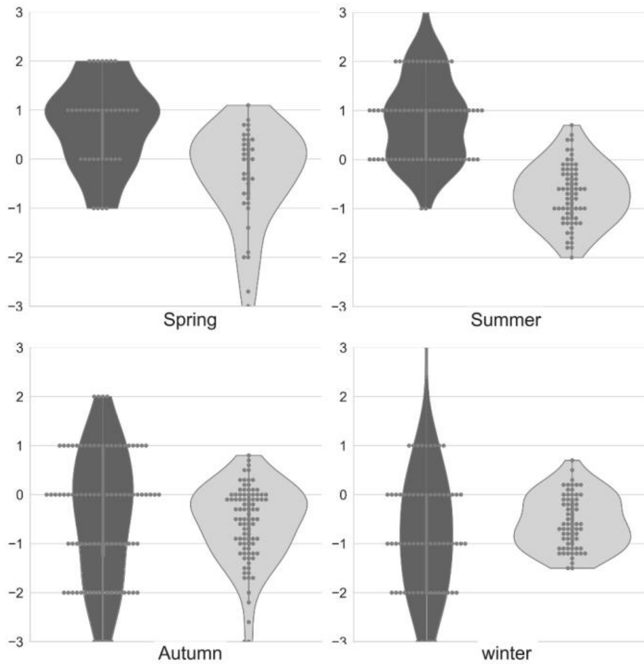

Figure 8 – Violin plots of the recorded TSV's (dark grey) against the calculated PMV's (light grey) in Spring (the 21st of March to the 20th of June), Summer (the 21st of June to the 20th of September), Autumn (the 21st of September to the 20th of December) and Winter (the 21st of December to 20th of March).

4.2.2 Adaptive Model

Figure 99 shows seasonal plots for the adaptive model for occupied hours (7:00-23:00]. The standard ASHRAE 55 [58] requires at least 80% of occupied hours within the comfort band. Spring is the season with the most significant percentage found within the 80% acceptability comfort band, with 42% living room hours. In contrast, only 36% and 34% of the hours are within 80% acceptability parameters during summer and autumn. The Winter season provided the worst quality as only 22% of the hours were found within the specified comfort band. This may be due to 50.5% of the data points in winter of the mean outdoor air temperature $T_{a,out}$ [°C] (x-axis) are below the minimum validity threshold of 10 °C from the ASHRAE 55 standard.

Among the monitored houses, 55% were located outside the adaptive model's 80% acceptability comfort band. In total, 30% of the hours monitored are below, and 25% of the monitored temperatures were found above the comfort band, as shown in Figure 9.

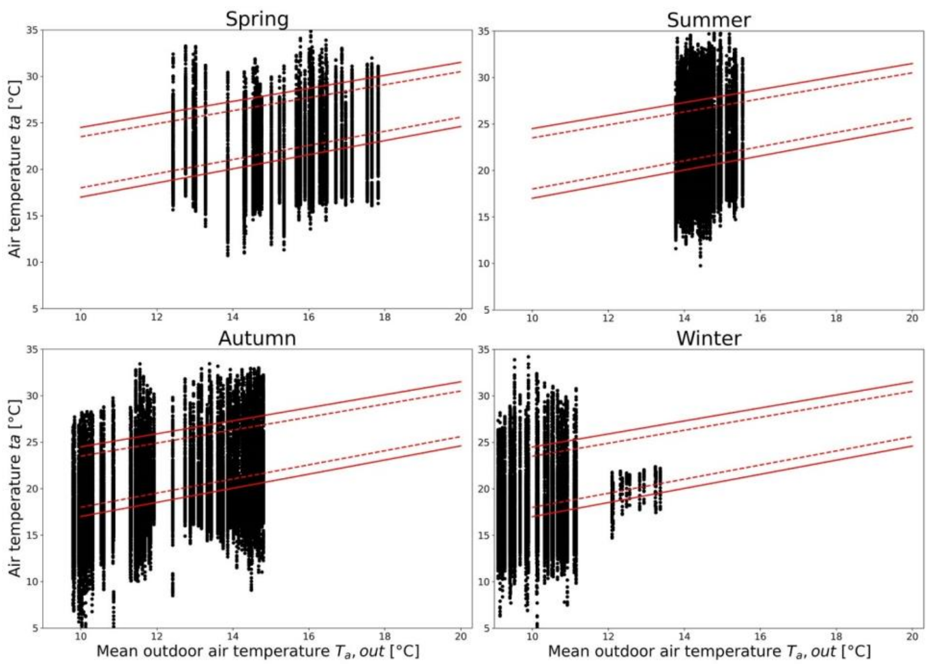

Figure 9 - Spring 2018, Summer 2018, Autumn 2018, and Winter 2018-2019 scatter plots of indoor operative temperatures T_{op} [℃] against outdoor running mean temperatures T_{rm} [℃]. Slanted lines show the acceptable operative temperature ranges by ASHRAE 55. The segmented line represents the 90% acceptability threshold, and the continuous line represents the 80% acceptability. We present data for T_{op} < 10 ℃ for completeness though the ASHRAE 55 standard is not valid at these temperatures.

Figure 100 plots the TSV votes recorded in different seasons against the ASHRAE 55 adaptive model recommendations. We observe that neutral votes fall below the recommended lower limit in spring and summer, contrary to winter and autumn. Votes in the latter seasons are more consistent with the standard as we also observe all except two votes in both seasons that are ≤1 fall below the recommended lower limit. Only 23% and 16% were observed in spring and summer within the TSV$\in$ [-1, +1] range. In both cases, 50% of the comfort votes were below the band. Autumn and winter had the most significant amount of discomfort votes, and hence only 11% and 22% of the recorded TSV's were inside the comfort band. This may mean that the adaptive model described in the ASHRAE 55 standard may not be the best fit for the Mexican context. In fact, a study by Morgan and Gomez-Azpeitia [72] found that 14 thermal comfort datasets (including two cities from the Meseta) found a neutral temperature of 4 °C higher than the one set in the ASHRAE 55.

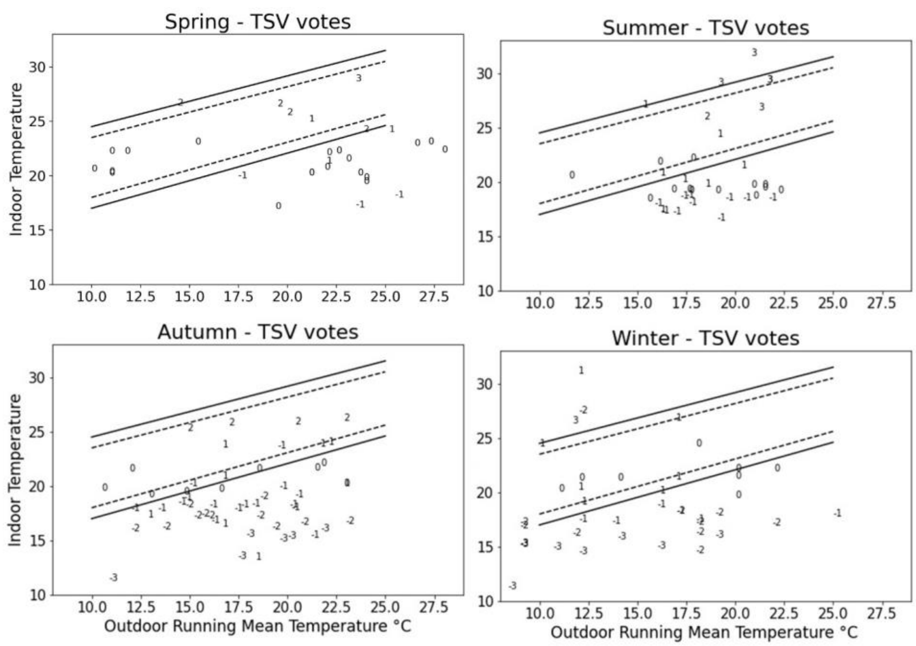

Figure 10 Seasonally separated TSV ∈ [-3,+3] over the monitored period, against the ASHRAE 55 80% (Dashed) and 90% acceptability (Solid) boundaries. The number shown represents the recorded Thermal Vote

4.2.3 Derived neutral temperatures

We regressed the monitored air temperatures and TSV's in order to find the neutral temperatures (T_n), a practice that has become common in thermal comfort studies [22, 60]. One of the implications of the adaptive model is that the T_n is strongly seasonally dependant, expected to be lower in winter and higher in summer, as seen in other studies [60, 71]. However, in our case, after regressing our data seasonally, we observed the opposite. Table 10 shows the gradient (α) and intercept (β) values of the models for each season and a single model for the year. The provided p-value indicates a significant relationship between the internal temperatures and the TSV variable. We observe that r^2 is highest on the summer model. This is likely the result of the small sample size for this study as we observe the coefficient of determination generally, though not always, improves with sample size. The overall neutral temperature calculated is 20.4 °C. Contrary to the expected, we have colder T_n in Summer than during the other seasons. The regression plots of the yearly and seasonal regressions can be seen in Annex 4.

Table 10 - Neutral temperatures calculated using linear regression, ranked by r^2. "n" stands for the number of observations.

	T_n [°C]	p-value	r^2	n	α / °C	β	Votes	
Summer	19.62±0.02	2.72 e-13	0.79	36	-5.6	0.29	$\bar{x}$ = 0.4	σ = 1.4
Spring	21.19±0.02	1.09 e-09	0.74	30	-6.1	0.30	$\bar{x}$ = 0.4	σ =1
Winter	21.19±0.02	1.77 e-09	0.62	39	-6.5	0.28	$\bar{x}$ = -1.2	σ =1.7
Autumn	21.10±0.02	3.06 e-11	0.57	54	-6.9	0.33	$\bar{x}$ = -0.9	σ =1.3
Year	21.19±0.02	3.33 e-40	0.67	159	-6.7	0.32	$\bar{x}$ = -0.3	σ = 1.5

4.2.4 Griffiths method

Given our reduced number of site visits, the neutral temperatures were also computed according to the Griffins method [72]. This method is widely accepted to calculate neutral temperatures in studies with a limited number of TSV's [15]. The value of 0.5 / K is the most commonly used for the G coefficient [73]. However, Ryu et al. [74] derived this constant from a study in residential buildings, estimating it to be 0.356 / K. This method was then calculated as below:

$$T_{nG} = T_{op} + \frac{(0 - TSV)}{G} \quad (5)$$

Where T_{nG} is the neutral temperature according to Griffiths in ℃, T_{op} is the operative temperature, TSV is the thermal sensation vote, and G is the Griffith's coefficient, being 0.356/K as described.

Table 11 – Average comfort temperatures divided by season, computed under the Griffiths method, where G= 0.356/K

Season	T_{nG} *in* ℃	σ (℃)
Spring	20.72	1.4
Summer	19.81	1.8
Autumn	20.77	2.6
Winter	22.12	2.6
Year	20.88	2.4

Table 11 shows the result of the neutral temperatures per season according to the Griffiths method. These results confirm the seasonally independent tendency seen in section 4.3.3, where T_{nG} is warmer during cold months and vice versa. In fact, the difference between the values of T_n and T_{nG} is always less than 0.5 ℃, except for Winter, where it varied 0.93 ℃, corroborating the certainty of our neutral temperatures found.

4.2.5Key influencing factors

To answer Research Question 3, a Machine Learning Linear Regression model was created based on the 159 observations recorded. Linear regression in Statistical learning predicts quantitative responses, in our case, the TSV values. First, we created a prediction model based on the following environmental variables: *external air temperature*, *relative humidity,* and *operative temperature*, and personal variables: *age*, *income*, and *clothing insulation*. Then we split the dataset 70% to training and 30% to testing. The analysis was undertaken with the Statistical learning tool: "*scikit learn*" on Python. The residual histogram, as well as the results of the Mean Absolute Error (MAE), Mean Squared Error (MSE), and the Root Mean Squared Error (RMSE) that verifies the validity of the model can be seen in Annex 5.

Table 12 – Ranked β coefficients provided by the linear regression model against the TSV.

Variable	**β**
Clothing Insulation	-0.685
External Air Temperature	-0.016
Age	-0.003
Income	0
Metabolic Rate	0
Relative Humidity	0.004
Internal Operative Temperature	0.339

Our model yielded the results shown in Table 122. Here, holding all the variables fixed, an increase of 1 TSV unit is associated with a change according to the value set in the $\boldsymbol{\beta}$ column.

For instance, we observe in our model that clothing insulation clo, and internal operative temperature T_{op} have a high influence on the thermal sensation vote of the building occupant. However, in the case of clothing, it is clear that T_{op} dictates clo and not the opposite due to the absence of systematic or central heating. Hence, the variable T_{op} can be named as the main influencer on the subjects' thermal response, as expected. The variables 'age', 'external temperature', 'relative humidity, and 'income' show a low to null influence in our model, as changes on these variables do not predict a significant shift in the occupant's TSV.

4.3 Overheating

Here we show the results of the overheating analysis described in section 3.8. The first analysis (Criterion 1a) showed that twelve homes (46%) overheated during the summer period. Amongst these, four presented hours in exceedance slightly above the allowed 3% threshold, ranging from 3.7% to 4.9%. Although the rest are progressively higher, two homes overheated over 30% of their hours, as seen in Figure 1111.

Figure 1212 shows the number of days where Criterion 2 was not met per month. We observe that the houses slightly above the 3% threshold from Criterion 1a passed Criterion 2. However, the two homes with the large percentage of H_e from Criterion 1a, presented a large percentage of days where Criterion 2 was not met (64%-id11 and 38% -id37). On the other hand, Criterion 3 (Figure 13) was not met in 11 homes (42%). We can observe that 85% of the homes that failed Criterion 2 also failed the other two. These results are not coherent to our TSV votes recorded during the "summer period". Even if 46% of the homes were overheated, the TSV votes averaged 0.43 (sd=1.4), suggesting a high level of adaptation to high temperatures in this population.

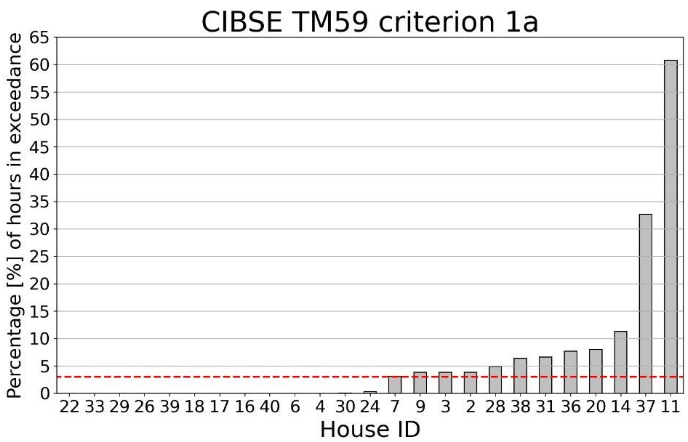

Figure 11 – Percentage of hours in exceedance according to the TM59 Criterion 1a for the monitored homes in rank order. The red dotted line represents the allowed 3% threshold.

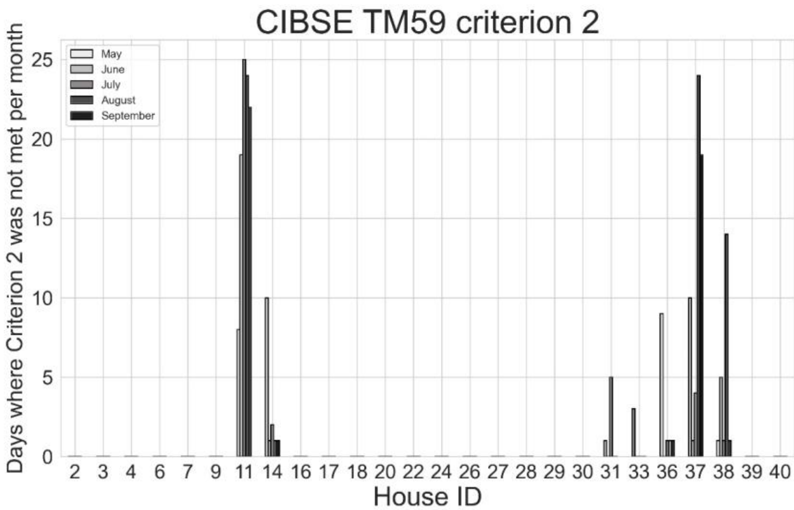

Figure 12 – Number of days per month where the houses exceeded the daily weighted threshold, and therefore not meeting the requirements set in the TM59 Criterion 2.

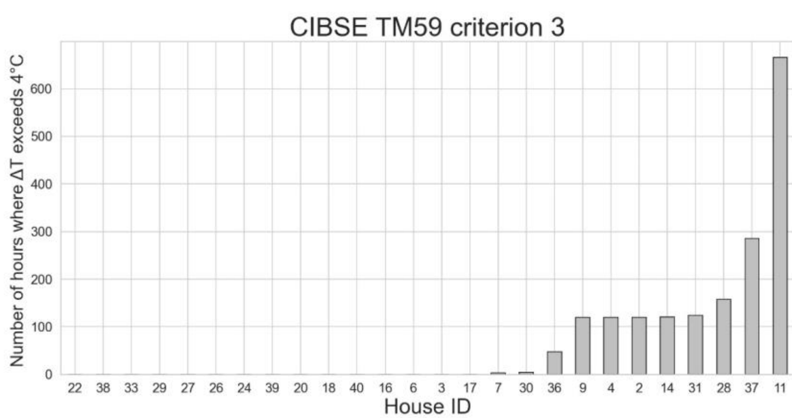

Figure 13 – Number of hours per house where the living room temperature was 4°C above the upper limit throughout the "summer design year".

4.4 Indicative analysis by income

The OECD divides income classes by *'lower-income'* (households with an income lower than 75% of the median national income), *'Middle-income'* (households with an income between 75% and 200% of the median national income), and *'Upper-Income'* (households with an income above 200% of the median national income) [75]. In Mexico, the OECD reports a median monthly income of MXN$ 5,040 pesos [76]. According to these definitions, 36% of the Mexican population fits the 'lower-income' category (less than MXN$ 3,780 pesos per month), 45% the middle-income (between MXN$ 3,780 – 10,081), and 19% the *'Upper-Income'* group (more than MXN 10,081). In our sample, after dropouts, we had 37% of the *lower-income* group, 40.7% of *'Middle-income'*, and 22.2% of *'Upper-Income'*, indicating a good match with national data.

We undertook an indicative analysis to spot potential differences in TSV due to house type. Our surveys included questions about the respondents' salaries. This information was used to divide our sample by income levels. The TSV averages split by the season of the different income groups is seen in Table 13. In winter, the average TSV for the total population was -0.71. This is the farthest to the four seasons' neutral vote but still within the acceptable range of TSV∈ [-1, +1]. The "Upper-Income" group showed higher thermal dissatisfaction in winter (TSV -1.42) on average due to three factors: (i) That these usually have a greater fenestration area for aesthetic reasons; (ii) That the spaces within the homes from this group are generally more extensive, and (iii) That the composition of the fabric allows significant heat losses (i.e., lightweight materials). It is also observed that the “Middle income” group showed a TSV mean of -1.3 (outside the allowed range), and the “Low income” group of -0.84, but with a large standard deviation, suggesting a large number of votes outside the acceptability range. This suggests the following four statements. (i) That the “Low and Middle income” groups may be experiencing energy-poverty (discussed further in Section 4.4); (ii) under the Latin American context, it is commonly thought that homes of those with higher incomes may be better adapted to cold temperatures and hence may provide better operative temperatures. The findings in this article, in fact, show the opposite, due to the reasons mentioned above (Building fabric built with the same configuration as the low income -Figure 2- but in larger spaces) (iii) that the housing fabric typology in the Mexican Meseta is not adequate against the low temperatures experienced in winter and (iv) that the population may be better adapted to hot climates. The latter is supported by the results of the overheating analysis (Section 4.4), where the overheated homes still presented TSV votes within the acceptable range of TSV∈ [-1, +1].

Table 13 - Mean seasonal TSV values split by income group. “$\bar{x}$” stands for mean, and “σ” represents the standard deviation, and “n” is the number of observations.

Season	**Income**	**TSV**		
		$\bar{x}$	σ	n
Spring	Low	0.27	0.96	11
	Middle	0.33	1.24	6
	Upper	0.46	0.74	13
Summer	Low	0.64	1.44	14
	Middle	-0.09	1.08	11
	Upper	0.54	1.15	11

	Low	-0.73	1.24	19
Autumn	Middle	-1.09	1.5	11
	Upper	-0.58	1.46	24
	Low	-0.84	1.65	13
Winter	Middle	-1.3	1.3	12
	Upper	-1.42	1.34	14
	Low	-0.16	1.42	67
Year	Middle	-0.67	1.4	43
	Upper	-0.26	1.42	73

4.5 Behavioural Adaptations

During the survey visits throughout the year, participants were asked to describe their different thermal adaptations. We found that while 80% of our respondents do not use any means of heating such as gas heaters or chimneys during winter. The remaining 20% stated to use "rarely", electric radiators (10%), and ethanol fireplaces[1] (10%). The reason for this behaviour is not known. However, it may be influenced by various factors such as financial – people may not

[1] An ethanol fireplace generates heat through the combustion of denatured alcohol. It is normally placed on a ceramic base, and it causes indoor air pollution.

be able to afford the increase in energy bills, as 20% reported fuel poverty at some point throughout the survey visits; or cultural (i.e., the people's general idea of living in a warm country, and therefore not needing heating systems).

Since all the surveyed houses are naturally ventilated, we considered it necessary to note occupants' reasons for opening their windows. Generally, the external temperatures of Toluca in the mornings and nights range between 0 °C and 10 °C [77]. However, almost half of the people (47%) said they never open their windows to make their spaces cooler during Summer. The most voted options were "to improve the air quality" and "to create drafts", with 64% of the respondents choosing "often" and "sometimes" for the first one and about 70% for the second one as seen on Figure 14.

Smoking in enclosed spaces is hazardous, even for those who do not smoke [78], and it is reported to worsen heart conditions [79]. In 2018, Mexico reported 0.011% of its population (13,200 people) lung cancer fatalities. In addition, deaths related to heart conditions are the number 1 cause in Mexico (35.7%, 42.8M) [80]. In our sample, 60% stated they never open the windows to smoke, whereas 28% reported doing it "often" or "always".

Humidity is another factor that may worsen people's health and quality of life. It is reported that exposure to mould in indoor environments can be related to respiratory diseases in healthy people. It may worsen the symptoms of people with asthma and pneumonitis [81] and increase mortality due to the COVID19 virus [82]. Half of the sample reported that they never or rarely open their windows to reduce humidity or mould. It may be difficult to assess the reason behind this since 97% of the respondents stated that there is mould in their homes in at least one room.

The remaining 50% is distributed between participants who open their windows more often to reduce humidity levels.

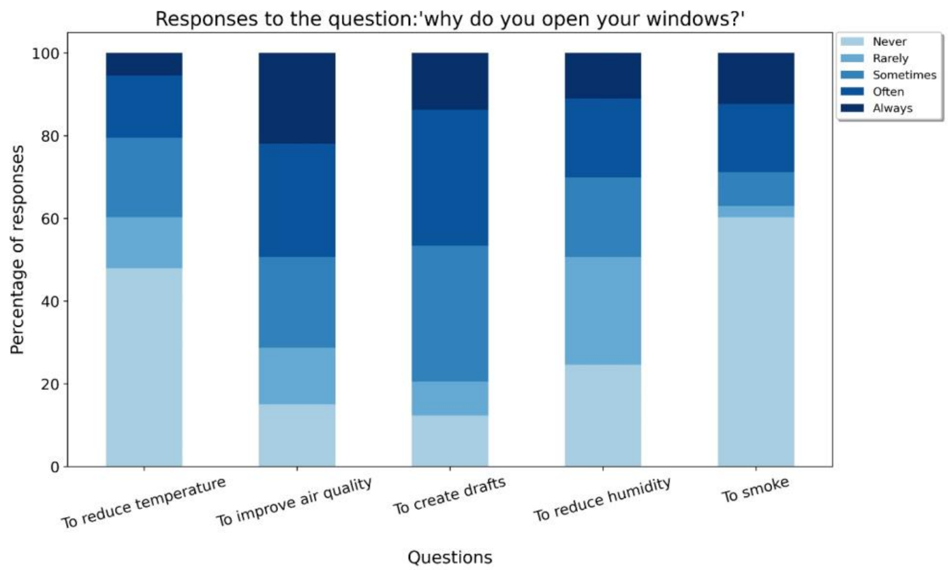

Figure 14 – Reported frequency to different reasons why the user opens their windows.

As mentioned previously, only 20% of our population used external means of heating (none used mechanical cooling) that consume energy to reach a comfortable (neutral) thermal condition. Therefore, we looked at their different behaviours and adaptations. We found that the most common behaviours were to use extra blankets at night and to wear additional layers of clothing, adding up to 1.5 Clo, a value where the ASHRAE 55 is no longer applicable.

Half of the respondents stated that they never undertake activities such as staying long hours in bed, exercising, or taking hot showers in cold conditions. In addition, most people (90%)

reported that they never use gas, electric heaters, and 83% never use chimneys. A general pattern was that people took action in particular cases. For instance, we noted that if they stated that they would wear extra layers of clothing if they felt cold, they would never or rarely undertake a different activity. The rest of the adaptive activities taken by our sample can be seen in the figure 16.

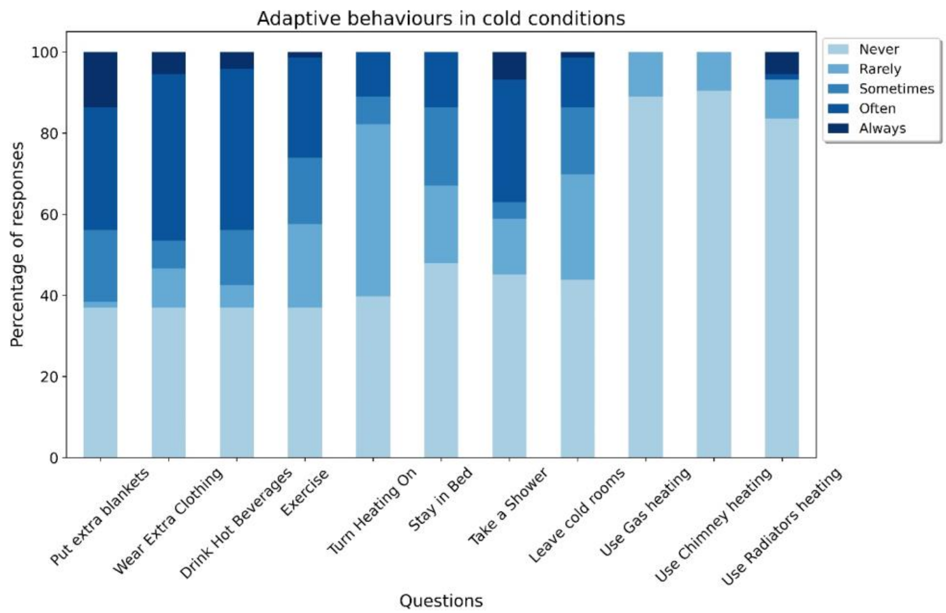

Figure 15 - Reported adapted behaviours in cold conditions. The legends on the x-axis where the options we provided to our sample to the question "how frequently do you do the following behaviours, when you are feeling too cold?".

5.0 Conclusions

This study represents one of the first Class II thermal comfort study in Mexico's Meseta Central in residential buildings with fixed temperature and relative humidity sensors and survey visits for eleven months. We present below the findings of this study:

(1) A large percentage (70.3%) of the subjects voted within the comfortable TSV∈ [-1,+1] throughout the year. Most of these "comfortable" votes were collected during the spring and summer months, with 83% for each season. This percentage decreases significantly during the cold months, initially to 60.2% in autumn and a worryingly low 47.5% in winter. These results support our hypothesis that the studied dwellings do not provide adequate internal temperatures (RQ1) during the colder months.

(2) Unlike the cold period and despite 46% of homes failing the Criterion 1a of the CIBSE TM59 overheating standard (23% failing Criterion 2 and 38% failing Criterion 3), the majority (59 %) of TSV votes were still between [-1,+1] in summer. This suggests a better adaptation to warm weather in this region. Although the CIBSE standard was developed in the UK, it utilises the adaptive standard which is localised to our study, and hence, this is a significant result.

(3) Seasonal neutral temperatures (T_n) suggest a slightly cooler temperature preference in the summer (19.6 °C) than in spring, autumn, and winter (21.1 °C). As this is a generally cool climate, the preference for warmer than expected temperatures in spring, autumn and winter may be an indication of negative thermal alliesthesia [83], given that the majority of the homes do not have continuous heating.

(4) We provided a survey-based translation of the ASHRAE 55 7-point Thermal comfort scale to Spanish from Mexico, as the official translation may lead to misunderstandings outside Spain. Due to its similarity to the Spanish spoken in the United States (40M native speakers), Central (34M) and South America (200M), we expect that our translation can serve as a tool to undertake thermal comfort surveys in these countries. In addition, its findings can assist policymakers in amending the voluntary standard Steady-state (PMV) based NMX-C-7730-ONNCCE-2018 regulation.

(5) The population's adaptive strategies leaned towards increasing the temperature of their houses in cold seasons. They reported having in general cold environments and a desire to improve internal temperatures during the cold months. Therefore, further research should be conducted exploring the concept of ‘underheating’ in low-income groups in Mexico. This may lead to policies and support to adequately retrofit their homes.

(6) Regarding future work. It is necessary to examine the potential strategies that improve the quality of environments, especially during cold periods. Further, these strategies must not raise the building's carbon footprint. In addition, it is essential to study whether the low temperatures found have any implication on the physical and mental health of the occupants of the houses.

6.0 Miscellaneous

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6.3 Data Access statement

The data created for this research are available at the University of Bath data archive (https://doi.org/10.15125/BATH-00973)

6.3 Declaration of conflict of interests.

The author(s) declared no conflict of interests

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8.0 Annex

Annex 1

Results of the Survey made to translate the ASHRAE 55 7-point to Mexican Spanish

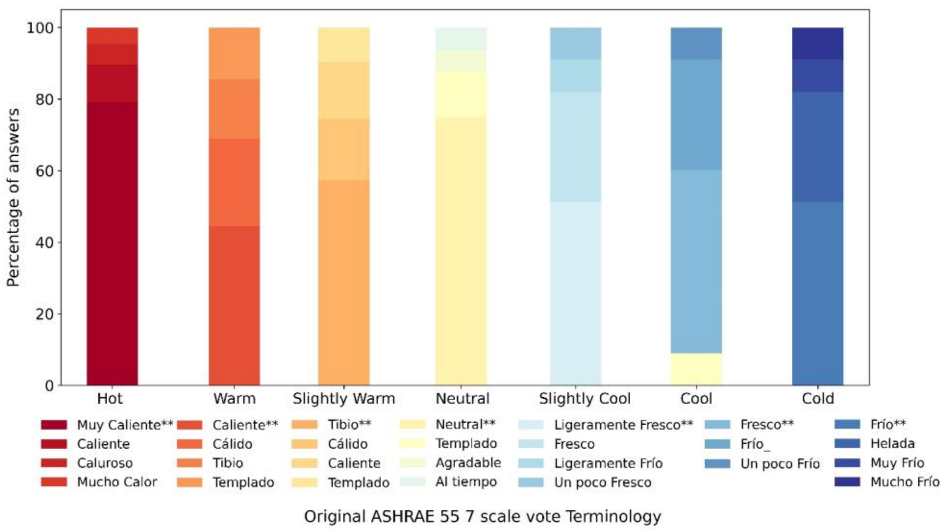

*Figure 16 - Results of ASHRAE 55 Translation survey to Spanish (Mex). Every bar chat shows the most common answers to each definition. Below every bar, we placed the answers from more (top) to less (bottom) common. The answer with two asterisks "**" next to it is the selected word.*

Annex 2

Minimum, maximum, average temperatures and diurnal range for each dwelling monitored, separated by season.

Spring temperatures (°C)				
House ID	Min	Max	Average	Diurnal Variation range

			Mean	Standard Deviation	Mean	Standard Deviation
2	16.8	20.2	18.8	0.1	0.3	0.2
3	15.4	23.4	18.5	0.8	2.5	0.8
4	17.6	24.2	20.5	0.6	2.1	1
6	16.6	24.3	20.2	0.3	1	0.5
7	15.6	23.9	19.2	0.3	1.2	0.4
9	17.5	25.1	21.2	0.6	2.2	1.2
11	20.3	31	26.1	1.7	5.1	1.1
14	23.6	32	27.6	0.9	3.2	1.2
16	16.7	28	22.2	0.7	2.6	0.9
17	17.4	28.1	21.5	1.2	3.9	1.3
18	18.9	24.8	21.5	0.5	1.5	0.5
20	nan	nan	nan	nan	NaN	NaN
22	15.7	24.3	19.1	0.6	2.1	0.8
24	13.1	29.8	20.9	1.9	6.2	2.1
26	16.2	22.5	18.8	0.5	1.6	0.7
27	18.2	26.4	21.5	0.8	2.5	0.8
28	14.6	26.2	20.1	1	3.3	1.3
29	19.3	22.2	20.8	0.2	0.5	0.4
30	18.3	24.9	21.2	0.4	1.1	0.5
31	19	30.8	24.8	0.9	2.8	1.2
33	14.3	25.2	20.2	0.7	2.4	0.9
36	17.5	35.4	24.9	2	6.3	1.8

37	19.1	30.8	26.1	1.3	4.1	1.5
38	14.1	35	23.5	1.1	3.8	1.3
39	16.1	21.2	18.4	0.2	0.8	0.3
40	17.4	24	20.5	0.6	2	0.8
Summer temperatures (°C)						
House ID	Min	Max	Average		Diurnal Variation range	
			Mean	Standard Deviation	Mean	Standard Deviation
2	15	22.3	18.4	1.4	0.6	0.4
3	14.5	20.9	17.5	1.1	2.2	0.6
4	16.1	21.4	18.8	0.7	1.8	0.6
6	15.1	22.3	19.3	1.5	0.9	0.4
7	15.4	20.5	17.5	0.8	1.1	0.3
9	16	22.9	19.1	1	2.4	0.9
11	24.4	37.6	30.2	1.9	5.4	0.9
14	21	29.5	25.4	1.2	2.6	0.7
16	12.6	22.2	18.7	1.4	2.3	0.6
17	17.2	25.2	20.5	1.4	4	1
18	18.8	23.2	20.7	0.8	0.9	0.3
20	12.9	22.3	19.1	1.2	2.8	1.2
22	15	21.1	17.7	0.9	1.9	0.5
24	12.5	29.1	19.2	2.8	5.3	1.7
26	13.9	22.9	18.3	1.3	2.8	1.5

27	10.8	25.3	20.7	1.8	2.5	1.1
28	14	27	20.2	2.4	3.5	1.3
29	15.7	22.3	19.3	1.7	0.7	0.5
30	17.4	22.1	19.1	0.8	1.1	0.5
31	15.2	30.9	24.7	2.1	5	2.2
33	14.9	22.9	18.8	1.1	2.2	0.7
36	16.3	30.1	22.2	2.5	5.3	1.2
37	23.3	33.3	27.7	1.9	3	1
38	18.9	31.2	24	2.3	3.5	0.9
39	16.3	18.9	17.6	0.5	0.6	0.3
40	17.1	22.9	19.4	0.8	1.7	0.5
Autumn temperatures (°C)						
House ID	Min	Max	Average		Diurnal Variation range	
			Mean	Standard Deviation	Mean	Standard Deviation
2	14.4	24.4	18.5	2.5	0.7	0.5
3	10.8	19.4	15.9	1.4	2.2	1.1
4	13.5	21.7	18.1	1.3	2	0.6
6	14.1	21.9	18.8	1.6	1.3	0.7
7	12.5	18.9	16.5	1.3	0.7	0.3
9	14	20.3	17.4	1.3	1.9	0.6
11	19.4	33	27.6	2.6	4.9	1.2
14	15.2	27.2	22.9	2	4.2	1.4

16	13.6	26.6	21.2	1.7	3.3	1
17	13.3	26.6	19.1	2.3	5.4	1.5
18	15.5	21.5	18.9	1.5	0.8	0.3
20	9	21.5	17.1	1.9	3.1	1.4
22	11.9	21	16.4	1.4	2.5	0.9
24	4.4	22.5	14.6	2.8	4.3	1.3
26	6.8	20.2	15.8	2.1	3.2	1.7
27	13.1	25.1	19.2	2.4	2.7	0.9
28	12.6	24.8	18.5	2.1	3.4	1.2
29	15	19	17.1	0.8	1	0.3
30	15.7	22.3	18.8	1.1	1.4	0.6
31	13.5	28.5	22.4	2.9	5.6	1.7
33	11.9	21.9	17.1	1.7	2.3	0.8
36	10.5	26.7	18.8	2.7	5.6	1.4
37	15.6	32.2	26.1	2.9	5.1	1.1
38	10	25.7	17.4	3.5	3.2	1
39	11.9	19.5	17	1.2	0.9	0.6
40	13	20.4	17.3	1.6	1.5	0.6
Winter temperatures (°C)						
House ID	Min	Max	Average		Diurnal Variation range	
			Mean	Standard Deviation	Mean	Standard Deviation
2	14.4	24.4	18.5	2.5	0.7	0.5

3	10.8	19.4	15.9	1.4	2.2	1.1
4	13.5	21.7	18.1	1.3	2	0.6
6	14.1	21.9	18.8	1.6	1.3	0.7
7	12.5	18.9	16.5	1.3	0.7	0.3
9	14	20.3	17.4	1.3	1.9	0.6
11	19.4	33	27.6	2.6	4.9	1.2
14	15.2	27.2	22.9	2	4.2	1.4
16	13.6	26.6	21.2	1.7	3.3	1
17	13.3	26.6	19.1	2.3	5.4	1.5
18	15.5	21.5	18.9	1.5	0.8	0.3
20	9	21.5	17.1	1.9	3.1	1.4
22	11.9	21	16.4	1.4	2.5	0.9
24	4.4	22.5	14.6	2.8	4.3	1.3
26	6.8	20.2	15.8	2.1	3.2	1.7
27	13.1	25.1	19.2	2.4	2.7	0.9
28	12.6	24.8	18.5	2.1	3.4	1.2
29	15	19	17.1	0.8	1	0.3
30	15.7	22.3	18.8	1.1	1.4	0.6
31	13.5	28.5	22.4	2.9	5.6	1.7
33	11.9	21.9	17.1	1.7	2.3	0.8
36	10.5	26.7	18.8	2.7	5.6	1.4
37	15.6	32.2	26.1	2.9	5.1	1.1
38	10	25.7	17.4	3.5	3.2	1
39	11.9	19.5	17	1.2	0.9	0.6

40	13	20.4	17.3	1.6	1.5	0.6

Annex 3

Percentage of relative humidity data of the homes monitored.

% Relative Humidity	Spring	Summer	Autumn	Winter
Mean	32.7%	37.5%	37.7%	31.2%
Std	6.1%	3.7%	4.3%	4.1%
Min	5.3%	16%	8.2%	6.6%
Max	63%	69.20%	71.84	65%

Annex 4

Regression plots of the Operative Temperature in ºC against the recorded TSV's. Seasonal charts are included, as well as annual.

Figure 17 - Regression plots of the TSV's against the Internal Operative Temperature (T_op) split by season covering Spring, Summer, Autumn 2018 and Winter 2018- 2019.

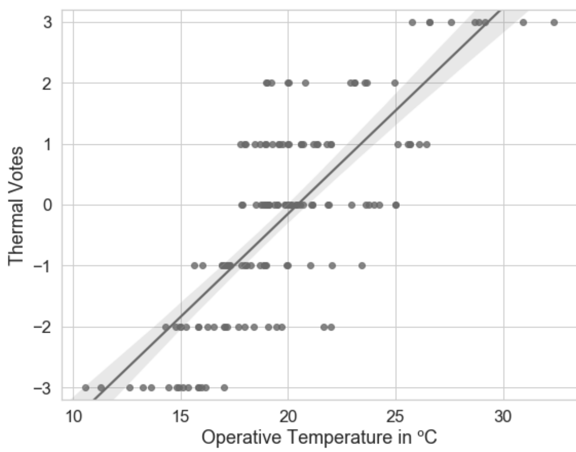

Figure 18 - Thermal Sensation Vote (TSV) plotted against the indoor operative temperature t_{op} on a scatter plot, with a fitted regression line.

Annex 5

Statistical learning Linear regression – Model Validation

Figure 19 below shows a scattered plot of the (actual) validation set matched against the predicted values created by our model. We ran a Shapiro distribution test to measure the normality of the residuals, and it gave a P-value of 0.628.

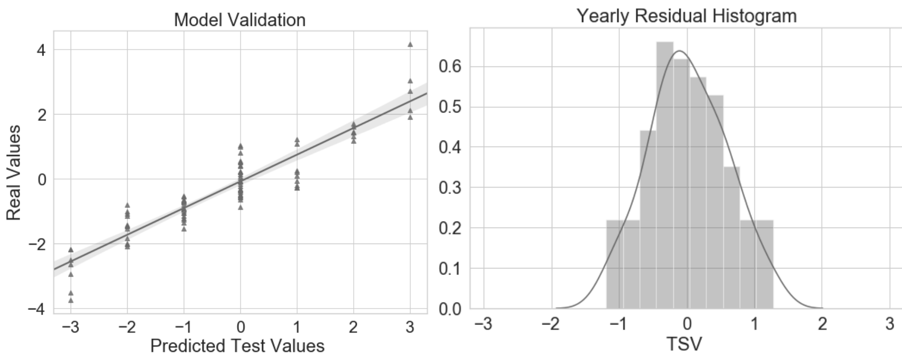

Figure 19 - Predictions provided by the linear regression model plotted against the real values (right) and the residual histogram of the difference between the real values and the predicted (right)

Table 14 - Validation of the linear regression model where MAE is Mean Absolute Error, MSE is the Mean Squared Error, and the RMSE is the Mean Squared Error

Validation	
MAE	0.46
MSE	0.32
RMSE	0.57