Evaluation of the thermal performance of an industrialised housing construction system in a warm-temperate climate: Morelia, Mexico

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Key words

Performance evaluation, Thermal comfort, Thermal adaptation, Housing design, Industrialised building systems, Mexico

Highlights

- The thermal performance of a low-cost concrete house building system is analysed.
- Monitoring and a field survey are used to assess environmental performance.
- Thermal adaptation is easier for subjects in the cool season than the warm season.
- Poor performance is blamed on a ubiquitous design unsuited to the local climate.

Abstract

This paper examines the performance of a case study of low-income housing situated in a warm-temperate climate (Morelia, Mexico). It represents the first comprehensive evaluation of thermal comfort in a widely used concrete formwork construction system in that country.

The study was conducted in two seasons, determined by climatic analysis identifying the months that presented the most extreme conditions during the year. Indoor thermal conditions were monitored and are compared with the adaptive comfort temperature and comfort zone derived from existing standards.

A thermal comfort field survey was also conducted, including the distribution of questionnaires in both seasons. The findings are compared with monitored data to assess the overall thermal performance of the housing typology.

The results reveal poor thermal performance with houses falling significantly outside the thermal comfort boundaries in both periods due to a number of factors, including the properties of the building envelope, the impact of solar radiation, the number of occupants and their behavior. The results indicate that it is easier for subjects to adapt to cooler rather than warmer conditions. These findings expand existing knowledge of the performance of this concrete formwork system in Mexico as well as other industrialised building systems in similar climates. It demonstrates the urgency of designing viable solutions according to local climate, and questions the use of identical housing prototypes across different climatic regions.

1. Introduction

The National Population Council of Mexico (CONAPO) estimated that in 2010 there would be nearly 30 million households, and by 2030 a total of 45.6 million households in the country, requiring the construction of an average of 780,000 new homes per year [1]. The Federal Government has arrived at a similar figure, proposing to create the necessary conditions to build 750,000 housing units per year [2]. As a result, federal agencies, international aid associations, and other private and public organisations have taken action to expand the housing sector in the country.

Highly capitalised developers control much of the housing market in Mexico, taking a lead role in the process of land acquisition, mortgage allocation, the marketing and delivery of new developments, as well as determining the design quality of new homes [3, 4]. Large construction firms have adopted Industrialised Building Systems (IBSs) that allow them to build higher numbers of houses at lower cost through the production of repetitive prototypes and the industrialisation of key processes [5, 6]. However, cost-savings are more often than not returned to shareholders rather than invested in improved design [3].

1.1. Energy demand in Mexico

Air conditioning or cooling represents the third largest electricity end use in Mexico with an average share of 24%, after refrigerators and televisions that have an average share of 35% and 26% respectively [7]. A significant number of new housing developments have serious comfort problems, reflected in a high consumption of energy [8]. Since 1996 the use of air-conditioning or other cooling systems has increased considerably, with an average annual growth rate of 7.5%, compared with an annual growth in housing stock of 2.7% (see fig. 1).

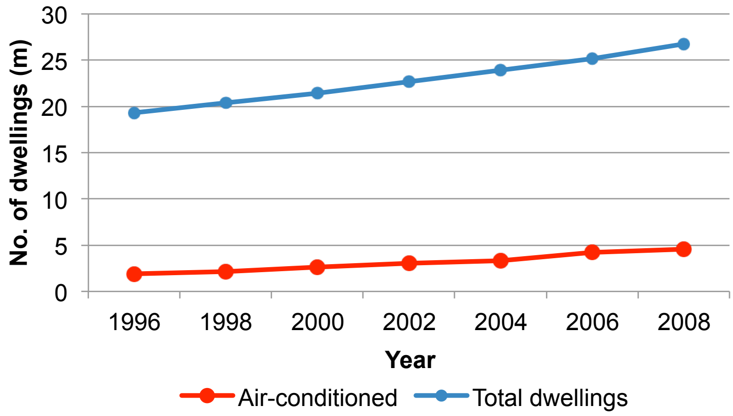


Fig. 1. Number of air-conditioned dwellings in Mexico. Source: (Rosas-Flores et al., 2011).

The World Bank estimates that electricity consumption from air-conditioning in Mexico might increase ten times by 2030, easily exceeding the current energy consumption of the entire residential sector [9].

Reducing greenhouse gas emissions from the residential sector is therefore a priority in Mexico; but if this is to happen a more viable construction solution to meet housing demand has to be developed. This study contributes to this effort by examining the major issues regarding thermal comfort and energy efficiency that arise from the use of precast concrete systems.

1.2. House construction in Mexico

Mexico has a rich tradition of environmentally responsive vernacular architecture, including the use of heavy weight materials in response to the warm climate. In particular, adobe houses have been constructed in Mexico since the pre-colonial period, and are still found throughout the country, with tiled roofs in mountainous regions characterised by higher levels of rainfall, and *terrados* or flat roofs in drier climates. Lighter weight *Bajareque* construction, comprised of latticework covered in straw-reinforced loam, is found in more humid areas of the country, particularly on the Pacific coast. Both form of construction retain heat during the day, which is released to the environment at night as the indoor temperature falls [10].

The influence of these vernacular traditions can be seen in the bioclimatic strategies evident in the work of Luis Barragán, who also used high capacitive materials, and a range of external spaces such as gardens, terraces, porticoes and courtyards to provide opportunities for adaptation to warmer conditions through a range of indoor-outdoor environments [11].

More recently, the need to increase the volume of housing for low-income families has meant that industrial processes employing new construction materials have replaced traditional building techniques. As with the Concrete Formwork System investigated in this study, these new strategies differ from traditional construction techniques through a more efficient use of materials (e.g. thinner walls), but rarely incorporate energy-efficient solutions such as the use of insulation or double-glazing.

2. Background

Morelia is located in the central area of Mexico (19.7° north, 101.2° west). It is 1,929m above sea level and has a built area of 1,250 km². This study examines the largest low-income housing development in Morelia, with around 14,000 homes, constructed between 2007 and 2014. The modularity and repeatability of the construction process, together with the large available sample, provide an opportunity to study the performance of a specific building typology under a variety of orientations and environmental conditions. The involvement of the developer was crucial in this research; providing detailed information about housing design, materials and the industrialised construction system used.

2.1. Building envelope performance

Previous studies have reported positive findings from the use of multi-layer construction strategies for houses in warm climates such as Turkey [12] and Mexico [13]. Findings indicate that when two construction systems with the same thermal resistance and thermal capacity are compared, the system with more layers results in an improved thermal performance, defined as a reduction in the decrement factor or increase in the time lag (see section 3.2.). Other studies have investigated the optimum location and distribution of insulation layers, for example in Mexico [14] and Saudi Arabia [15]. Notably, they found that installing the insulation layer on the exterior rather than the interior side of the building envelope also results in an improved thermal performance.

While these studies investigate the relative thermal performance of different configurations of the building envelope, little data has been collected on the thermal comfort of houses constructed employing the industrialised building systems widely used in Mexico today.

Fig. 2. Mass housing development illustrating typical house design.

2.2. The Concrete Formwork System

The Concrete Formwork System uses two main components: concrete and steel or aluminium reinforcement; allowing accurate calculation of material inputs and as a consequence, reduced waste. Working in this way, significant savings can be achieved and higher profits can be achieved [3].

All elements of the house are cast simultaneously by pouring the concrete in the formwork, which is positioned to form walls and ceilings. The uninsulated floor, wall and roof fabric has a u-value of approximately 3-4W/m^{2}K. Prefabricated details are added in a final stage. Aluminium-framed, single-glazed sliding windows (u-value: 5.7 W/m^{2}K) are installed. This systematic process of identical and repetitive actions is a linear method that can be easily replicated, allowing total control of housing production. Typically the houses are constructed without insulation, and the only means of climatic control is cross-ventilation by opening windows.

Fig. 3. Precision steel formwork system is being used to build exterior and interior walls and ceilings at one time.

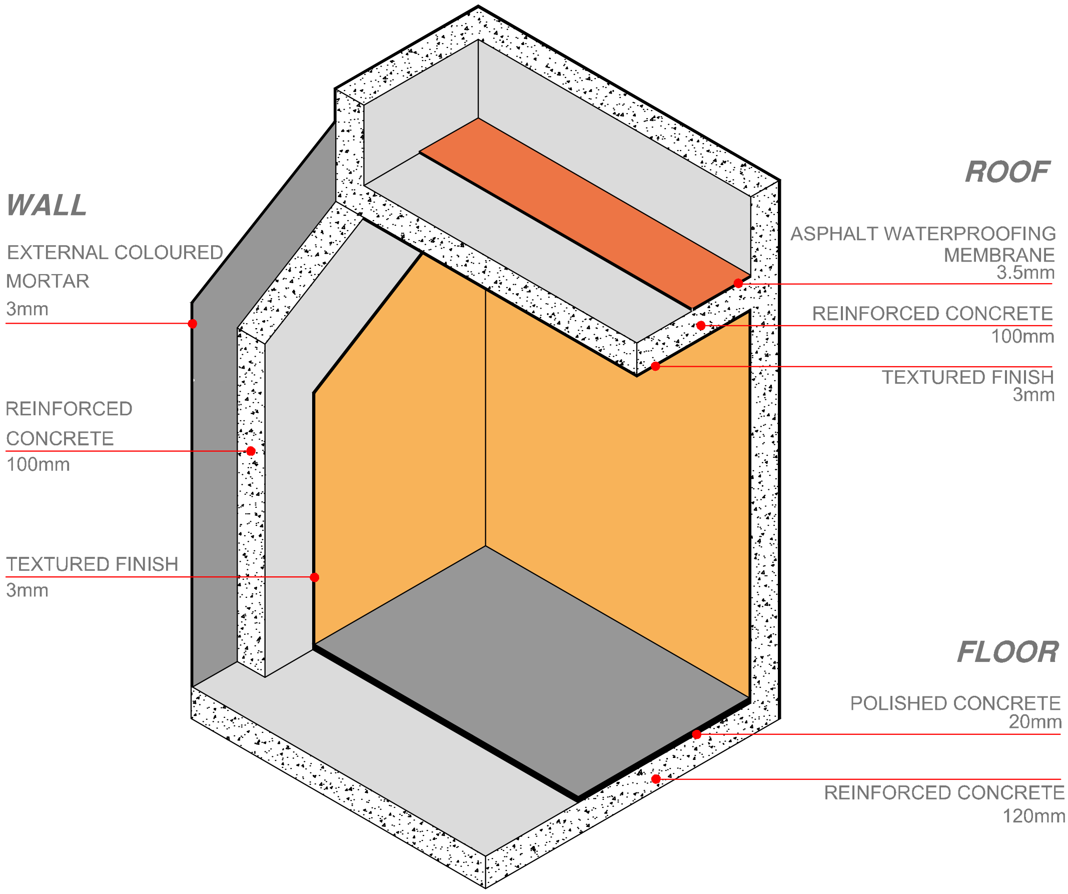


Fig. 4. Building elements and materials.

2.3. Thermal comfort studies in tropical and subtropical regions

Over the past couple of decades, numerous thermal comfort studies have been conducted in both tropical and subtropical regions, including China, India, Nepal, Bangladesh, Sri Lanka, Singapore and Mexico. Table 1 reviews some of these thermal comfort studies conducted in naturally ventilated buildings. Neutral temperatures in Aw-type tropical climates range from 28.0 to 30.9 °C. In Af-type tropical climates a similar range is evident, from 28.5 to 32.3 °C. In C-type subtropical climates the range of neutral temperatures is smaller (between 28.0 and 29.1 °C) in the warm season. These studies suggest that occupants in tropical and subtropical regions have a higher temperature tolerance and feel comfortable in warmer environments. The field studies carried out in Mexico are reviewed in more detail in the next section.

Table 1
Thermal comfort field studies in tropical and subtropical regions

Climate (Köppen Classification) (Kottek et al., 2006)	Location	NV Building Type	Season	Neutral Temperature (Tn) ◦C	Reference (Author and year)
Tropical wet and dry (Aw)	Kharagpur, India	Classrooms	All	29	(Mishra and Ramgopal, 2015)
	Calcutta, India	Classrooms	All	30.9	(Pellegrino et al., 2012)
	Hyderabad, India	Residential	All	29.2	(Indraganti, 2010)
	Dhaka, Bangladesh	Residential	All	28	(Mallick, 1996)
	Colima, Mexico	Residential	Warm dry Warm wet	28 28.6	(Gómez-Azpeitia et al., 2009)
	Culiacan, Mexico	Residential	Warm dry	28.1	(Gómez-Azpeitia et al., 2009)
Tropical warm fully humid (Af)	Colombo Sri Lanka	Factories	Warm	30	(Wijewardane and Jayasinghe, 2008)
	Singapore	Classrooms	All	28.8	(Wong and Khoo, 2003)
	Singapore	Residential	All	28.5	(de Dear et al., 1991)
	Mérida, Mexico	Residential	All	32.3	(Gómez-Azpeitia et al., 2009)
Subtropical warm fully humid (Cfa)	Guangzhou, China	Classrooms Dormitories	All	28	(Zhang et al., 2010)
Subtropical warm humid (Cfa/Cfa/Cwa)	Changsha, Guangzhou and Shenzhen, China	Residential	Warm	28.6	(Han et al., 2007)
Subtropical warm temperate (Cw)	Dhading, Nepal	Residential	Warm Cool	29.1 24.2	(Rijal et al., 2010)

2.4. Previous thermal comfort studies in Mexico

The CONAFOVI 2004-01-20 project [16] was conducted by 45 researchers from seven universities[1] located in Hot Dry and Warm Humid weather regions of the country. The main objective of this project was to establish the ranges of thermal comfort of users from low-income housing and to evaluate thermal sensation in order to develop a generic thermal comfort model for the Mexican population.

Transverse surveys were applied to users of naturally ventilated low income housing in the seven cities studied, and simultaneously indoor environmental conditions were recorded. The variables analysed were: air temperature, black globe temperature, wind speed and relative humidity, metabolic activity, and level of clothing. The questionnaire was based on ISO 10551 [17] and ISO 7730 [18] standards using the ASHRAE thermal sensation scale. The sample size was approximately 1,800. The measurement periods were established based on the climatic characteristics of each city. The results from this study yielded very high neutral temperatures (Tn) of above 30 °C during the warm season. Subjects appeared to be comfortable under severe weather conditions. A neutral temperature (Tn) of 35.2 °C was registered in the hot dry season (July, August) in Mexicali given a mean monthly outdoor temperature of 33.7 °C, and a neutral temperature of 32.3 °C was registered in the hot humid season (May, July) in Mérida given a mean monthly outdoor temperature of 28.2

[1] Universidad de Colima (UCOL), Universidad Autónoma de Sinaloa (UAS), Universidad de Sonora (UNISON), Universidad Autónoma de Baja California Sur (UABCS), Universidad Autónoma de Yucatán (UADY),Universidad Autónoma de Baja California (UABC) and Universidad Veracruzana (UV).

°C. Comfort temperatures found in this study are above the values that leading authors have described as uncomfortable. This study emphasises the high capacity of subjects to adapt under extreme environments, and demonstrates that the use of the presented models, including the ASHRAE-55 [19] standard, are inadequate in hot dry and warm humid weather regions of Mexico.

This study aims to establish the thermal comfort boundaries of housing located in the previously unstudied warm temperate region of Mexico, and to test the use of the Adaptive Comfort Standard from ASHRAE-55 [19] through validation in one case study over different seasons.

2.5. Climate Analysis

According to the modified Köppen climatic classification by Garcia [20], Morelia is in the "Cw" warm temperate semi-humid climatic zone with moderate rainfall during summer, and dry conditions in winter. A significant climatic characteristic of this city (in a Mexican context) is the seasonal temperature variation, with average temperatures of 17.2°C in the coldest period (December-January) and 22.9°C in the hottest period (May-June). However, minimum temperatures reach 3.5°C in winter and maximum temperatures reach 32.9°C in summer (see fig. 5). The seasons can be considered to be of approximately equal duration.

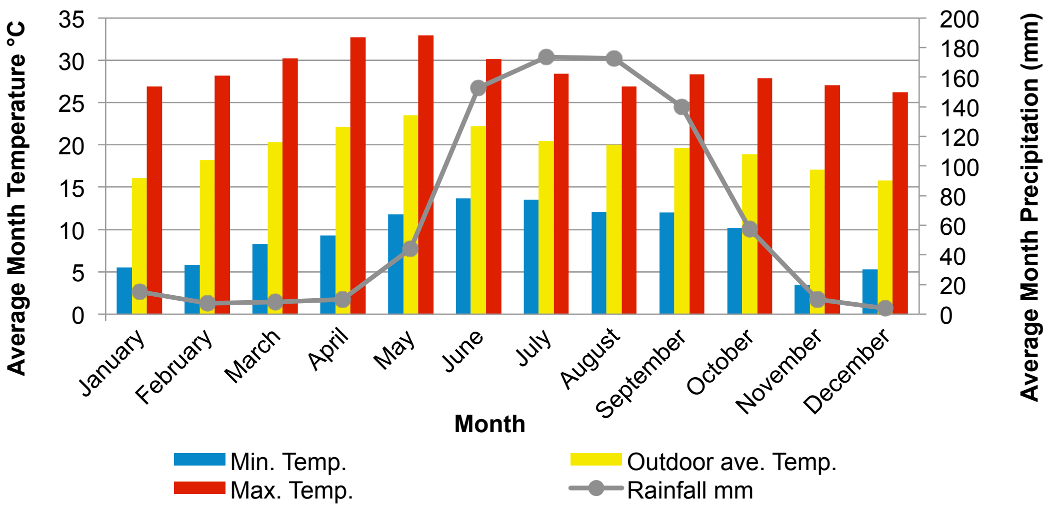


Fig. 5. Monthly temperature profile and precipitation in Morelia [21, 22].

Large diurnal temperature variations are also a key feature of the climate. In the coldest months (December and January) and warmest months (April and May) the diurnal variation reaches 15K. Large diurnal variations allow the use of heavyweight materials and natural ventilation as the main passive design strategies to achieve acceptable levels of thermal comfort. Broadly speaking, heavyweight materials combine high capacity to store heat with moderate thermal conductivity (good thermal mass) [23]; the use of these materials in building translates into stabilising indoor temperatures and introducing a thermal time lag.

Annual rainfall ranges from 700-1000 mm. The rainy period lasts from June to September, with a maximum precipitation of 170 mm in July and August. Relative Humidity (RH) ranges from 39% to 69% with an average of 54%. RH is higher in the months of July, August, September and October.

Maximum direct solar radiation occurs in the month of February at 678 W/m^2, while July presented the lowest levels of direct solar radiation with a maximum daily average of 412

W/m^2. Diffuse solar radiation is highest during the months of May, June and July with an average maximum of 331 W/m^2.

During most of the year, Morelia has comfortable wind speeds, indicating that direct cooling and night cooling can be used as a passive technique during warm periods. Prevailing winds in Morelia mostly come from a southwest direction, while in January they come from the northwest, and during the months of March and April they tend towards a southerly direction.

3. Research approach

The location of the selected monitored houses and their orientation is shown in fig. 6. 12 houses were monitored in total. H1-H10 were monitored in both seasons. As the occupants moved out of houses H11 and H12 between the monitored periods, two identical houses in another block (with the same orientation) were monitored during the warm season. All of the houses are occupied by families, and none are equipped with air conditioning or any type of space heating system.

The fieldwork was conducted in two main phases that consisted of a longitudinal housing survey (on-site monitoring) and a transverse subject survey. The housing monitoring was carried out over 42 consecutive days in each season: the cold period from the 17th of December 2008 to the 27th of January 2009 and the warm period from the 11th of May to the 21st of June 2009. These periods were determined by climate analysis of the region using an hourly weather data template for Morelia generated using Meteonorm software in order to identify the months with the most extreme conditions. The software presents monthly average values for periods of at least ten years, including wet and dry bulb temperature, relative humidity, wind speed and direction, cloud cover, precipitation and solar radiation (global, direct and diffuse).

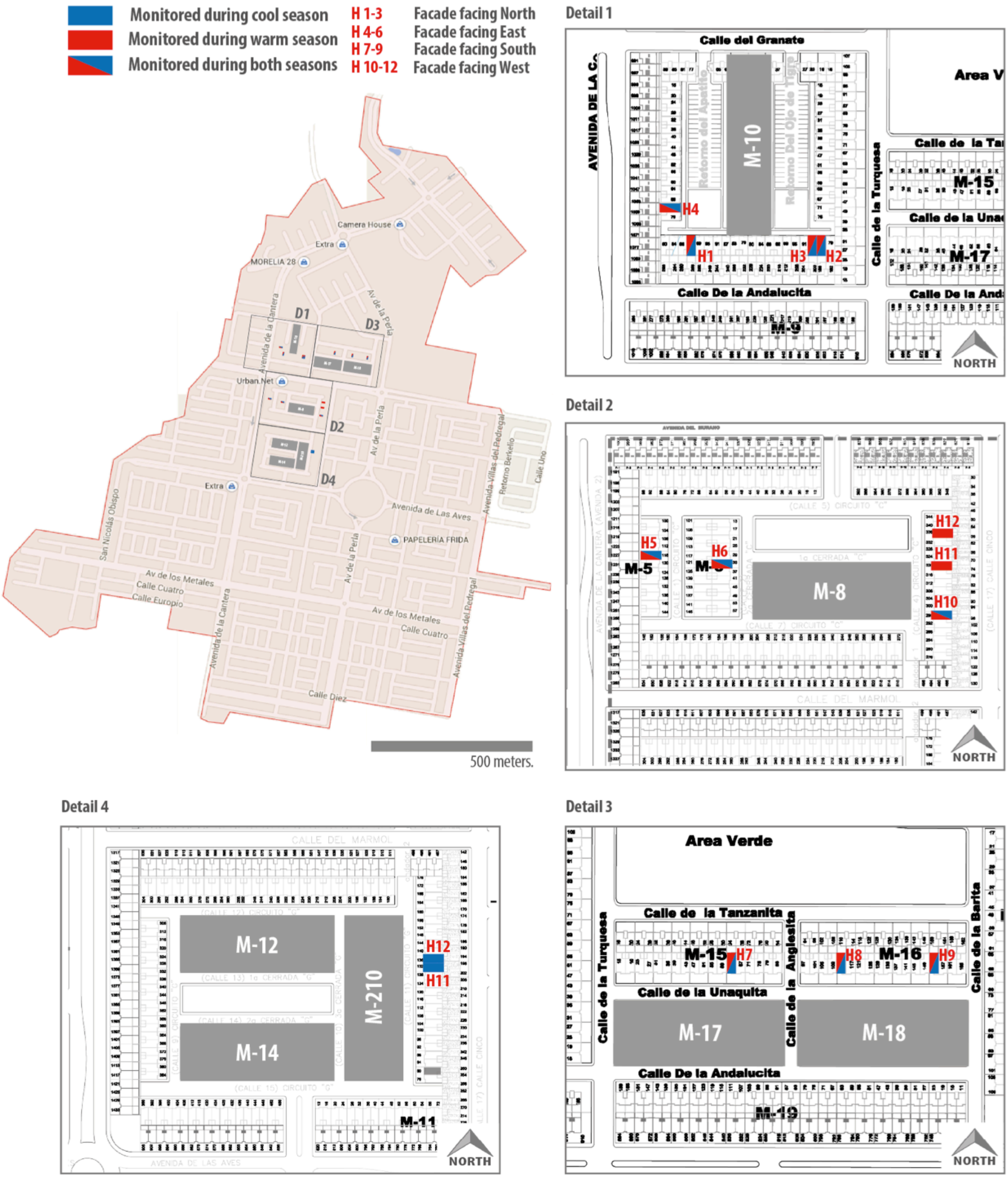


Fig. 6. Location and orientation of monitored houses.

3.1. Monitoring of case study houses

Three dwellings per each orientation were studied, with facades facing north, east, south and west. Two data loggers were used in each house, collecting data from the bedroom and from the living spaces (kitchen, dining and living room) where the residents spend most of their time. Data-loggers were individually identified and labelled with a unique reference code, and their serial numbers were also registered. The data-loggers were set to record air temperature and relative humidity at 10 minutes intervals. Before the equipment installation, the researcher inspected each house and judged the most suitable location aiming to obtain homogeneous measurements. Care was taken to avoid impacts on the measurements from solar radiation, air drafts (air vents, doors or open windows) and internal heat sources (such as incandescent lamps, refrigerators, television).

Fig. 7 shows a layout, section and facade of the house design under study, and the location where the data-loggers were installed. The data-loggers were fixed to the wall in the middle of each room, approximately 1.80 m high from the floor. This prevented children from reaching the loggers, and represents air temperature at head height for a standing subject. Air temperature may be slightly lower for sedentary subjects, though the vertical temperature gradient is minimised by a high air change rate and the avoidance of convection currents from passive heat sources.

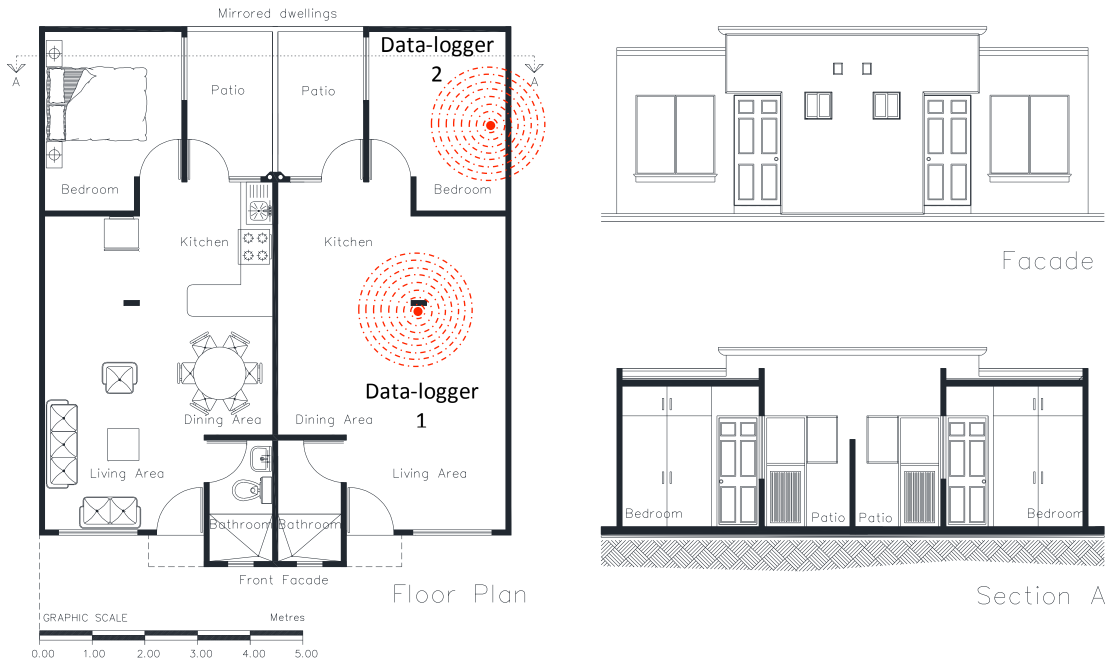


Fig. 7. Floor plan, facade and section of the house model selected and typical location of the data-loggers.

Two-channel Temperature/Relative Humidity Onset HOBO data-loggers (U10-003 model) were used. This type of data-logger has been widely used in studies of indoor thermal environments, for example [24, 25], complying with the ranges and accuracy levels specified on table 2 of Standard ISO 7726 [26] for measuring the physical variables of the environment. The equipment offers an operating temperature range of -20° to 70°C with a resolution of 0.02°C and a range of 0 to 95% for Relative Humidity with a resolution of 0.1%. Accuracy for temperature is ± 0.4°C from 0°C to 40°C, and for RH ± 3.5% from 25% to 85% over the range of 15°C to 45°C, ± 5% from 25% to 95% over the range of 5°C to 55°C. The time accuracy is ± 1 minute per month at 25°C. The HOBO U10-003 has a capacity to store 52,000 measurements, which is sufficient to collect data for the monitoring season with the settings stabilised.

All the HOBO data-loggers used in the monitored houses were new, and were previously tested and calibrated by the manufacturer. The instruments were also simultaneously checked against each other to ensure that the precision of measurements matched those prescribed by the manufacturer.

Outdoor climate measurements were obtained from the closest meteorological station, controlled by the operator of the potable water and sewage system of Morelia (OOAPAS) which is located approximately 2.5 km from the case study area (+19° 41' 35.92" latitude, -101° 16' 23.17" longitude).

3.2. Assessment criteria

Thermal comfort and performance was assessed utilising Discomfort Hours (DH), Percentage of Discomfort Hours (PDH), Discomfort Degree-Hours (DDH) and Mean Discomfort Degree-Hours (MDDH), in accordance with ISO 7730 [18] and ISO 15251 [17] standards for "Long term evaluation of the general thermal comfort conditions".

DH and PDH are hourly criteria indicators that describe when the indoor temperature is outside a specified range, providing an indication of the amount of time that the rooms will require heating or cooling to meet desirable thermal conditions. Its use is recommended when dissemination of results is required to non-experts (e.g. in the case of this research, housing developers and occupants) [27].

DDH and MDDH are the product of how long and how far the indoor temperature falls outside the comfort zone; a good indicator of a building's thermal energy performance, which can be used to calculate the energy required to cool or heat a building in order to meet comfort criteria [28, 29].

Time lag (TL) and decrement factor (DF) are crucial to determine the heat storage capabilities of materials. These thermal factors are important in regions where there are wide temperature oscillations and average temperatures are within the comfort range [30], as in Morelia. The time lag is defined by the time required for the heat wave to transmit from the outer surface to the inner surface and the decrement factor is defined by the temperature attenuation during the transient process [31]. Time lag and decrement factor are defined as follows:

$TL = t\,(T_{inmax}) - t\,(T_{extmax})$

$TL = t\,(T_{inmin}) - t\,(T_{extmin})$

$DF = (T_{inmax} - T_{inmin})/(T_{extmax} - T_{extmin})$

In general, as the decrement factor (DF) decreases and the lag time (LT) increases, thermal performance improves [32, 33]. DF and LT values vary with construction build-up and season but generally speaking, a DF of <0.2 and an LT of >6.0 may be taken to reflect a good standard of thermal performance in a warm climate [33].

3.3. Thermal comfort field survey

The thermal comfort field survey was conducted while the monitoring took place, consisting of 440 questionnaires completed over the two seasons. The surveys were conducted orally by a team of trained volunteers in order to obtain complete and accurate responses. 90% of subjects who were approached agreed to participate in the survey. Surveys were completed during the daytime, however distinct comfort sensation votes and preference votes were obtained for the preceding morning, afternoon and night. The first survey was carried out in the cool season, involving 203 subjects, and the second survey in the warm season, involving 237 subjects. Of the 440 questionnaires, 108 were completed by 54 individuals in both seasons, and 332 were completed by different individuals in each season. The ages of the subjects ranged from 12 to 74 years with a mean age of 30 years and a median age of 28 years. The gender distribution of the subjects was 3:1 female to male. This represents a typical low-income family structure where men are more likely to be absent from home.

The questionnaire, based on the CONAFOVI 2004-01-20 questionnaire [19], collected thermal sensation votes, preference votes and general thermal acceptability to find the average thermal conditions of the studied housing type from the occupants' perspective (see Appendix A). The presence of climate control systems was to be recorded to ascertain whether any houses were built or retrofitted with air-conditioning or space heating. These houses were to be ruled out of the investigation; however none were recorded in the survey.

4. Thermal Performance Assessment

Table 2 shows the comfort temperatures and thermal boundaries for occupant acceptability of 90% and 80% in each season, based on measurement data from the 12 monitored houses. Tn was calculated using the equation from the adaptive comfort standard (ACS) of ASHRAE-55 [19] (Tn=17.8+0.31 •Tm); the average outdoor temperatures (Tm) were calculated over the 42 monitored days of each season. The ACS model does not specify the limits of relative humidity levels in terms of thermal comfort. Literature and standards indicate that RH levels from as low as 30% to as high as 80% are still acceptable, depending on the level of physical activity and the type of clothing worn [1, 34-36]. These limits were used to define the optimal comfort conditions for occupants in this study.

Table 2
Comfort temperatures and thermal boundaries of Morelia over the two seasons under this study.

			90% acceptability		*80% acceptability*	
42 days period measurement	T out	Tn	Tn max	Tn min	Tn max	Tn min
Cool season	15.4	22.6	25.1	20.1	26.1	19.1
Warm season	21.6	24.5	27.0	22.0	28.0	21.0

4.1. Cool season

An overview of the thermal performance of the houses over the 42 day cool season is presented in this section (see table 3 for nomenclature of the houses). The lowest outdoor temperature registered was 5°C and the highest was 26.40°C. Overall, the sample of houses performed in a similar manner. Indoor temperatures followed outdoor temperatures, but the daily fluctuations were less pronounced than outdoors; the average maximum temperature of all rooms was 23.32°C and the average minimum was 15.97°C.

Week five registered the lowest outdoor temperatures in the season, this has impacted on the indoor climate where the average temperature was 18.40°C. The average maximum temperature was 22.22°C and the average minimum was 15.47°C. Fig. 8 shows a detail of the thermal pattern over a typical 48 hour period from week five. Broadly speaking, all rooms followed similar oscillations, with little discernable difference due to orientation except for houses facing south (7, 8, 9), particularly in the common spaces, which tended to be a little warmer.

Table 3
Nomenclature for the houses and spaces analysed.

Orientation (Façade facing)	*House*	*Common space (Kitchen, dining and living room)*	*Bedroom*
North	1	1A	1B
	2	2A	2B
	3	3A	3B
East	4	4A	4B
	5	5A	5B
	6	6A	6B
South	7	7A	7B
	8	8A	8B
	9	9A	9B
West	10	10A	10B
	11	11A	11B
	12	12A	12B

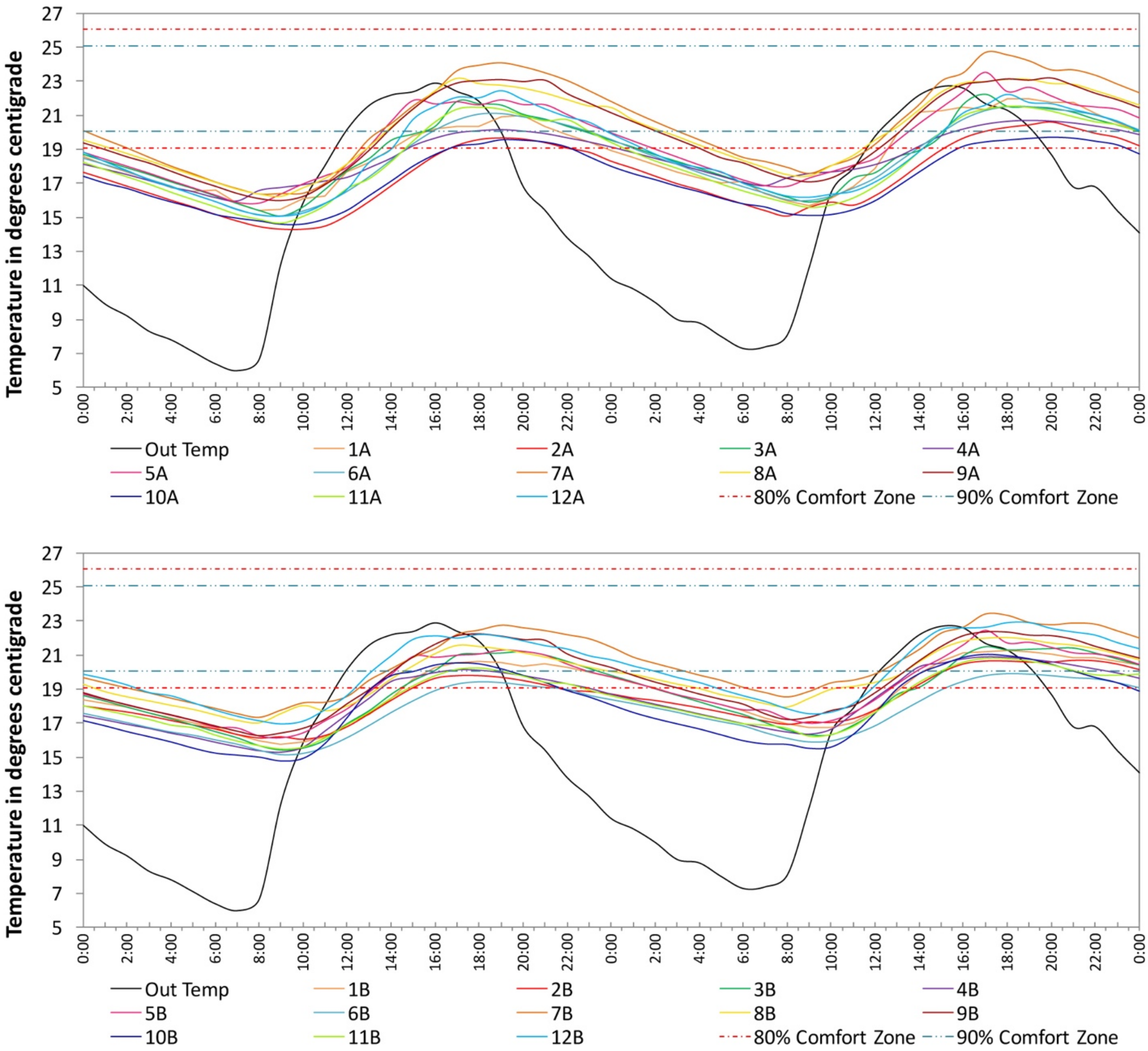


Fig. 8. Outdoor and indoor air temperatures profile of the 12 common spaces (above) and 12 bedrooms (below) over 48 hours period (19/20 January 2009).

Fig. 9 Shows the 24-hour thermal cycle observed from calculated indoor averaged temperatures from all rooms. From this figure indoor temperature attenuation can be observed, where the amplitude of indoor air temperature is far less pronounced that the amplitude of outdoor temperature. The decrement factor was 0.32 and the time lag was 2.5 hours for the highest temperature and 2 hours for the lowest temperature. These parameters are expected from high-density concrete, which has a large thermal capacity but low thermal resistance.

Despite outdoor air temperatures descending to a low of 6.0°C, indoor temperatures never fell below 14.2°C. This indicates that the thermal capacity of the concrete is helping maintain a more steady thermal condition inside the houses, however, due to the lack of insulation, the heat stored during the day is lost relatively quickly after a few hours. These conditions may still prove comfortable at nighttime with the aid of thick blankets, but generally speaking the lowest temperatures were recorded at around 9am, only reaching the 80% comfort zone at around 1pm.

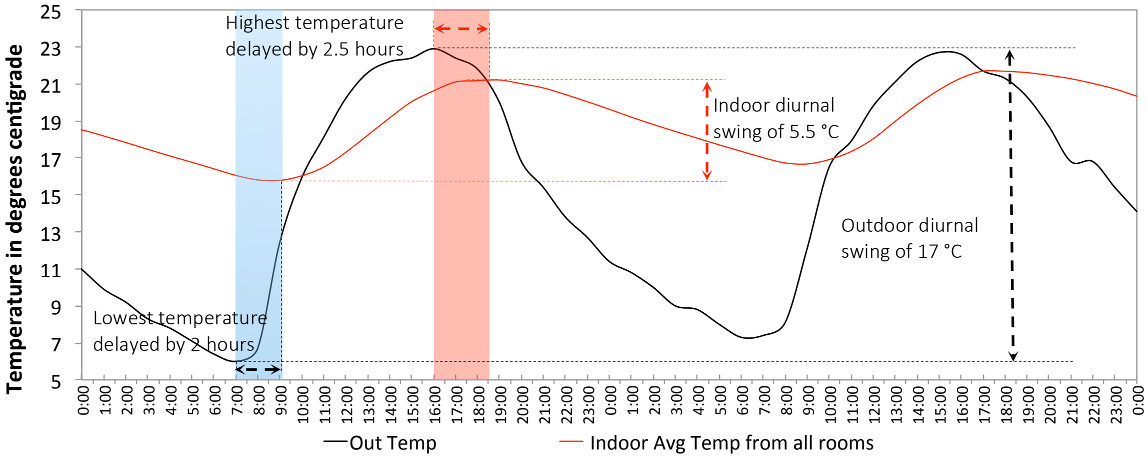


Fig. 9. 24-hour thermal cycle from all rooms average indoors temperatures (19 January 2009).

Table 4 shows the results of Pearson's correlations (r) between outdoor temperature and indoor temperature in the 24 rooms monitored during the cool season, where all cases presented a strong positive correlation with *r* values above 0.5 with significant level of <0.01. This indicates that the indoor environment in the houses is largely affected by varying outdoor conditions. The highest correlation *r* value is for common space 5A, suggesting that this space is almost 'free running' with little impact due to varying occupancy patterns or occupant behavior. Lower *r* values in bedrooms 6B and 11B suggest more occupant interference (e.g. more variation in occupancy patterns, or more appliances providing internal heat gains). Occupant interference is further discussed in section 4.4.

Table 4
Results of Pearson's correlation (r) between outdoor temperature and indoor temperatures of the 24 rooms monitored during the cool season.

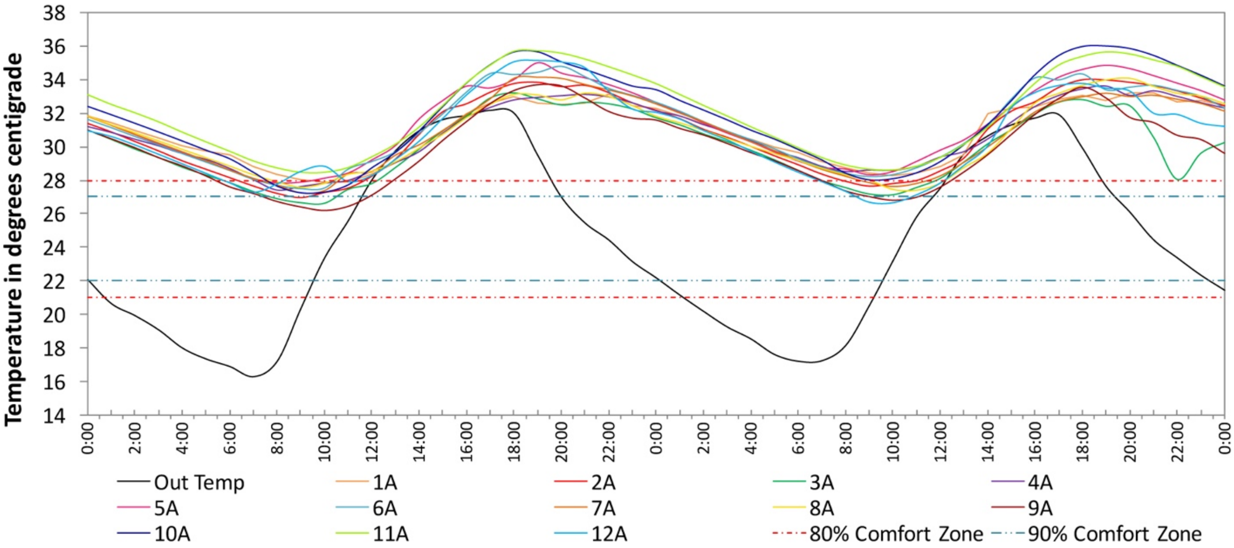
Façade Facing	*NORTH*			*EAST*			*SOUTH*			*WEST*		
Common space	**1A**	**2A**	**3A**	**4A**	**5A**	**6A**	**7A**	**8A**	**9A**	**10A**	**11A**	**12A**
Pearson Correlation (r)	0.79	0.76	0.78	0.88	0.90	0.72	0.80	0.84	0.82	0.62	0.76	0.81
P Significant (2-tailed)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
R^2	0.63	0.60	0.58	0.78	0.81	0.52	0.64	0.71	0.67	0.39	0.58	0.66
Nº of samples	42	42	42	42	42	42	42	42	42	42	42	42
Bedroom	**1B**	**2B**	**3B**	**4B**	**5B**	**6B**	**7B**	**8B**	**9B**	**10B**	**11B**	**12B**
Pearson Correlation (r)	0.84	0.80	0.76	0.84	0.84	0.64	0.80	0.83	0.84	0.78	0.54	0.80
P Significant (2-tailed)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
R^2	0.71	0.64	0.57	0.70	0.70	0.40	0.64	0.68	0.71	0.60	0.30	0.64
Nº of samples	42	42	42	42	42	42	42	42	42	42	42	42

4.2. Warm season

This section presents an overview of the thermal performance of the houses over the warm season. The lowest outdoor temperature registered was 12.91°C and the highest was

32.15°C. The sample of houses again performed in a similar manner. Indoor temperatures followed outdoor temperatures; however, during this season, indoor temperatures exceeded outdoor temperatures. The average maximum temperature of all rooms was 32.07°C and the average minimum was 23.42°C.

Week five registered the highest outdoor temperatures in the season, where the average maximum temperature was 34.39°C and the average minimum was 26.18°C. Fig. 10 shows a detail of the thermal pattern over a 48 hour period from all monitored rooms. The differences between rooms are less pronounced in comparison with the cool season.



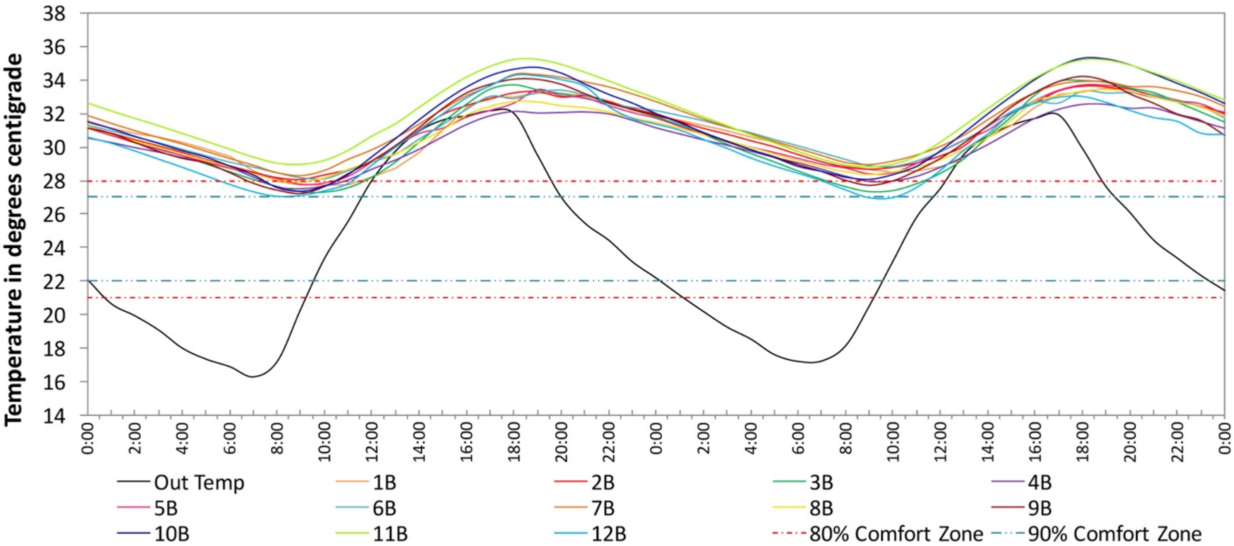


Fig. 10. Outdoor and indoor air temperatures profile of the 12 common spaces (above) and 12 bedrooms (below) over 48 hours period (12/13 June 2009).

Fig. 11 shows the 24-hour thermal cycle observed from calculated indoor averaged temperatures from all rooms. Similar to the cool season, this figure shows a high indoor temperature attenuation, where the amplitude of indoor air temperature is far less pronounced that the amplitude of outdoor temperature. The Decrement factor was 0.38 and the time lag was 2 hours for the highest temperature and the lowest temperature.

In this season indoor maximum temperatures exceeded the outdoor maximum temperatures of 32.2°C in all rooms (room 10A presented the highest temperature of 36.1°C). The indoor air temperatures registered were outside the comfort zone and all houses require cooling to meet comfort standards. This analysis indicates that due to the high thermal inertia and low thermal resistance of the concrete, it absorbs and stores heat during the day, which is re-radiated inside the house, keeping indoor temperatures higher than outdoor temperatures. This may indicate a lack of adequate natural ventilation, particularly at nighttime, possibly exacerbated by residents' unwillingness to open their windows due to security concerns.

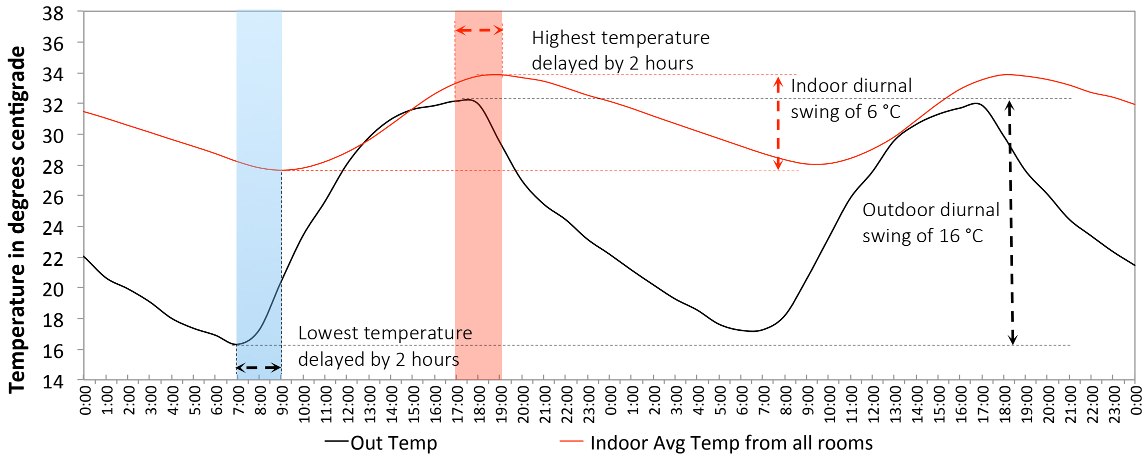


Fig. 11. 24-hour thermal cycle from all rooms average indoors temperatures (12 June 2009).

Table 5 shows the results of Results of Pearson's correlations (r) between outdoor temperature and indoor temperature in the 24 rooms monitored during the warm season, where all cases presented a strong positive correlation with *r* values above 0.5 with significant level of <0.01. This indicates that during the warm season the indoor environment in the houses is also largely affected by varying outdoor conditions.

Table 5
Results of Pearson's correlation (r) between outdoor temperature and indoor temperatures of the 24 rooms monitored during the warm season.

Façade Facing	*NORTH*			*EAST*			*SOUTH*			*WEST*		
Common space	**1A**	**2A**	**3A**	**4A**	**5A**	**6A**	**7A**	**8A**	**9A**	**10A**	**11A**	**12A**
Pearson Correlation (r)	0.86	0.88	0.87	0.86	0.88	0.89	0.83	0.87	0.87	0.87	0.87	0.92
P Significant (2-tailed)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
R^2	0.74	0.77	0.76	0.74	0.78	0.80	0.68	0.76	0.76	0.76	0.75	0.84
Nº of samples	42	42	42	42	42	42	42	42	42	42	42	42
Bedroom	**1B**	**2B**	**3B**	**4B**	**5B**	**6B**	**7B**	**8B**	**9B**	**10B**	**11B**	**12B**
Pearson Correlation (r)	0.86	0.87	0.88	0.84	0.86	0.85	0.84	0.86	0.88	0.88	0.88	0.90
P Significant (2-tailed)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
R^2	0.73	0.76	0.78	0.70	0.74	0.73	0.71	0.74	0.77	0.77	0.78	0.81
Nº of samples	42	42	42	42	42	42	42	42	42	42	42	42

4.3. Discomfort hours analysis

Fig. 12 shows the percentage of discomfort hours per room outside the wider comfort zone (7K) for 80% acceptability. In the cool season, the results correspond to "cold" conditions only, as none of the rooms reached “hot” conditions (above the upper comfort limit). In a six week period, the average PDH for A and B rooms facing north, east, and west was significantly higher than rooms facing south at around 50%; therefore rooms with north, east and west orientations require heating around 50% of the time to achieve comfortable conditions. In the warm season, the results correspond to “warm” conditions only, as none of the rooms reached “cold” conditions (below the lower comfort limit). The difference in PDH between different orientations was less pronounced in comparison with the cool season. However, the PDH of rooms facing west (10A, 11A, 12A and 10B, 11B, 12B) are slightly higher.

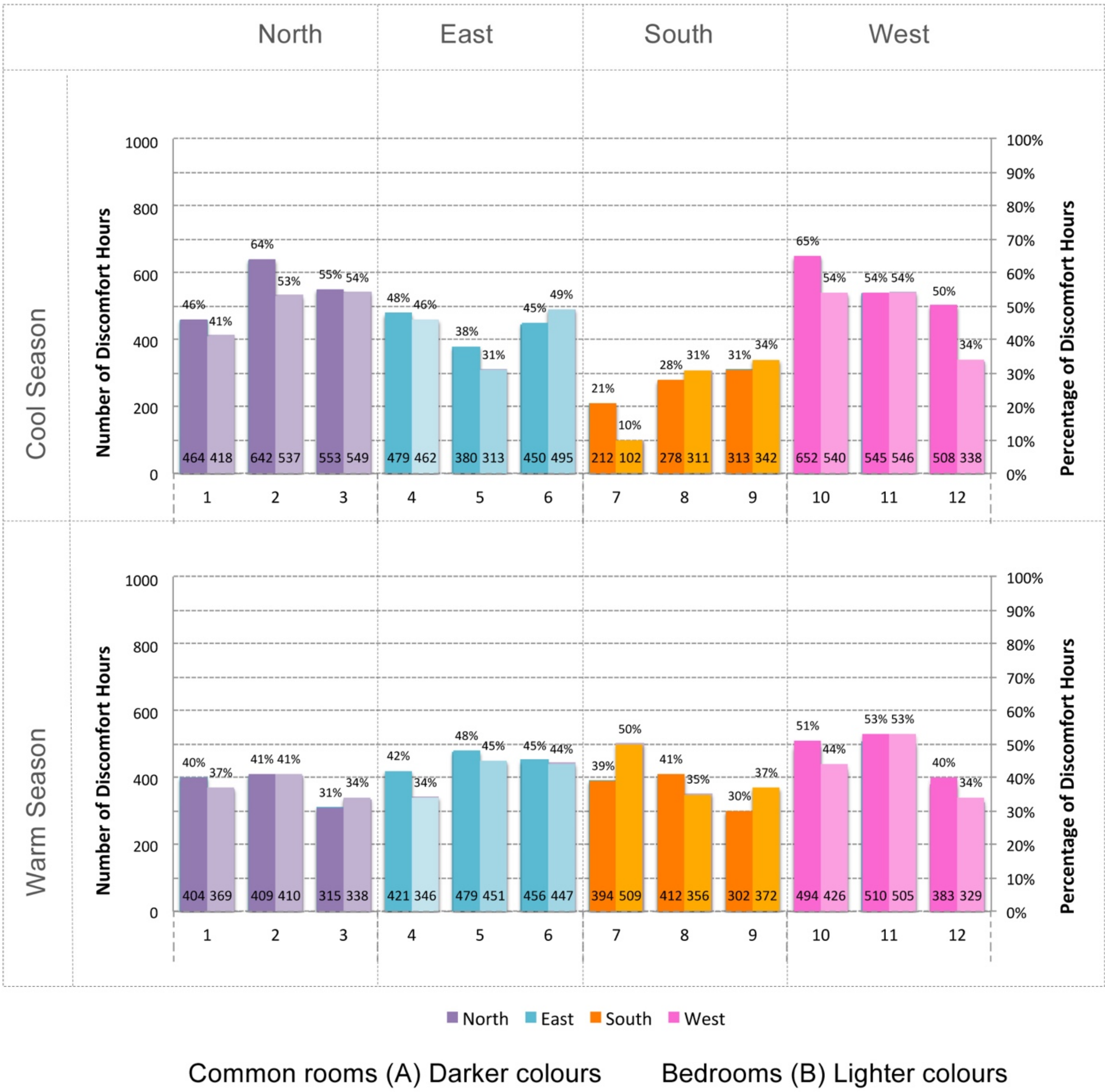


Fig. 12. Discomfort hours per individual rooms from monitored cool season and warm season. Each monitored season sums a total of 1008 hours, this value represents 100%.

4.4. Degree hours analysis

Fig. 13 shows the results of discomfort degree-hours and mean discomfort degree-hours. During the cool season, rooms facing south (7A, 8A, 9A and 7B, 8B, 9B) have a better thermal performance; the difference in DDH is significant in comparison with other orientations (t (22) = 4.03, p = 0.0006). Mean discomfort degree-hours also vary between rooms with the same orientation, with a difference of 0.60 MDDH in A rooms facing north.

During the warm season, there is a marked difference between A rooms facing south (7A, 8A, 9A) and A rooms facing west (10A, 11A, 12A). A rooms facing west recorded an average of 1125 DDH, nearly double A rooms facing south with an average of 675 DDH. The difference in DDH of B rooms was less marked; rooms facing north, east and south recorded an average of 709 DDH, 714 DDH, and 715 DDH respectively, while rooms facing west averaged 993 DDH. Differences in DDH between rooms with the same orientation were also observed, however, the differences are less marked in this season compared with the cool season. MDDH varied between rooms with the same orientation by up to 0.39 MDDH.

It is likely that the number of occupants, their activities and the operation of openings will have a significant impact on indoor conditions. These variables were observed to have more of an impact on thermal performance in the cool season, suggesting that in the warm season the thermal properties of the concrete are the main determinant in the thermal performance of the houses, even when different orientations are examined.

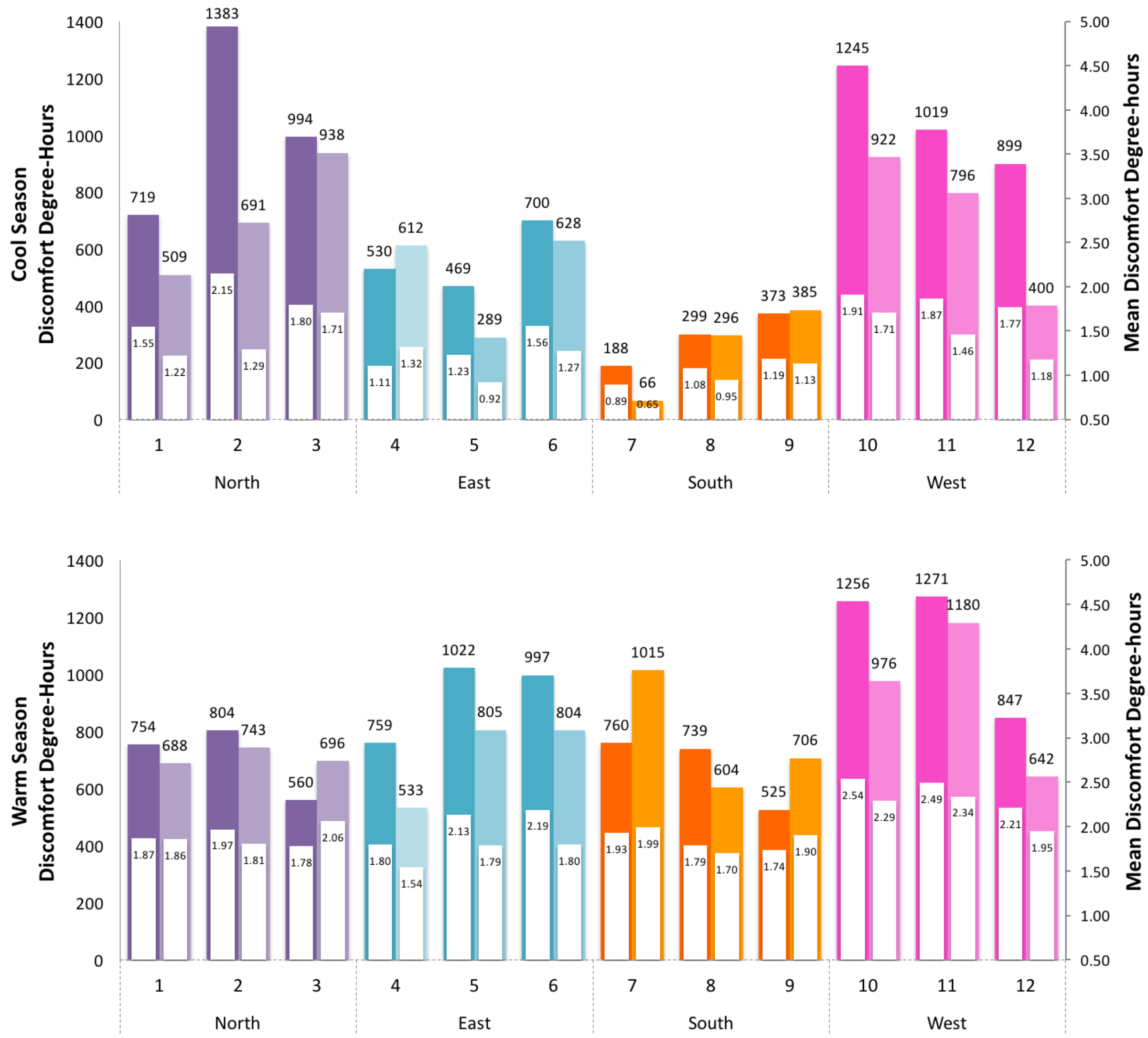


Fig. 13. Discomfort degree-hours per individual rooms from monitored cool season and warm season.

As expected, there were some differences in performance between A rooms and B rooms. A rooms are larger than B rooms and the surface area exposed to direct solar radiation is different. Additionally, A rooms receive more internal gains from appliances such as refrigerators and televisions, and are occupied intermittently throughout the day, while B rooms are occupied predominantly at night. In general, the thermal performance of B rooms (bedrooms) is better in comparison with A rooms (common spaces), with the exception of houses facing south. However, differences in the performance of rooms with the same orientation indicate that occupants' behavior also significantly impacts thermal performance.

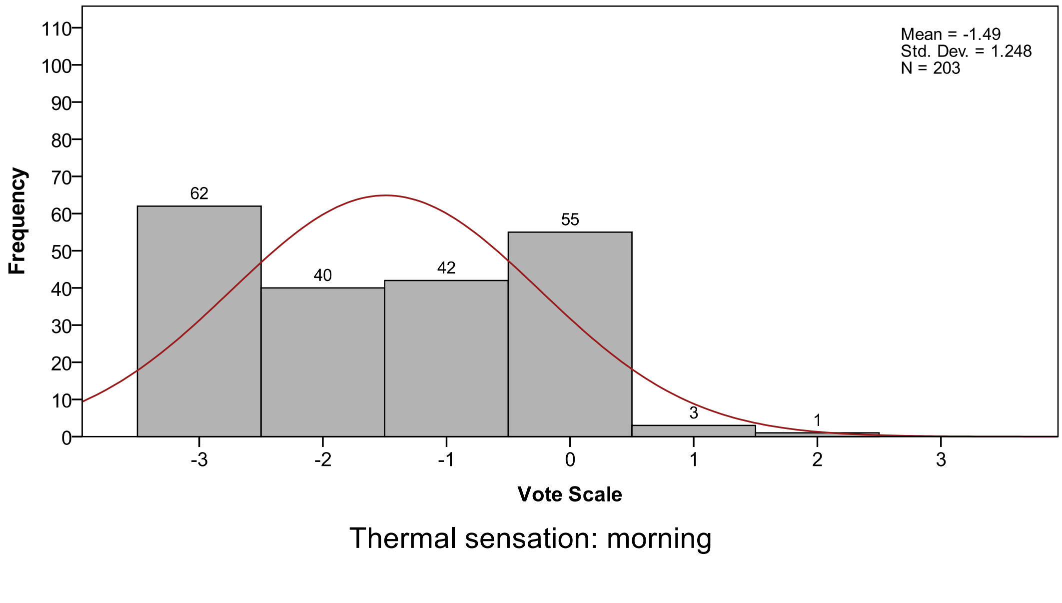
5. Thermal Comfort Field Survey

This section presents the results and discussion of the thermal comfort field survey. It includes thermal comfort parameters such as thermal sensation, thermal preference and general acceptance of climatic conditions. Thermal sensation votes and preference votes were gathered for the morning, afternoon and night.

5.1. Cool season

A categorical ASHRAE scale, -3 (Cold), -2 (Cool), -1 (Slightly cool), 0 (Neutral), 1 (Slightly warm), 2 (Warm) and 3 (Hot), was used to assess thermal sensation. Fig. 14 shows the results of thermal sensation in the morning, afternoon and night during the cool season. The graphs include a histogram of votes distribution and the normal distribution curve for better understanding.

ASHRAE-55 [19] defines an acceptable thermal environment theoretically as the condition where 80% of occupants vote for the three central categories: (-1, 0, +1) slightly cool, neutral and slightly warm. According to this definition, the thermal environment was not acceptable in the cool season as the percentage of votes in the central category were 49.26% in the morning, 77.83% in the afternoon and 54.68% at night.



Thermal sensation: morning

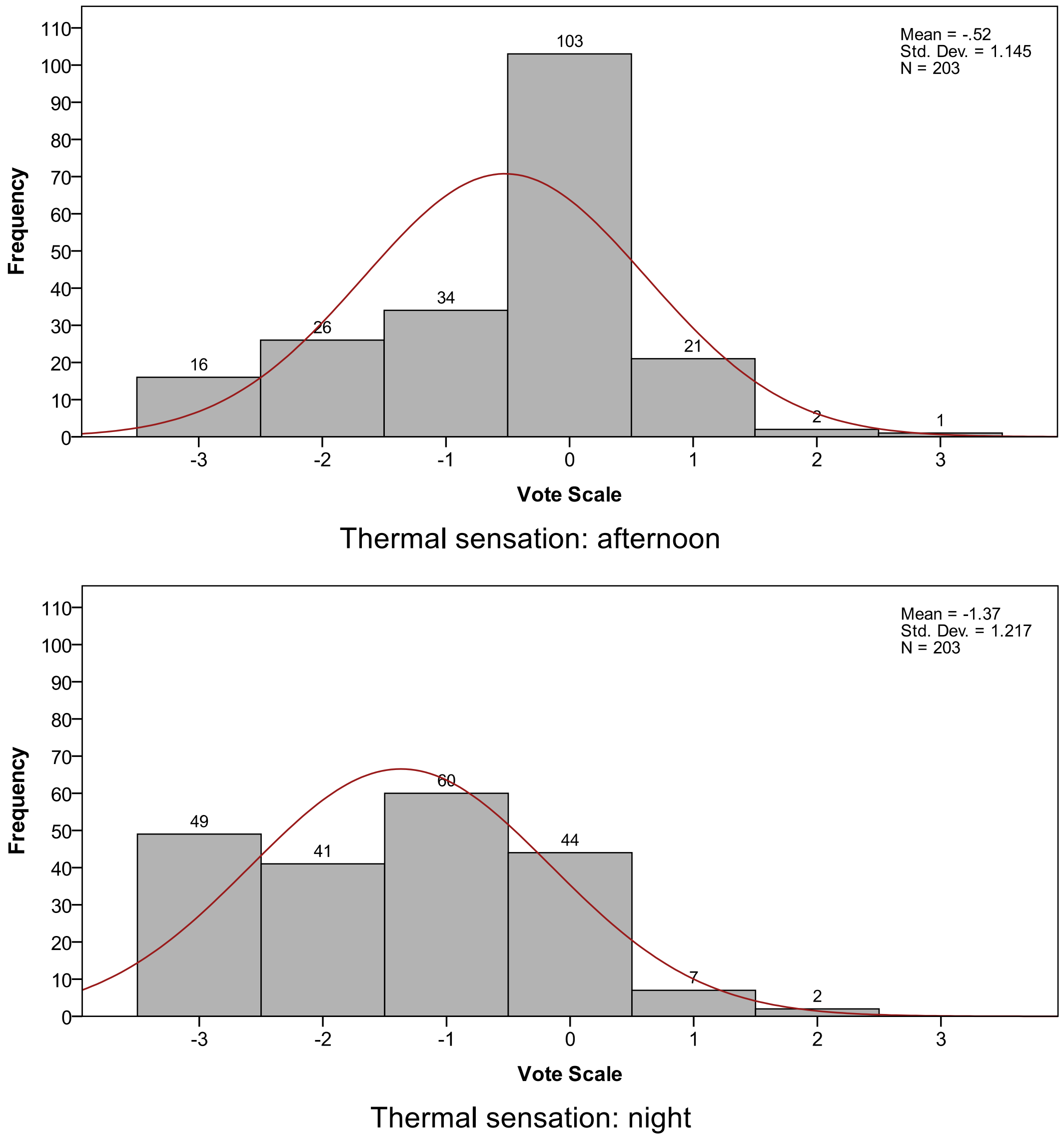


Fig. 14. Thermal sensation in the cool season.

The scale used for preference votes is the McIntyre scale [37], -1 (Warmer), 0 (No change), +1 (Cooler). Crosstabulation between thermal sensation votes and preference votes demonstrates how subjects interpreted their votes in two different subjective scales. Tables 6-8 show the crosstabulation results for morning, afternoon and night. The majority of preference votes reflected thermal sensation votes in this season, with small percentage differences between "No change" preference votes and thermal sensation votes within the three central categories in each case (6% in the morning, 5.3% in the afternoon and 4.9% at night). Generally in this season, when subjects feel "slightly cool", "cool" or "cold" they preferred warmer conditions.

Table 6
Cross tabulation of thermal sensation and preference votes in the morning during the cool season.

Thermal sensation in the morning	Preference votes in the morning			Total
	Cooler	No change	Warmer	
Cold	1.6% (1)	9.7% (6)	88.7% (55)	30.5%
Cool	2.5% (1)	22.5% (9)	75.0% (30)	19.7%
Slightly Cool	2.4% (1)	50.0% (21)	47.6% (20)	20.7%
Neutral	1.8% (1)	89.1% (49)	9.1% (5)	27.1%
Slightly Warm	33.3% (1)	66.7% (2)	0.0% (0)	1.5%
Warm	0.0% (0)	100.0% (1)	0.0% (0)	0.5%

Hot	0.0% (0)	0.0% (0)	0.0% (0)	0.0%
Total	2.5%	43.3%	54.2%	100.0%

The number inside parentheses ( ) represent the actual number of votes

Table 7
Cross tabulation of thermal sensation and preference votes in the afternoon during the cool season.

Thermal sensation in the afternoon	Preference votes in the afternoon			Total
	Cooler	No change	Warmer	
Cold	0.0% (0)	6.2% (1)	93.8% (15)	7.9%
Cool	0.0% (0)	26.9% (7)	73.1% (19)	12.8%
Slightly Cool	0.0% (0)	67.6% (23)	32.4% (11)	16.7%
Neutral	1.9% (2)	95.1% (98)	2.9% (3)	50.7%
Slightly Warm	19.0% (4)	76.2% (16)	4.8% (1)	10.3%
Warm	0.0% (0)	100.0% (2)	0.0% (0)	1.0%
Hot	100% (1)	0.0% (0)	0.0% (0)	0.5%
Total	3.4%	72.4%	24.1%	100.0%

The number inside parentheses ( ) represent the actual number of votes

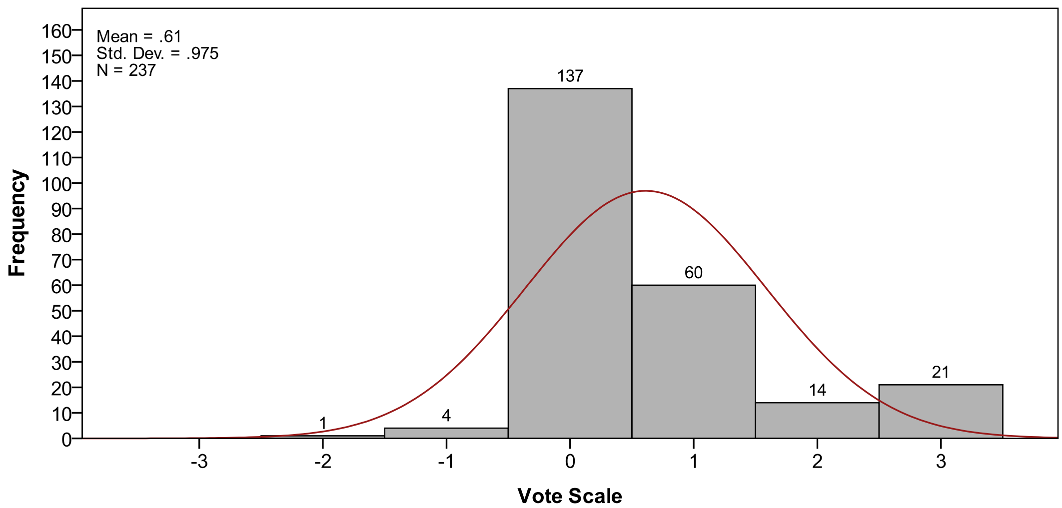
Table 8
Cross tabulation of thermal sensation and preference votes at night during the cool season.

Thermal sensation at night	Preference votes at night			Total
	Cooler	No change	Warmer	
Cold	2.0% (1)	10.2% (5)	87.8% (43)	24.1%
Cool	0.0% (0)	34.1% (14)	65.9% (27)	20.2%
Slightly Cool	1.7% (1)	56.7% (34)	41.7% (25)	29.6%
Neutral	0.0% (0)	88.6% (39)	11.4% (5)	21.7%
Slightly Warm	0.0% (0)	100.0% (7)	0.0% (0)	3.4%
Warm	0.0% (0)	100.0% (2)	0.0% (0)	1.0%
Hot	0.0% (0)	0.0% (0)	0.0% (0)	0.0%
Total	1.0%	49.8%	49.3%	100.0%

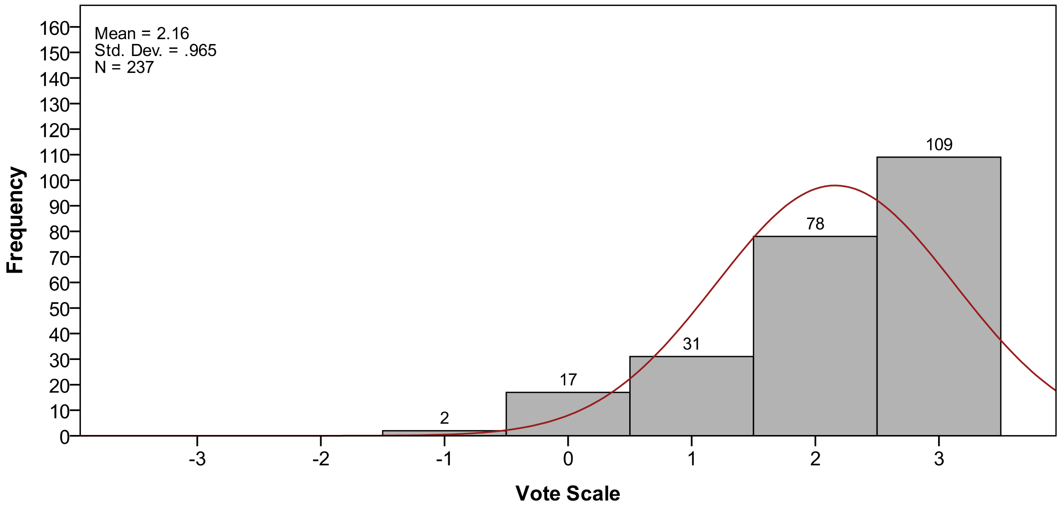
The number inside parentheses ( ) represent the actual number of votes

5.2. Warm season

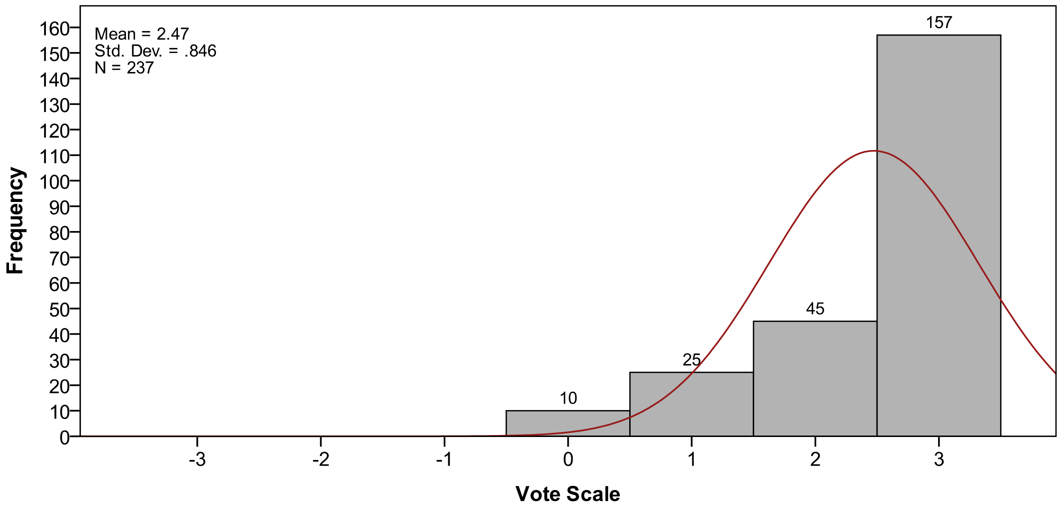
Fig. 15 show the results of thermal sensation in the morning, afternoon and night during the warm season. According to the ASHRAE-55 [19] definition, the thermal environment in the morning was acceptable as the percentage of votes in the central category was 84.82%. However the thermal environment was not acceptable in the afternoon and night as the percentage of votes in the central category were extremely low at 21.09% and 14.77% respectively.



Thermal sensation: morning



Thermal sensation: afternoon



Thermal sensation: night

Fig. 15. Thermal sensation in the warm season.

Tables 9-11 show the crosstabulation results for morning, afternoon and night. The percentage differences between “No change” preference votes and thermal sensation votes within the three central categories were very small in the afternoon and night (2.5% in and, 2.6% respectively). However, in the morning 62% of the subjects voted for “no change” while 84.8% voted within the central three categories of the ASHRAE scale. A significant number of subjects that voted “slightly warm” indicated that they would prefer to be cooler. Generally in this season, when subjects feel “slightly warm”, “warm” or “hot” they preferred cooler conditions.

Table 9
Cross tabulation of thermal sensation and preference votes in the morning during the warm season.

Thermal sensation in the morning	Preference votes in the morning			Total
	Cooler	No change	Warmer	
Cold	0.0% (0)	0.0% (0)	0.0% (0)	0.0%
Cool	100.0% (1)	0.0% (0)	0.0% (0)	0.4%
Slightly Cool	25.0% (1)	75.0% (3)	0.0% (0)	1.7%
Neutral	21.9% (30)	78.1% (107)	0.0% (0)	57.8%
Slightly Warm	43.3% (26)	56.7% (34)	0.0% (0)	25.3%
Warm	78.6% (11)	21.4% (3)	0.0% (0)	5.9%
Hot	100.0% (21)	0.0% (0)	0.0% (0)	8.9%

Total	38.0%	62.0%	0.0%	100.0%

The number inside parentheses ( ) represent the actual number of votes

Table 10
Cross tabulation of thermal sensation and preference votes in the afternoon during the warm season.

Thermal sensation in the afternoon	Preference votes in the afternoon			Total
	Cooler	No change	Warmer	
Cold	0.0% (0)	0.0% (0)	0.0% (0)	0.0%
Cool	0.0% (0)	0.0% (0)	0.0% (0)	0.0%
Slightly Cool	0.0% (0)	100.0% (2)	0.0% (0)	0.8%
Neutral	47.1% (8)	52.9% (9)	0.0% (0)	7.2%
Slightly Warm	51.6% (16)	48.4% (15)	0.0% (0)	13.1%
Warm	80.8% (63)	19.2% (15)	0.0% (0)	32.9%
Hot	97.2% (106)	2.8% (3)	0.0% (0)	46.0%
Total	81.4%	18.6%	0.0%	100.0%

The number inside parentheses ( ) represent the actual number of votes

Table 11
Cross tabulation of thermal sensation and preference votes at night during the warm season.

Thermal sensation at night	Preference votes at night			Total
	Cooler	No change	Warmer	
Cold	0.0% (0)	0.0% (0)	0.0% (0)	0.0%
Cool	0.0% (0)	0.0% (0)	0.0% (0)	0.0%
Slightly Cool	0.0% (0)	0.0% (0)	0.0% (0)	0.0%
Neutral	50.0% (5)	50.0% (5)	0.0% (0)	4.2%
Slightly Warm	36.0% (9)	64.0% (16)	0.0% (0)	10.5%
Warm	75.6% (34)	24.4% (11)	0.0% (0)	19.0%
Hot	94.3% (148)	5.7% (9)	0.0% (0)	66.2%
Total	82.7%	17.3%	0.0%	100.0%

The number inside parentheses ( ) represent the actual number of votes

The results from the field survey shows that the distribution of thermal sensation votes followed a seasonal inclination towards the “cold” side of the ASHRAE scale during the cool season and the “hot” side in the warm season, as expected. However, the seasonal inclination was more marked in the warm season. The distribution of preference votes was divided between “no change” and “warmer” on the McIntyre scale in the cool season. However, the distribution of preference votes was more marked in the warm season, where subjects expressed a preference to feel “cooler”. This suggests that people in this region find it easier to adapt to the thermal environment in the cool season.

5.3. Relationship between indoor temperatures and thermal comfort survey results

In order to find the relationship between the monitored temperatures and the thermal comfort surveys, recordings of the temperatures were divided into three periods; morning from 6am to 12pm, afternoon from 12pm to 6pm, and night from 12am to 6am. The evening period was discounted as residents would often spend this time outdoors, leading to confusion with the night period when they returned indoors. As subjects are normally asleep for much of the night period, interviewees were asked to comment on thermal sensation and preference immediately before going to sleep or immediately after waking (subject to the alignment of individual routine with the 12am to 6am period). This may have an impact on the reliability of nighttime data, though as figs. 16 and 17 show, the distribution of recorded votes appears consistent with monitored temperatures.

Average temperatures were subsequently calculated in both seasons, obtained from 36,288 observations from all monitored rooms for each period of time. The Neutral temperature (Tn) of the sample of this study is obtained by conducting a linear regression analysis between observed thermal sensation votes and indoor air temperature using the Griffiths’ method, assuming a relationship between comfort vote and temperature to derive a predicted comfort temperature for each vote (each point on the comfort scale is treated as equivalent to a 3K difference in temperature) [38]. This method employed all 606 recorded comfort votes in the cool season and 711 in the warm season (figs. 16, 17). For the purposes of this study the categorical votes are considered to be linearly distributed; a more accurate analysis may be obtained for categorical data by employing an ordinal regression analysis.

Tables 12 and 13 compare the results of the comfort survey and indoor temperatures in each season. In the cool season, the three average indoor temperatures were below the neutral temperature derived from ASHRAE-55 (22.6°C). However, in the afternoon the percentage of thermal sensation and preference votes was close to the 80% acceptance threshold as the indoor temperature approached the neutral temperature. During the warm season, the three average indoor temperatures were above the neutral temperature (24.2°C). The percentage of satisfactory thermal sensation and preference votes was highest in the morning when the average indoor temperature was only 1.3K above the neutral temperature, but still within the comfort zone.

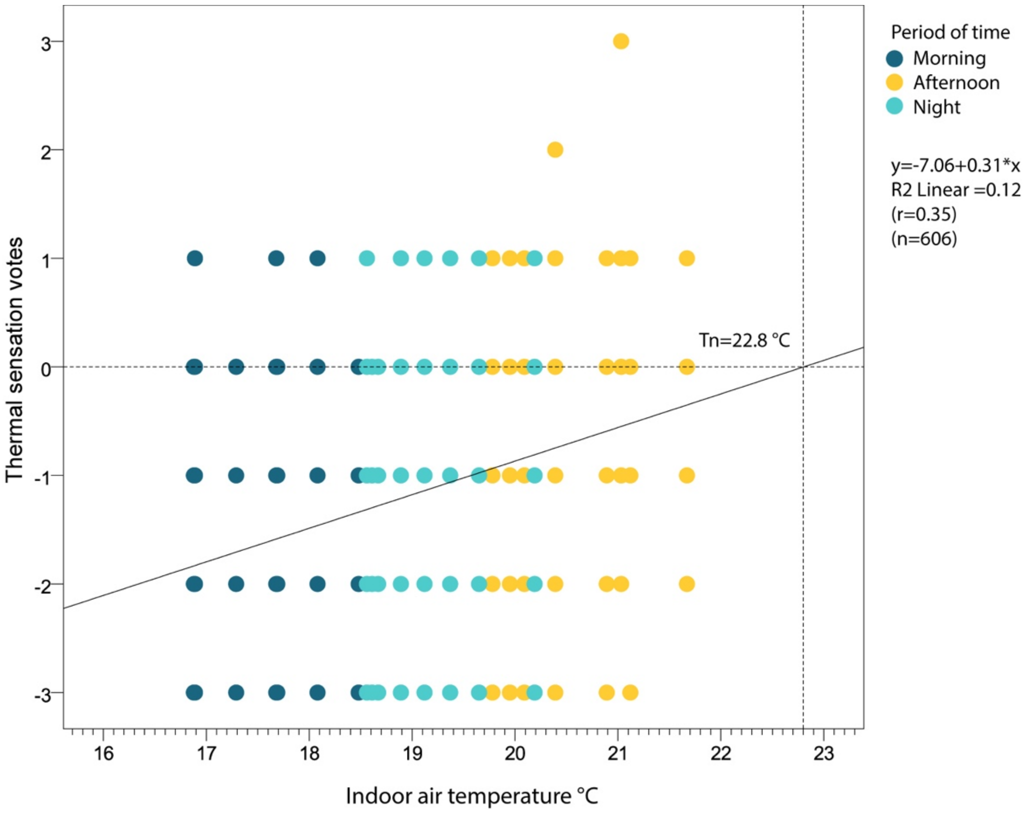


Fig. 16. Regression relationship between thermal sensation votes as a function of indoor air temperature during the cool season.

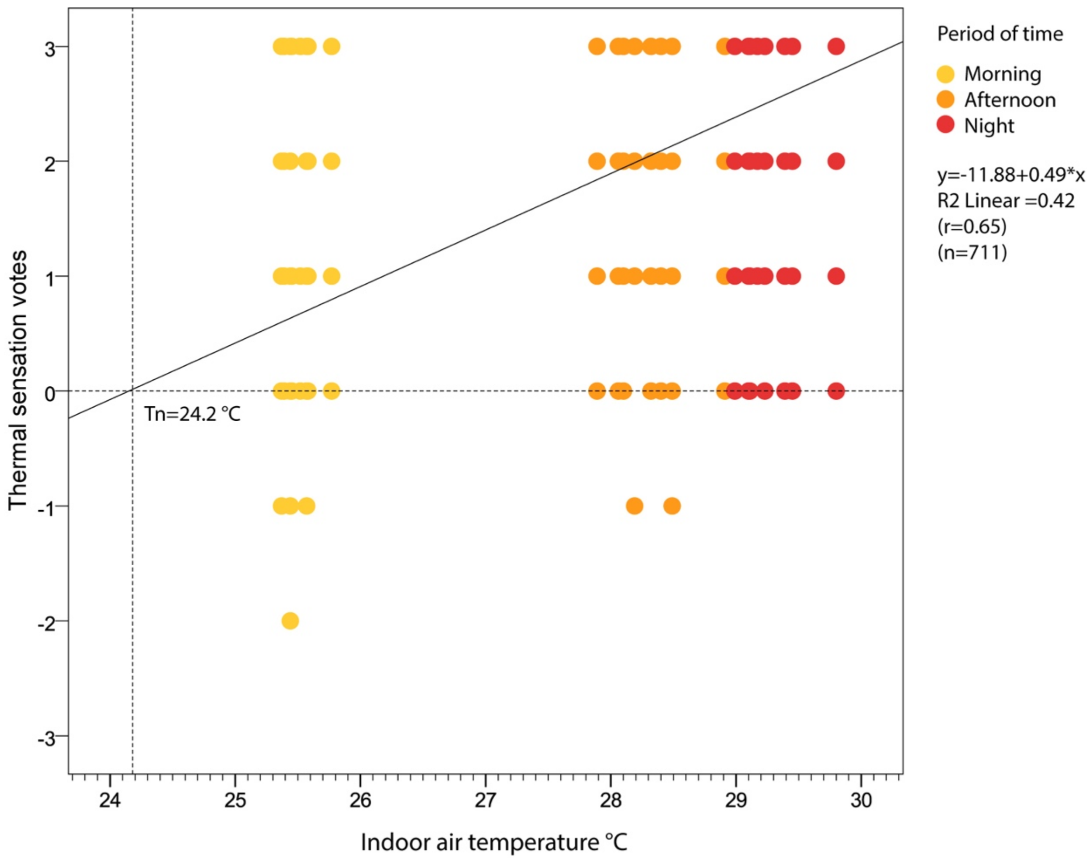


Fig. 17. Regression relationship between thermal sensation votes as a function of indoor air temperature during the warm season.

Table 12
Comparison between thermal comfort survey results and average indoor temperature along three different periods of the day during the cool season.

	Thermal sensation votes		Preference votes		Avg. Temp	Avg. Temp - Tn
	Mean vote	*%(-1,0,+1)*	*Mean vote*	*%(0)*		
Morning	-1.49	(49.26%)	+0.52	(43.35%)	17.5°C	-5.3K
Afternoon	-0.52	(77.83%)	+0.21	(72.41%)	20.5°C	-2.3K
Night	-1.37	(54.68%)	+0.48	(49.75%)	19.1°C	-3.7K

Table 13
Comparison between thermal comfort survey results and average indoor temperature along three different periods of the day during the warm season.

	Thermal sensation votes		Preference votes		Avg. Temp	Avg. Temp - Tn
	Mean vote	*%(-1,0,+1)*	*Mean vote*	*%(0)*		
Morning	+0.61	(84.82%)	-0.38	(62.03%)	25.5°C	1.3K
Afternoon	+2.16	(21.09%)	-0.81	(18.57%)	28.3°C	4.1K
Night	+2.47	(14.77%)	-0.83	(17.30%)	29.3°C	5.1K

The neutral temperatures calculated employing the ACS were 22.6°C for the cool season and 24.5°C for the warm season. The difference between the ACS neutral temperature and the neutral temperature calculated in this research was only 0.2°C in the cool season and 0.3°C in the warm season. The findings of this research therefore closely align with the Adaptive Comfort Standard (ACS) from ASHRAE-55 [19], and the results from a study conducted in a similar climate, with similar characteristics and conditions [39]. This suggests that the results presented from this fieldwork represent an accurate description of the thermal comfort levels measured, and that the ACS is suitable to use in warm-temperate regions.

6. Limitations and Further Work

This research identified that occupancy and occupant behavior have an impact on thermal performance, as identical houses with the same orientation revealed differences in terms of thermal performance: up to 0.60 mean discomfort degree-hours (MDDH) in common rooms in the cool season, and 0.39 MDDH in the warm season. However the actions of users were not recorded. Further exploration of occupant behaviour may help identify the user actions that affect housing performance both positively and negatively.

The climatic analysis of the region studied identified key aspects that can be used to improve performance; in particular large diurnal variations suggest that the application of heavy weight materials with high thermal capacity and natural ventilation should be the main passive design strategies to achieve acceptable levels of thermal comfort. However, the low thermal resistance of the high-density concrete used in the construction of the houses in this study has resulted in a poor thermal performance.

Unlike the vernacular precedents or the Critical Regionalist approach of Luis Barragán described in section 1.2., there is little opportunity in the design of mass low-income housing for a variety of spaces such as terraces, porticoes and courtyards with more connection to the outdoors to facilitate thermal adaptation in different seasons. This means that the thermal properties of the fabric and the use of passive airflow systems are even more important in order to offer comfortable conditions to the occupants.

Further investigation including simulation and full-scale tests of the thermal performance of Industrialised Building Systems would be beneficial for both designers and housing developers. To this end, the monitored data collected in this thesis can be used as the basis for the validation of simulation models and to measure the impact of improvements.

A recent study conducted in the hot-dry region of Coahuila, northern Mexico, compared the heat transfer through the construction envelope of a similar monolithic concrete system in two outdoor test cells over a year [16], showing that an insulation layer on the outside of the concrete resulted in a 50% increase in hours meeting thermal comfort criteria compared with a single layer of concrete. Further experimental work should focus on testing a wider set of building envelope configurations and materials as well as other passive techniques identified (e.g. from vernacular precedents), including possible solutions to retrofit existing houses in order to improve thermal performance.

7. Conclusions

The results from the thermal assessment indicated that variations in solar radiation due to orientation have an impact on the thermal performance in the cool season. The effect of orientation is also present in the warm season, however it does not substantially influence the overall performance. While results from the thermal assessment indicate that the number of occupants and their behaviour in the building (operation of openings, indoor activities) also have a significant impact on the overall thermal performance of the houses, the distribution of thermal sensation votes and preference votes during the warm season showed a more marked inclination towards the extreme sides of the rating scale when compared to the cool season. Furthermore, thermal acceptability was rated at 68% during the cool season and only 33% during the warm season. These results may suggest that these houses are more suitable for the cool season; however the divergence from the neutral temperature was of a similar magnitude in both seasons (see tables 12, 13). It may be concluded therefore that people in this region find it easier to cope or adapt to cooler conditions with the aid of warmer clothing during the day and the use of thick blankets at night, but find it more difficult to adapt to warmer conditions. This finding is also supported by the observed behaviour of residents who would often spend the evening (the hottest period of the day) outdoors.

The use of industrialised building systems for low-income housing in México has been a success in terms of delivering mass quantities of housing to cope with high demand. However, from an environmental perspective, the industrialised building system under observation falls significantly outside the thermal comfort boundaries in both periods studied. The results from the extensive post occupancy evaluation have demonstrated that, even using the adaptive comfort standard with a wide comfort band (7K for 80% acceptance), the concrete formwork system demands the use of further heating and cooling around 50% of the time (in both warm and cold seasons) in order to provide suitable indoor thermal comfort conditions. Furthermore, opinions from the occupants indicated a high level of dissatisfaction with the thermal indoor conditions in the analysed typology.

Many similar mass housing developments can be seen throughout Mexico. The author investigated the five climatic regions of Mexico to find that the same concrete formwork construction system described in section 2.2. is being systematically applied in all. Across the five regions the houses are differentiated only by the colour of the external finish.

The wide applicability, engineering advantages, and significant financial and socio-economic benefits derived from mass industrialised housing production mean that this approach is highly likely to continue and expand in the future. In this context, it is essential that designers, developers and decision-makers implement practices to overcome easily avoidable problems, especially during the early stages of the design process. There is an urgent need to contextualise the use of such industrialised construction systems according to the climatic region. This would potentially improve thermal comfort and prevent the retrofit of air-conditioning systems in the future, helping reduce energy consumption. This research provides a clear picture of the thermal behaviour of the studied industrialised building system and indicates the weaknesses of such systems to designers, researchers, and other stakeholders involved in the further development of mass industrialised housing production.

Acknowledgements

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Appendix A: English version of questionnaire

"Low income Housing in Mexico: A new approach for energy efficiency and thermal comfort "
Case study Villas del Pedregal, Morelia, Michoacan ,Mexico

UNIVERSITY OF SHEFFIELD
SCHOOL OF ARCHITECTURE

I. - GENERAL DATA

Reference No:	Address:
Occupant's Name:	

II - TEMPORARY DATA

Date		Time	

III - INFORMATION OF THE HOUSE

A	NW N NE / W E / SW S SE		B		Climate control systems activated in the house
			1	☐	NONE
			2	☐	FAN
	ORIENTATION		3	☐	CONDITIONED AIR
	☐ WINTER	☐SUMMER	4	☐	HEATING
	No. of people :		5	☐	OTHER

IV. - ENERGY USE

C		G E Boiler	☐ Dishwasher	☐ Microwave	☐ Blender
Low energy bulbs	N F A	G E Cooker	☐ Clothes washer	☐ Toaster	☐ Hair dryer
Gas bill		☐ Fridge	☐ Clothes dryer	☐ Coffee maker	☐ Clothes iron
Electricity bill		☐ TV	☐ DVD	☐ Sound system	☐ Video Games

V. - INFORMATION OF THE OCCUPANT

D	Body mass		Weight (Kg)	Height (Cm)	Age (Years)
E	Gender		Male ☐	Female ☐	
			1 Passive	**2** Moderate	**3** Intense
F1	Activity	Morning	M	M	M
F2		Afternoon	A	A	A
F3		Evening	E	E	E

Type of clothes

		1		2		3		4		5
G1	M	VERY LIGHT	M	LIGHT	M	NORMAL	M	SHELTERED	M	VERY SHELTERED
G2	A		A		A		A		A	
G3	E		E		E		E		E	

VI. - INFORMATION ON THE PERCEPTION OF THE INNDOR ENVIRONMENT OF THE HOUSE

		1	2	3	4	5	6	7
H1 / H2 / H3	Thermal Comfort sensation	M A E Cold	M A E Cool	M A E Slightly cool	M A E Neutral	M A E Slightly warm	M A E Warm	M A E Hot
K1 / K2 / K3	Thermal preference	M A E Much cooler	M A E No change	M A E Much warmer				
L	General acceptance of the house environment	Generally acceptable ☐	Generally inacceptable ☐					