

Thermal comfort in multi-family social housing in a warm climate in Colombia

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Abstract: Residential energy consumption in Colombia increased by 30% between 2010 and 2018, due, in part, to spending on active air conditioning of social interest housing (VIS). Research on single-family VIS reported "very hot" thermal sensations with the PMV-PPD model in hot weather. The objective of the present research is to complement the state of the art by evaluating the thermal environment of a multifamily SIV with two different comfort models: 1) the PMV-PPD and 2) the adaptive model. The methodology had two phases: 1) monitoring of a VIS environment, and 2) assessment using the two models mentioned above. The results indicated thermal dissatisfaction due to excess heat with both models during daytime hours, very similar to what has been reported in the state of the art for single-family typology. However, a 35% saving in energy dedicated to air conditioning was also found if evaluated with the adaptive model. The absence of solar protection in openings was evidenced, and the high values of air temperature and mean radiant temperature indicated that the thermal insulation of the vertical envelope of these buildings is insufficient to provide thermal comfort. Passive improvements are proposed to ameliorate the habitability of these dwellings and their mandatory inclusion in Regulation 0549, to reduce energy consumption and its environmental impact.

Key words: bioclimatic architecture; sustainable construction; ASHRAE 55; PMV-PPD model; adaptive model

1 Introduction

This research article is one of the opening chapters of a doctoral dissertation in Architecture and Urban Planning at the National University of La Plata, Argentina, titled: Optimization of Thermal Comfort in an Equatorial Climate Using Passive Technologies in Facades: The Case of Social Housing in Cali, conducted by the lead author under the supervision of the two co-authors, as part of a teaching research grant awarded by the Universidad del Valle in Cali, Colombia. The thesis is linked to the research project "Strategies for Adapting to Climate Change in Buildings and Cities" and evaluates the thermal comfort of Colombian social interest housing (VIS) in warm climates. Furthermore, the aforementioned thesis will propose and evaluate passive construction solutions with the aim of improving habitability while simultaneously reducing energy consumption for climate control. For its part, the main contribution of this article is the experimental assessment of thermal comfort in Colombian social interest housing (VIS) of multifamily in warm climates, an assessment not yet carried out in the current state of the art.

The phenomenon of global warming must be addressed through a paradigm shift in the construction industry; this shift must promote energy efficiency in buildings to prevent the emission of greenhouse gases (GHGs) generated during

electricity production, whether from the burning of fossil fuels or from large hydroelectric plants.

In Colombia, energy demand has grown by nearly 30% from 2010 to 2018 (National Interconnection System, 2018); most of this demand is used for active climate control of social housing units (VIS) (International Energy Agency, n.d.; Giraldo et al., 2015), which has necessitated the expansion of large hydroelectric infrastructure, causing negative environmental impacts (Dinero Magazine, 2019).

VIS is built to ensure the right to housing for low-income households; in addition, they comply with all urban planning regulations (Municipal Planning, Mayor's Office of Santiago de Cali, 2014), architectural standards (Ministry of Environment, Housing, and Territorial Development, Republic of Colombia, 2011), and construction codes (MINVIVIENDA, 2000; Ministry of Mines and Energy, 2009; Colombian Association of Seismic Engineering, 2010; Ministry of Mines and Energy, 2013), without exceeding a construction cost of 135 monthly minimum wages, equivalent to USD 36,000 (TRM as of June 27, 2018) (Congress of Colombia, 1997). According to the National Department of Statistics (DANE, 2017), VIS constitutes a significant percentage of the built environment in Colombia, accounting for 49% of housing; despite this, compliance with the Sustainable Construction Regulations, contained in Resolution 0549 of 2015 (Ministry of Housing, City, and Territory, 2015), is optional for this type of building; these regulations recommend a 20% reduction in energy consumption relative to a baseline defined by the government.

In the country, there are two types of VIS: 1) multi-family housing (apartments), and 2) single-family housing (houses). In terms of quantity, multi-family housing predominates, accounting for 68%, compared to single-family housing, which represents only 32% (DANE, 2017). In terms of construction, there is a wide variety of systems available (Echeverry Campos and MetroVivienda, 2000); however, 99% of them are based on high-density materials such as concrete masonry, clay, and industrialized systems, such as Outinord or Contech (García López et al., 2016), which consist of solid reinforced concrete walls with thicknesses ranging from 8 cm to 12 cm. These construction systems have high thermal transmittance, which is detrimental to the thermal performance of buildings in hot climates. This statement is based on the fact that a 10-cm concrete wall has a thermal transmittance of $4.16 \text{ W/m}^2\cdot\text{K}$, compared to a 10-cm wall in a high-density expanded polystyrene system, which has a thermal transmittance of $0.05 \text{ W/m}^2\cdot\text{K}$.

Based on the climate classification of the Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM) included in Annex 2 of Regulation 0549 of 2015 (Ministry of Housing, City, and Territory, 2015), more than 80% of Colombia's territory has a warm climate, a classification that includes major cities such as Cali, Barranquilla, Cartagena, and Buenaventura, among others. For this type of climate, Olgyay (1998), Givoni (1976), and Santamouris and Asimakopoulos (2001) note that solar control and natural ventilation strategies must primarily be applied to achieve thermal comfort; however, when these recommendations are not considered in architectural design or construction, it is nearly impossible to achieve thermal comfort passively, as in the case of social housing (VIS) in Cali, Colombia (Giraldo and Herrera, 2017).

According to ISO 7730 (International Organization for Standardization, 2005), thermal comfort is the mental state in which satisfaction with the thermal environment is expressed, and for this reason, the conditions required to achieve it are not the same for everyone; however, through laboratory and field research, it has been possible to statistically establish the conditions under which most people are thermally comfortable.

The main variables that influence thermal comfort are: air temperature (T_{air}), relative humidity (H_r), air velocity (V_{air}), mean radiant temperature (T_{mr}), clothing level (C_{lo}), and metabolic rate (Met). Pioneers in the field, such as Olgyay (1998), Givoni (1976), and Fanger (1970), proposed models to assess comfort using these variables.

Fanger's model is widely used because it incorporates all the aforementioned variables into two indices: 1) the

Predicted Mean Vote (PMV), which indicates thermal sensation on a 7-point scale ranging from -3, or "very cold," to +3, or "very hot," and 2) the Predicted Percentage Dissatisfied (PPD), which indicates the percentage of people dissatisfied with the environment. In this model, the ideal thermal comfort condition is a PMV value of 0, or "Neutral," and a PPD of no more than 20%. This model has been adopted in international standards such as ISO 7730, since 1984, and ASHRAE Standard 55, since 1992 (American Society of Heating, Refrigerating and Air-Conditioning Engineers [ASHRAE], 2017). It has also been adopted at the national level in Regulation 0549 on Sustainable Construction (Ministry of Housing, City, and Territory, 2015). It is widely accepted for evaluating mechanically conditioned environments, because numerous studies have found discrepancies; particularly in naturally ventilated buildings, where occupants express thermal satisfaction across a wider range (Carlucci et al., 2018; Forgiarini Rup et al., 2015). For this reason, the adaptive model was included in subsequent versions of the same standards.

In particular, Fanger's model establishes a static comfort range for T_{air} between 21 °C and 25 °C, regardless of the climate being evaluated; in contrast, the adaptive model considers temperatures up to 3.5 °C above and below the average T_{air} of the evaluated climate to be comfortable.

The adaptive model uses the operating temperature (Top) as its evaluation parameter, which is a weighted average of T_{air} and T_{mr} . For example, for a climate with an average T_{air} of 25 °C, such as Cali, the ideal situation is for its Top to be at that same value; however, values between 29 °C and 22 °C are within the acceptable range.

Providing passive thermal comfort in homes has an inherent advantage: that of wellbeing and healthiness (Ormandy and Ezra-tty, 2012; Kaushik et al., 2020); however, there are other benefits, such as economic and sustainability advantages. The economic benefit stems from savings on energy consumption, which are particularly well-received by the social housing community; while the sustainability benefit stems from the reduction in global warming, as lower energy consumption also reduces GHG emissions; it is estimated that half of the energy produced worldwide is consumed by households, and of that half, nearly 40% is used for active climate control devices (United Nations Commission on Human Settlements, UN, 2011).

Gamboa et al. (2011) evaluated thermal comfort in VIS in Cali. In the urban context, they concluded that thermal comfort could be improved by promoting microclimates that mitigate the urban heat island effect through landscaping. In the architectural context, through surveys and monitoring, they determined that thermal dissatisfaction is widespread in single-family homes, where they recorded "very hot" thermal sensations and a PPD reaching up to 100%. Using thermography, they revealed high levels of surface temperatures in building envelopes, such as roofs and facades, reaching up to 49 °C. Finally, the authors demonstrated, through the installation of a radiant barrier under the roof, that it is possible to achieve comfort economically in this housing type.

Iturre (2013) worked with the VIS in Buenaventura, which has a warm, humid climate. Through monitoring and surveys of more than 200 homes, his study identified that 53% of them constantly used mechanical air conditioning to achieve comfort during the day and part of the night. According to the author, this is mainly due to the heat gained through the roof and due to its low thermal resistance. In addition, the author found a lack of cross-ventilation, high heat absorption, and low thermal resistance in the facade walls. The theoretical solution proposed to improve this condition consisted of improving the thermal resistance of the roof, changing the color of the facade walls to reduce heat absorption, and creating cross-ventilation by adding new openings.

Similarly, Barona (2016) determined the thermal performance of the two most commonly used facade construction systems in social housing (VIS) in Cali: structural masonry with fired clay blocks and solid reinforced concrete walls. This study was conducted in single-family homes built in municipalities surrounding Cali, such as Candelaria and Jamundí,

which share the same climatic characteristics. Through monitoring and mathematical calculations, Barona determined the thermal conditions of the homes and evaluated thermal comfort using the Fanger index. It was concluded that the vertical building envelopes do not have sufficient capacity to thermally insulate against the heat radiated by the sun and provide thermal comfort, since the most common thermal sensation was "very hot," which means a dissatisfaction rate exceeding 90%.

Finally, Giraldo et al. (2015) conducted a computational simulation analysis using a VIS multi-family model with a 0.08-m thick reinforced concrete envelope. The authors found that from 10:00 a.m. to 21:00 p.m., the thermal sensation in an apartment falls outside the comfort ranges. They also propose some solutions, which consist of increasing the thermal resistance of the building envelope and providing solar shading for the windows. These improvements resulted in a 60% reduction in the thermal load inside the apartment; furthermore, they represented only a 16% additional cost in the initial construction, which can be recouped within 3 years of operation.

The experimental studies by Gamboa et al. (2011), Iturre (2013), and Barona (2016)—all conducted in warm climates—consistently report thermal discomfort in single-family VIS units constructed with brick or concrete masonry systems, allowing this finding to be generalized. In contrast, for the multi-family typology, only the computational study by Giraldo et al. (2015) is available; therefore, it is necessary to continue the thermal analysis of the multi-family VIS, among other reasons, because it far outnumbers the single-family type nationwide, and its thermal gain is very different. In single-family housing, the thermal load received by the roof is significantly greater, as it constitutes the largest area of the building envelope; whereas, in multifamily housing, the heat gained by the roof affects only the residential units on the top floor. In multi-unit apartment buildings, the largest area of the building envelope corresponds to the facades, which encompass all of the apartments.

Similarly, these studies have assessed thermal comfort using the PMV-PPD model, even though these homes are naturally ventilated. This study proposes to evaluate thermal comfort using both models: the PMV-PPD, to maintain the same rating scale as previous studies, and the adaptive model, to obtain more precise assessments and compare results from the perspective of energy efficiency and sustainability.

Therefore, the main objective of this study is to evaluate the level of thermal comfort provided by a multi-family dwelling in the VIS of Santiago de Cali, Colombia—where the climate is hot and dry—through field monitoring and the comparative use of the PMV-PPD and adaptive models.

2 Methodology

2.1 Experimental building

The building selected for this study is a five-story apartment block belonging to the Calicanto residential complex, located in the southern part of the city of Santiago de Cali, between Streets 42 and 45 and Avenues 95A and 96A. The building's construction system consists of reinforced masonry using exposed fired clay structural blocks with plaster and paint on the interior; it also has a window-to-wall ratio of 30% and a floor area ratio of 1:1.7. The monitored space corresponds to the master bedroom of a 56 m² apartment located in the southwest corner of the building's fourth floor.

Figure 1 shows, on the left, the architectural floor plan of the fourth floor, where the location of the apartment within the building is indicated by shading. Meanwhile, on the right is shown the floor plan of the apartment, in which the bedroom of interest is also indicated by shading; it has interior dimensions of 2.7 m × 3.0 m. Figure 2 shows an exterior view of the apartment building; the housing unit under analysis is indicated by a black dashed line.

2.2 Data collection

Data collection sought to follow ISO 7726 (International Organization for Standardization, 2002). The environmental

variables such as T_{air} , H_r , V_{air} , and T_{mr} were measured using sensors, while for personal variables such as Clo and Met , a dynamic profile was established based on the occupants' habits.

To obtain T_{air} and H_r , a digital data-logging thermo-hygrometer recorded these variables hourly in front of the bed at a height of 1.1 m. This sensor was shielded from radiation by a perforated polished aluminum box.

V_{air} data were obtained using a hot-wire anemometer positioned in the operable area of the double-pane sliding window. This device continuously measured air velocity, and an hourly average of these readings was calculated. During the measurement, the window was operated freely at the occupants' discretion, but the door remained closed.

The T_{mr} was obtained by recording the surface temperatures of the six planes that make up the room every hour using an infrared thermometer, and was then calculated using the following formula, proposed by Dunkle (1963) and subsequently adopted by ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers):

$$T_{mr} = \left[\sqrt[4]{\sum_n f_p \epsilon (t_i + 273.15)^4} \right] - 273.15$$

Where:

t_i = temperature of surface i in °C.

f_p = view factor between the central point of the room and the surface.

ϵ = emissivity of the material.

Figure 3 shows an interior view of the bedroom, with a diagram of the sensor installation, and Table 1 lists each variable along with the instrument used to measure it and its specifications.

Finally, the metabolic rate (Met) and clothing level (Clo) were determined by observing the daily habits of the occupants and the subsequent assignment of values in accordance with the ASHRAE Handbook: Fundamentals (ASHRAE, 2001). The assessment was divided into two stages: 1) activity and 2) rest.



Figure 1. Experimental building. Architectural floor plans: fourth floor of the building; the selected apartment is highlighted (left) and the apartment indicating the monitored room (right). Source: own elaboration (2019)

2.3 Monitoring period

Monitoring was conducted during the first week of January 2016. According to climate databases (Institute of

Hydrology Meteorology, and Environmental Studies, Weather and Climate in Colombia [IDEAM], 2016), this is one of the periods characterized by high levels of solar radiation and air temperature. Additionally, at this time of year, the bedroom under analysis receives direct solar radiation not only through the west facade but also through the south facade, creating a critical period of external thermal load.

2.4 Data processing

Using the data collected during the week, a typical day was constructed based on the hourly averages of each variable. Subsequently, the values for this typical day were entered into the PMV Calc v2 software (Department of Technology and Built Environment - Laboratory of Ventilation and Air Quality - University of Gävle, n.d.), freely available, to calculate hourly PMV and PPD indices.

On the other hand, to evaluate thermal comfort using the adaptive model, a graph was generated based on Figure 5.3 of ASHRAE Standard 55, which plots T_{op} on the vertical axis and the average T_{air} on the horizontal axis (ASHRAE, 2017); this graph, in turn, relies on a spreadsheet that calculates the operating temperature using the T_{air} and T_{mr} values for a typical day via the following formula:

$$T_{op} = A \cdot t_a + (1 - A) \cdot t_{mr}$$

Where:

T_{op} = Operating temperature

A = Air velocity coefficient

t_a = Air temperature

t_{mr} = Mean radiant temperature

Subsequently, the T_{op} is combined with the predominant average outdoor temperature in Cali (25 °C), which was calculated using one year's worth of data from measurements taken at the weather station of the School of Architecture, University of Valle in Cali, at its Meléndez campus..

3 Results

3.1 Air temperature

Figure 4 shows the T_{air} trend during the measurement week; the comfort range — between 22 °C and 29.5 °C — recommended by Olgyay (1998) and Givoni (1976) is indicated by the shaded area. The maximum T_{air} recorded was 34.7 °C, and the minimum was 20.9 °C. The upper limit of the comfort range was significantly exceeded on 5 of the 7 days monitored, generally from 10:00 a.m. to 18:00 p.m. Note that this period coincides with the daytime hours when solar radiation is incident on the south and west facades, from which it can be inferred that there is a lack of effective solar protection strategies for walls and windows. Additionally, the bedroom's air temperature was slightly below the comfort range on 3 of the 7 monitored days; generally, from 4:00 a.m. to 6:00 a.m. The air temperature conditions during this period are ideal for cooling spaces through natural nighttime ventilation, so that they are cooler when receiving thermal loads in the morning and afternoon.

Table 1. Specification of the instruments used. Source: own elaboration (2019)

Variable	Instrument
Air temperature. Relative humidity.	Extech digital thermo-hygrometer (datalogger), model RHT30. Sensitivity for air temperature (T_{air}) ranges from $-30\text{ }^{\circ}\text{C}$ to $70\text{ }^{\circ}\text{C}$, with a resolution of $0.1\text{ }^{\circ}\text{C}$ and accuracy of $\pm 0.5\text{ }^{\circ}\text{C}$. For relative humidity (RH), the device has a measurement range of 0.1% to 99.9% , with a resolution of 0.1% and accuracy of $\pm 3\%$.
Surface temperature or radiant temperature (Tr).	Extech infrared thermometer, model IR 42500. Measurement range from $-20\text{ }^{\circ}\text{C}$ to $260\text{ }^{\circ}\text{C}$, with an accuracy of 97% to 98% .
Air velocity.	CEM digital hot-wire thermo-anemometer, model DT-8880. Measurement range from 0.01 to 25 m/s . Resolution of 0.01 m/s .



Figure 2. Exterior view of the experimental building, indicating the analyzed housing unit. Source: Google Earth (2019)



Figure 3. Schematic diagram of the instrument installation inside the monitored bedroom. Source: own elaboration (2019)

3.2 Relative humidity

Figure 5 shows the RH behavior during the 7 days of monitoring. It indicates the comfort range proposed by Olgyay (1998), between 30% and 70% , as shown by the shaded area. The maximum RH reached was 84% , and the minimum was 34% . The space exhibited excess humidity on 6 of the 7 monitored days during the early morning hours. This excess humidity is not particularly problematic, since this is generally the rest period and is accompanied by comfortable air temperatures; therefore, excessive sweat evaporation is not necessary.

3.3 Air velocity

Figure 6 shows the behavior of air velocity during the 7 days of monitoring, in which the window was left open at the occupants' discretion (it was generally kept fully open in the morning and afternoon, and partially open at night and in the early morning), but the door remained closed. The graph shows that the air velocity in the room was lower during the early morning hours and increased during midday and the afternoon. Despite this, the readings ranged from 0.02 m/s to 0.25 m/s, which Olgyay (1998) classifies as calm or imperceptible wind.

These low air velocity values are attributed to the fact that the room lacks cross-ventilation, as it has only one sliding window, of which only 50% of the area is usable, through which air must enter and exit simultaneously. Unfortunately, this type of ventilation and window design is a general characteristic of VIS.

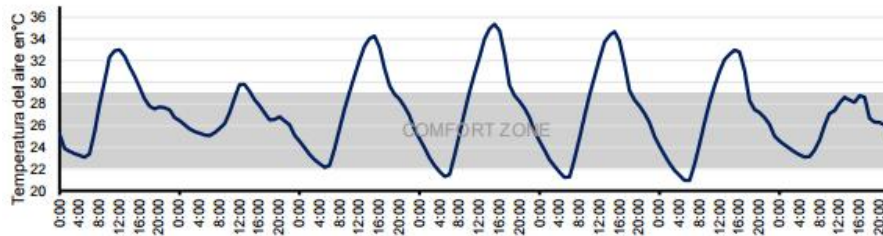


Figure 4. Air temperature during the seven-day monitoring period. Source: own elaboration (2019)

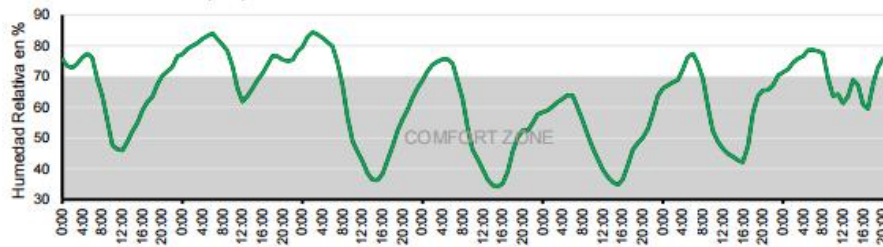


Figure 5. Relative humidity during the seven-day monitoring period. Source: own elaboration (2019)

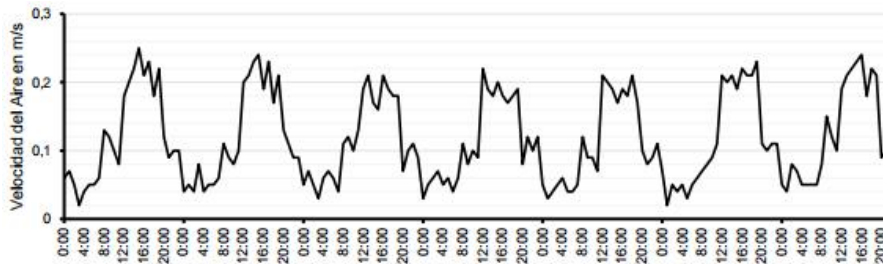


Figure 6. Air velocity during the seven-day monitoring period. Source: own elaboration (2019)

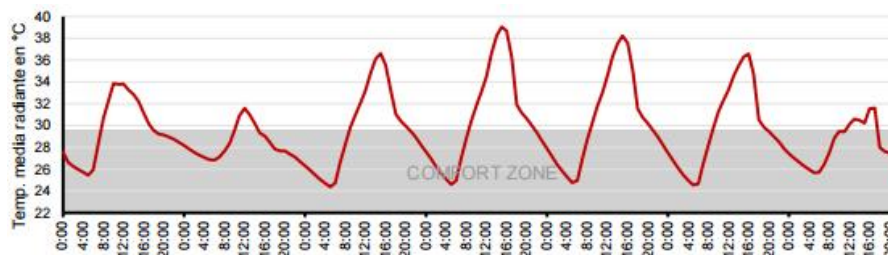


Figure 7. Mean radiant temperature during the seven-day monitoring period. Source: own elaboration (2019)

3.4 Average radiant temperature

Figure 7 shows the T_{mr} trend over the seven-day monitoring period. It indicates the comfort range proposed by Olgay (1998) and Givoni (1976), which is between 22 °C and 29.5 °C, indicated by the shaded area. The maximum T_{mr} reached was 38.7 °C, and the minimum was 24.36 °C. The upper limit of the comfort range was exceeded on all monitored days, from the morning hours until late afternoon or, in some cases, into the evening.

It should be noted that Figure 7 represents the T_{mr} , which calculates the surface temperatures of the entire bedroom (walls, floor, and ceiling) using the equation mentioned above; however, the surface temperature of the west facade reached the highest value, up to 48 °C, on the fourth day of measurement.

When considering the information presented in Figure 1 alongside the bed's proximity to the west-facing wall and its surface temperature of 48 °C, it is clear that occupants' bodies are exposed to very direct radiation from the heat accumulated there. This poor condition for thermal comfort is caused by the furniture layout proposed in the architectural design (note that this is the only suitable position for the bed), the small floor area of the bedroom, and the high thermal absorptivity and transmittance of the building envelope. Unfortunately, at least the last three factors are common characteristics of Colombian VIS.

3.5 Clothing level

Based on observations during monitoring and the Clo values listed in the ASHRAE Handbook Fundamentals (Table 8, Chapter 8) (ASHRAE, 2001), between 8:00 a.m. and 21:00 p.m., occupants wore light pants, short-sleeved shirts, and light footwear, which corresponds to a Clo of 0.6. Meanwhile, during rest hours, from 22:00 p.m. to 7:00 a.m., they wore pajamas and a blanket, which corresponds to a Clo value of 1.2.

Note that clothing levels are dynamic and adapt to environmental conditions, which are ultimately perceived by the users. In this case, the use of greater thermal insulation in clothing worn at night is attributed primarily to the reduction in T_{air} and T_{mr} .

3.6 Metabolic rate

Based on the activities performed by the occupants and the Met values listed in the ASHRAE Handbook Fundamentals (Table 4, Chapter 8) (ASHRAE, 2001), occupants engaged in moderate physical activity from 8:00 a.m. to 21:00 p.m., which corresponds to a value of 1.2; meanwhile, the period from 22:00 p.m. to 8:00 a.m. was spent sleeping, which corresponds to a value of 0.8.

3.7 Comfort evaluation using the Fanger PMV-PPD model

Based on the averages of T_{air} , H_r , V_{air} , and T_{mr} obtained over the seven days of measurement, and using the determined values of Clo and Met, a typical day was constructed, which was subsequently used to assess thermal comfort using the PMV and PPD indices.

Table 2 contains the mean values for each variable at each of the 24 hours of a typical day used to calculate these indices. The resulting PMV and PPD values for each hour are shown in the last two columns.

Finally, Figures 8 and 9 were created to visually review this data. Figure 8 shows the behavior of the PMV; it can be seen that the space achieves thermal sensations close to "neutral" only from 23:00 p.m. to 8:00 a.m.; whereas, from 9:00 a.m. to 22:00 p.m., it exceeds the "slightly warm" threshold and therefore remains between "warm" and "hot" sensations. Note also that between 13:00 p.m. and 17:00 p.m., the "hot" sensation is reached, which corresponds to the highest level of dissatisfaction due to excessive heat.

This information is supplemented by the percentage of dissatisfied people (PPD), shown in Figure 9; which shows that for 14 of the 24 hours of the day, the space remained outside the "acceptable" range of thermal comfort, set at 20%,

and reached dissatisfaction rates of up to 93.4% between 13:00 p.m. and 17:00 p.m..

3.8 Comfort evaluation using the adaptive model

Figure 10 shows the comfort evaluation using the adaptive model. This was developed by calculating hourly operating temperatures based on the weighting between T_{air} and T_{mr} for a typical day, taking into account that the predominant average outdoor temperature in Cali is 25 °C.

Figure 10 shows that the period between 19:00 and 9:00 falls within the 80% acceptability threshold, which equates to 15 hours of satisfaction; meanwhile, outside this threshold the period between 10:00 and 18:00, equivalent to 9 hours of thermal dissatisfaction. During this period, a maximum deviation of up to 4 °C from the acceptable operating temperature limits was reached between 14:00 and 15:00.

It should be noted that the amount of time outside the 80% acceptability limit differs by 5 hours from one evaluation model to another; that is, with the PMV-PPD model, there are 14 hours outside the range, while with the adaptive model, there are only 9, meaning that the operating time of active HVAC equipment is reduced by 35% with the latter model, because it has broader comfort ranges.

3.9 Discussion

As noted in the Introduction, Olgyay (1998), Givoni (1976), and Santamouris and Asimakopoulos (2001) prioritize bioclimatic strategies for solar control and natural ventilation in hot climates. Regarding the first of these two strategies, as shown in Figure 2, the VIS building under observation lacks solar protection elements on openings such as eaves or sunshades, and contrary to recommendations to use light colors to reduce solar radiation absorption, its exterior walls expose the dark clay blocks. Similarly, the thermal transmittance of the walls is part of this strategy; depending on their components, it reaches 2.37 W/m²·K, whereas Sustainable Construction Regulation 0549 (Ministry of Housing, City, and Territory, 2015) sets a maximum limit of 1.21 W/m²·K.

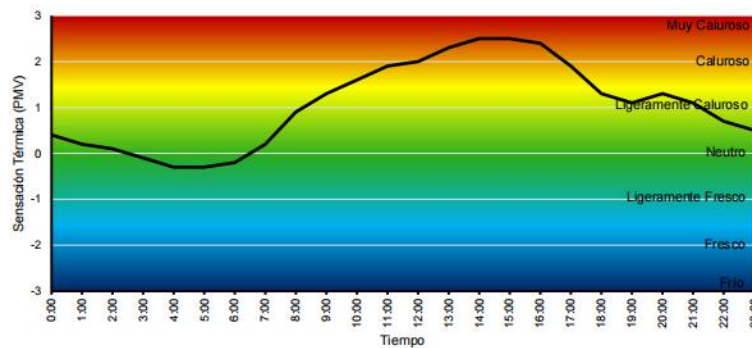


Figure 8. PMV chart (thermal sensation index) for the typical day. Source: own elaboration

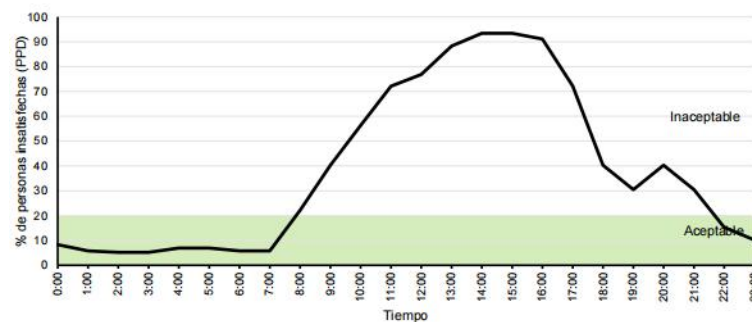


Figure 9. PPD chart (Percentage of Dissatisfied People) for the typical day. Source: own elaboration (2019)

Table 2. Typical day constructed from hourly mean values of each variable and the resulting PMV and PPD values

Source: own elaboration

Date	Time	Tair	Tomorrow	Wed	HR	Mid	Clo	PMV	PPD
Jan 02–Jan 08	0:00:00	24.7	27.0	0.05	71.01	0.8	1.2	0.40	8.30
Jan 02–Jan 08	1:00:00	23.9	26.6	0.05	72.18	0.8	1.2	0.2	5.80
Jan 02 - Jan 08	2:00:00	23.5	25.9	0.05	73.40	0.8	1.2	0.1	5.20
Jan 02 - Jan 08	3:00:00	23.0	25.5	0.05	74.25	0.8	1.2	-0.10	5.20
Jan 02 - Jan 08	4:00:00	22.3	24.9	0.05	75.44	0.8	1.2	-0.30	6.90
Jan 02 - Jan 08	5:00:00	22.4	24.6	0.05	76.57	0.8	1.2	-0.30	6.90
Jan 02 - Jan 08	6:00:00	22.5	25.2	0.05	76.28	0.8	1.2	-0.20	5.80
Jan 02 - Jan 08	7:00:00	23.7	26.9	0.05	72.30	0.8	1.2	0.20	5.80
Jan 02 - Jan 08	8:00:00	25.2	28.5	0.10	68.00	1.2	0.6	0.90	22.10
Jan 02 - Jan 08	9:00:00	27.15	29.7	0.10	60.66	1.2	0.6	1.30	40.30
Jan 02 - Jan 08	10:00:00	28.5	30.7	0.10	54.12	1.2	0.6	1.60	56.30
Jan 02 - Jan 08	11:00:00	29.7	31.7	0.10	51.03	1.2	0.6	1.90	72.10
Jan 02 - Jan 08	12:00:00	30.7	32.4	0.20	48.20	1.2	0.6	2.00	76.80
Jan 02 - Jan 08	13:00:00	31.5	33.4	0.20	47.60	1.2	0.6	2.30	88.30
Jan 02 - Jan 08	14:00:00	32.0	34.4	0.20	48.25	1.2	0.6	2.50	93.40
Jan 02 - Jan 08	15:00:00	31.8	34.6	0.20	48.40	1.2	0.6	2.50	93.40
Jan 02 - Jan 08	16:00:00	31.3	34.2	0.20	49.00	1.2	0.6	2.40	91.10
Jan 02 - Jan 08	17:00:00	29.8	32.7	0.20	52.20	1.2	0.6	1.90	72.10
Jan 02 - Jan 08	18:00:00	28.3	30.0	0.20	57.90	1.2	0.6	1.30	40.30
Jan 02 - Jan 08	19:00:00	27.5	29.1	0.20	61.60	1.2	0.6	1.10	30.50
Jan 02 - Jan 08	20:00:00	27.4	29.0	0.10	63.64	1.2	0.6	1.30	40.30
Jan 02 - Jan 08	21:00:00	26.9	28.3	0.10	64.80	1.2	0.6	1.10	30.50
Jan 02 - Jan 08	22:00:00	26.2	27.8	0.10	66.90	0.8	1.2	0.70	15.30
Jan 02–Jan 08	23:00:00	25.0	27.7	0.10	70.30	0.8	1.2	0.50	10.20

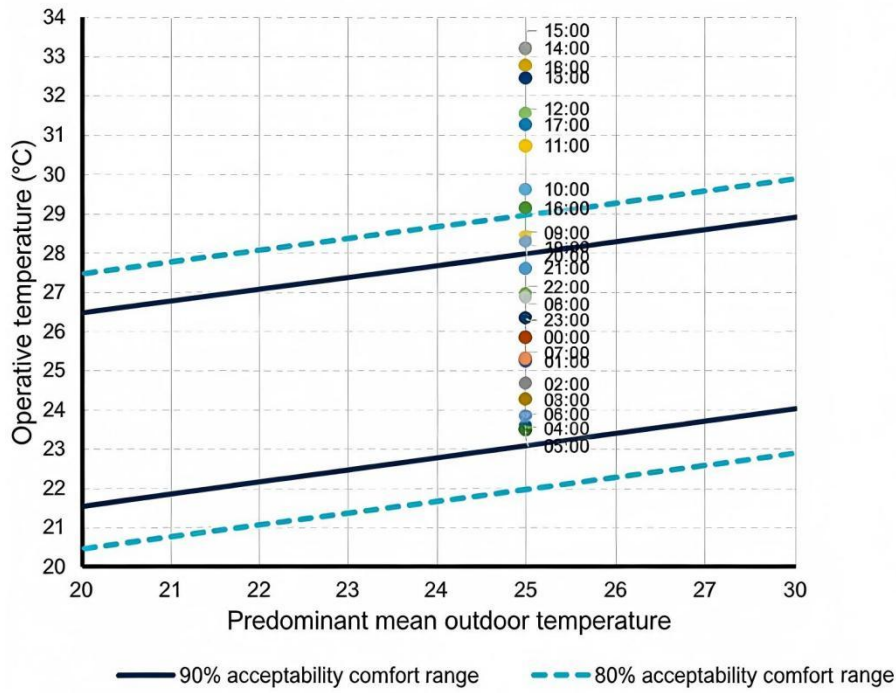


Figure 10. Thermal comfort evaluation chart using the adaptive model for the typical day. Source: own elaboration (2019)

Based on the results shown in Figures 8, 9, and 10, it is evident that the level of insulation in the opaque vertical envelopes of these homes is insufficient to provide thermal comfort to their occupants. This is reinforced by the T_{mr} records, which exceed the upper limits of the comfort range; in fact, measured values of up to 48 °C have been recorded for the internal surface temperature of the west facade.

Finally, another cross-cutting aspect typical of VIS developments identified in the analysis of T_{mr} analysis—and which also involves solar protection—is the short dimensions of the spaces, which does not allow for more flexible arrangements of bedroom furniture. This forces occupants to remain close to the facades with the highest surface temperatures.

On the other hand, regarding natural ventilation, it was found that only 30% of the building envelope consists of windows, whereas the recommended ratio is 40%, not only for ventilation but also for natural lighting (Ministry of Housing, City, and Territory, 2015). The low window-to-wall ratio is exacerbated by the fact that the windows are sliding and allow only 50% of the opening to be used for ventilation; they could well be replaced with casement or louvered windows, which would allow 100% of the opening to be utilized and are slightly less expensive. Furthermore, the door design is completely closed and could also be improved by including upper and lower openings to facilitate cross-ventilation without compromising privacy.

These characteristics of multifamily VIS that result in poor thermal comfort performance are common to those mentioned in studies on single-family VIS, as stated in the studies by Gamboa et al. (2011), Iturre (2013), and Barona (2016); however, a new one has been identified: the proximity of occupants' bodies to the building envelope, which has a high surface temperature—a situation resulting from the arrangement of furniture in the architectural design and the small floor area of the space.

With regard to comfort assessment models, it was found that, using the PMV-PPD model, the perceived temperature of the environment from 13:00 to 17:00 reaches the "very hot" level, resulting in dissatisfaction rates as high as 93.4%; and for 14 of the 24 hours of the day, acceptance is less than 80%. Meanwhile, using the adaptive model, periods of

dissatisfaction were also found, but only during 9 of the 24 hours of the day. Given the above, and considering that the literature review indicates the adaptive model as the most accurate for evaluating thermal comfort in naturally ventilated spaces (Carlucci et al., 2018; Forgiarini Rup et al., 2015), it is understood that using it from the design stages means savings in insulation materials during the construction phase. Furthermore, during the operational phase, this approach leads to energy and cost savings, as the period during which mechanical climate control is required will be reduced by 35%. As mentioned in the first part of this article, these types of savings in materials and energy are necessary to reduce GHG emissions generated during the production of construction materials and electricity, as well as to avoid the construction of new hydroelectric plants (International Energy Agency, n.d.; Giraldo et al., 2015; Revista Dinero, 2019).

Finally, it is worth noting that, despite the notable morphological differences among VIS typologies, the results obtained in this study when evaluating a multi-family housing area (maximum PMV of 2.5, or "very hot," and maximum PPD of 93.4%) are slightly less unsatisfactory, yet very similar, to those found by Gamboa et al. (2011), Iturre (2013), and Barona (2016) in this typology single-family homes, where PMV values ranging from 2.6 to 3.0 ("very hot") and PPD values ranging from 95.3% to 100% were identified; however, this demonstrates that thermal dissatisfaction is a widespread problem in VIS related to their design, materials, and construction systems, thereby reinforcing the findings of previous research regarding how uncomfortable it is to remain in them during certain periods of the day.

4 Conclusion

This study monitored and evaluated the thermal comfort of a VIS unit belonging to the multifamily housing typology in Cali, Colombia—a region characterized by a hot, dry climate—using two models: PMV-PPD and an adaptive model. Given that the state of the art indicates the adaptive model as the most accurate for evaluating naturally ventilated buildings, it was found that the PMV-PPD model requires greater thermal insulation and 35% higher energy consumption for climate control than the adaptive model, which must be considered in terms of resource and energy savings to mitigate climate change. This consideration should also be incorporated into Sustainable Building Regulation 0549, as it currently uses the PMV-PPD model.

The study concludes that the main cause of the high levels of thermal dissatisfaction experienced by occupants of multi-family social housing (VIS) is not a lack of financial resources, but rather a lack of innovation and the application of bioclimatic principles.

Thus, the study clarifies that Colombian social housing in hot climates requires interventions that improve thermal comfort and ensure health and safety; as stated in the introduction, the best solutions from an economic and sustainable standpoint are passive cooling strategies, which require little or no additional investment, such as natural cross-ventilation, solar shading for glazed elements, and reducing the thermal absorptivity and transmittance of the building envelope.

Finally, if Colombia wishes to reduce energy demand and make a genuine contribution to mitigating global warming through the construction sector, VIS must be included in the mandatory under the Sustainable Construction Regulations, rather than having optional compliance, as is currently the case. The results of this research, combined with those of the other studies cited in the literature review, justify this inclusion. If they are included, special attention must be paid to ensuring that energy savings are balanced with the provision of adequate levels of thermal, lighting, and air quality comfort for users. This implies intervention starting from the design phase for new buildings and remedial work for existing ones.

Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

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List of abbreviations

ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Clo: Clothing thermal insulation level – 1 Clo = 0.155 m²·°C/W.

GHG: Greenhouse gases.

RH: Relative humidity.

Met: Metabolic rate.

P M V: Predicted Mean Vote (thermal sensation index).

PPD: Predicted Percentage Dissatisfied.

Tair: Air temperature, or dry-bulb temperature.

Tmr: Mean radiant temperature.

Top: Operating temperature.

TRM: Market Representative Rate.

Vair: Air velocity.

VIS: Social housing.