Natural Ventilation Strategy in a Social Housing with Sub-humid Warm Climate Based on Thermal Comfort

Claudia Eréndira VÁZQUEZ-TORRES^{1*}, Adolfo GÓMEZ-AMADOR²,
 Gonzalo BOJÓRQUEZ-MORALES³, Arash BEIZAEE⁴, Pablo David ELÍAS-LÓPEZ⁵

^{1,2}*School of Architecture and Design, University of Colima, Colima-Coquimatlán Km 9, 28400, Mexico*

³*School of Architecture and Design, Autonomous University of Baja California, Mexicali, Mexico*

⁴*School of Architecture, Building and Civil Engineering, Loughborough University, Loughborough, United Kingdom*

⁵*Sciences and Arts for Design, Azcapotzalco Unit, Metropolitan Autonomous University, Tlalpan, 14387 Ciudad de México, Mexico*

Abstract – Natural ventilation was analysed in a low-income dwelling to control open or closed windows according to a dynamic simulation process in sub-humid warm climate. A selective algorithm to control natural ventilation was determined in an annual period per hour with the following findings: a) an algorithm to select open or closed windows was determined, b) comfort hours per year were evidenced with open, closed windows and selective algorithm to operate natural ventilation, and c) the schedule and periods of ventilation control were presented. Meteonorm® data were used on an hourly basis in Design Builder® simulations and the Meteorological System data based on 30 years of measurements were used to determine the comfort range. **Conclusions:** the potential benefits to be obtained by applying this ventilation strategy with a selective algorithm are observed in sub-humid warm climate.

Keywords – Dynamic thermal simulation; natural ventilation; passive systems; social housing; thermal comfort

SMN	National Meteorological System
ow	open windows
cw	closed windows
B1	Bedroom 1
sa	selective algorithm

1. INTRODUCTION

Generally, social housing has the minimum dimensions established by local and federal regulations [1], these characteristics limit ventilation in spaces with reduced volumes. Selecting when open or closed the windows on an hourly basis in one year represents a natural

* Corresponding author.

E-mail address: claudiaerendira@gmail.com

ventilation strategy with possibilities of increasing the permanence of an established thermal comfort range and, at the same time, ensuring the control of ventilation rate. ANSI/ASHRAE recommend that each living space has 4 % of the floor area or 0.5 m² for ventilation opening [2].

There is a global interest in establishing natural ventilation strategies to favour the use of passive systems mainly due to its potential to reduce energy costs and increase the thermal comfort of users [3]–[9]. It is common to find studies on indoor air quality with different aperture settings to determine wind behaviour by simulation [3], [4]. However, not in all cases, natural ventilation provides thermal comfort [5]. Therefore, the correlation between thermal comfort and energy performance due to the effects of natural ventilation represents a challenge for researchers [11]. From the perspective of thermal engineering, windows let the heat flow more easily between the indoor and outdoor [7]. These findings regarding natural ventilation are the background for the question: How can the use of natural ventilation in low-income dwellings be controlled without the implementation of mechanical systems?

Savings for house purchase in Mexico are accumulated mainly through earned income, so the structural characteristics of the labour market fundamentally determine the analysis of housing demand. 41.6 million dwellings were quantified in 2018, out of which 37 % were acquired through formal loans. Of the 125.8 million inhabitants in Mexico, 62 % have a salary of up to two times the minimum wage per day (11.5 USD) [12]. More than half of the economically active population can afford a low-income housing by means of a formal loan in Mexico.

In this study, a novel selective algorithm was developed to analyse open or closed windows according to an adaptive comfort range in a social dwelling in a sub-humid warm climate. The reason for selecting this typology of housing was the percentage of dwellers in Mexico that are able to purchase a social housing. It is important to point out that owners of low-income dwellings can hardly invest in mechanical strategies to guarantee their own comfort, so the use of passive systems controlled by the users themselves would support their thermal comfort and economy. With this background, the primary objective was to analyse the natural ventilation in a social housing in order to determine a control strategy as to whether keeping the windows open or closed according to an adaptive comfort range to establish a selective operation on an hourly basis per year.

2. METHODS

To achieve the primary objective of this study, a quantitative study was conducted [13]. The process of obtaining the results followed the correlational method steps [14] between the operative temperature and the time-dependent adaptive comfort range from the ASHRAE Standard 55 thermal comfort model [15] for natural ventilation. The data analysis used the Auliciem's equation [16] and the amplitude comfort range was determined by Szokolay's equation [17] considering the adaptation of users to low occupancy housing.

As the first step, the average air temperature of the Climatological Normals from 1981 to 2010 of the National Meteorological System (SMN by its Spanish acronym) was compared [18] to the interpolated data from Meteonorm version 7.3 in sub-humid warm climate (Fig. 1). As a result, there was a difference between 1 °C and 2 °C.

Fig. 1. Average air temperature in sub-humid warm climate.

To evaluate the correlation between Meteonorm v7.3 data and the observed dry-bulb temperature taken from the SMN data, the statistical method of the Percent Mean Absolute Relative Error (PMARE) was used, which is represented in Eq. (1) [19]. The PMARE validation results were acceptable, indicating a good performance rating for the model.

$$\text{PMARE}_{\text{,}}(\%) = \frac{100}{n} \sum_{i=1}^n \frac{\text{Abs}(O_i - P_i)}{O_i}, \quad (1)$$

where O_i = Observed dry – bulb temperature; P_i = Simulated dry – bulb temperature; Abs = Absolute value.

Once the similarities between the different climate file providers were established, the following steps were carried out:

1. Case study and boundary conditions.
2. Adaptive comfort range.
3. Dynamic Thermal Simulation: open windows (*ow*) and closed windows (*cw*).
4. Selective Algorithm (*sa*), to control natural ventilation.
5. Results and discussion.
6. Conclusions.

2.1. Benchmark Case and boundary conditions

The benchmark case was a social housing in the central region of Mexico with sub-humid warm climate; based on climatic characterization by the National Meteorological System and the Köppen-Geiger classification modified by García to adapt them to the climatic conditions of Mexico [19], [20].

In the benchmark case, the main façade faces north. Table 1 shows the doors and windows dimensions. The windows were made of 3 mm simple and clear glass, 0.10 m × 0.12 m ×

0.24 m block walls and 0.10 m concrete slab. The doors and windows' locations are indicated in Fig. 2.

TABLE 1. DOORS AND WINDOWS SIZE

Element	Size, m
W1	1.20×1.2
W2	0.60×0.6
P1	0.95×2.1
P2	0.80×2.1
P3	0.70×2.1
P4	0.85×2.1

For the simulation process, two virtual scenarios were used: open windows (*ow*) and closed windows (*cw*) with cross ventilation as shown in Fig. 2. The simulation process was carried out in Design Builder® software version 4.7. The influence area or selected space to perform the simulation analysis was Bedroom 1 (B1) with measurements of $2.81 \text{ m} \times 2.83 \text{ m}$ to axes, indicated with a dotted line in Fig. 2.

Bedroom 1 was selected as a representative space because the low-income housing belongs to the working class with regular 8-hour workdays; therefore, the place where users spend the longest amount of time in their own house corresponds to the bedrooms, while they are sleeping.

Fig. 2. Distribution and representative space in the benchmark case.

Calculated natural ventilation was selected to allow the windows to be open and closed in the one-year simulation process and an excellent infiltration model was used, according to the recommendations of the applicable regulations [15], [16]. A 50 % opening was considered concerning the windows' dimensions and the temperature control was done with air temperature. The 50 % selection aperture with respect to the whole window area complies with ANSI / ASHRAE Standard 62.2-2019 recommendations [2].

The heat gains in the simulation process were calculated as follows:

- A dynamic calculation was selected where the occupancy was based on internal temperatures and metabolic rate (value 1 in Design Builder v4.7).
- Computer: it was selected a value of 0.1, which means that the heat is transferred to the air node in the simulation (convective and radiative).

2.2. Adaptive comfort model

To obtain the adaptive comfort model, the average air temperature from the Climatological Normals per month (1981–2010) was taken as a basis [18], the Auliciems's equation was used together with the Szokolay's amplitude range for the adaptation of users to social housing [16], [17]. Table 2 shows the amplitude range results per month.

TABLE 2. THE COMFORT RANGE BASED ON AULICIEMS AND SZOKOLAY'S EQUATIONS IN SUB-HUMID WARM CLIMATE

Month	ADT ¹ °C	Comfort range, °C	
		Lower ²	Top ³
1	16.6	20.2	25.2
2	18.3	20.7	25.7
3	21.3	21.7	26.7
4	23.4	22.3	27.3
5	24.7	22.7	27.7
6	24.5	22.7	27.7
7	23.2	22.2	27.2
8	23.1	22.2	27.2
9	22.0	21.9	26.9
10	20.4	21.4	26.4
11	19.2	21.0	26.0
12	16.9	20.3	25.3

¹ Average Dry-bulb temperature. ² Lower comfort range (Lcr). ³ Top comfort range (Tcr)

2.3. Selective Algorithm

The 'selective algorithm (*sa*)' consisted of determining, between *ow* and *cw* simulations at hourly intervals, which scenario remained or was closer to the established adaptive comfort model, according to the selective algorithm in Table 3.

The selection criterion corresponds to the control that the users have over opening or closing their windows manually and without the use of active controls, which are hardly ever bought by users of social dwellings.

The comfort range from month 11 in Table 2 was used as an example in Table 3 and seven possible cases were established. The results obtained were integrated into a matrix to quantify

the different tasks (comfort, heating and cooling) and facilitated the results analysis presented in Section 3.

TABLE 3. SELECTIVE ALGORITHM. THIS EXAMPLE USES THE COMFORT RANGE FROM TABLE 2

Comfort range		Simulation			if	Select
Lower	Top	<i>ow</i>	<i>cw</i>	<i>sa</i>		
		T1	T2	T3		
21	26	22	23	$T3C_1$	T1 and T2 are within the <i>cr</i>	0
		27	28	$T3C_2$	T1 and T2 are at the top of the <i>cr</i>	The closest one to Tcr
		19	18	$T3C_3$	T1 and T2 are below the <i>cr</i>	The closest one to Lcr
		25	27	$T3C_4$	T2 is at the top of the <i>cr</i> and T1 is within the <i>cr</i>	T1
		22	20	$T3C_5$	T2 is below the <i>cr</i> and T1 is within the <i>cr</i>	T1
		27	25	$T3C_6$	T1 is at the top of the <i>cr</i> and T2 is within the <i>cr</i>	T2
		20	22	$T3C_7$	T1 is below the <i>cr</i> and T2 is within the <i>cr</i>	T2

where:

Lcr = Lower comfort range;

Tcr = Top comfort range;

ow/T1 = Operative temperature resulting from the open windows simulation;

cw/T2 = Operative temperature resulting from the closed windows simulation;

sa/T3C₁₋₇ = Operative temperature resulting from the selective algorithm strategy;

cr = Comfort range.

2.4. Representative Day

To determine the representative day, the dry-bulb temperature data from the Meteorological System and the climatic characterization by Gómez-Azpeitia were used [17], [20]. The representative day was firstly estimated from the analysis of the 12 months of the year divided by two seasons, which resulted in one representative month per season; then, using the representative month of each season, the representative day was obtained.

The climatic characterization developed by Gómez-Azpeitia presented an evaluation of the dry-bulb temperature and relative humidity according to Köppen climate classification for Mexican localities. As a result, this locality had characteristics of a sub-humid warm climate throughout the year, with the two and representative seasons shown in Table 4.

TABLE 4. CLIMATIC CONDITIONS IN SUB-HUMID WARM CLIMATE

Indicator	Season A	Season B
Climate classification	Humid warm	Sub-humid temperate
Average Dry-bulb temperature	22.5 °C	18.9 °C
Average monthly rainfall	65.6 mm	19.6 mm
Average relative humidity	68.9 %	60.2 %
Average absolute humidity	13.3 g/kg	9.3 g/kg
Month	Mar to Sep	Jan, Feb, Oct, Nov, Dec

A representative month (or day) is that in which the temperature behaviour is the closest to the behaviour of a given season, and the difference in its thermal oscillation is the closest to

zero. The representative month was estimated using Eq. (2) in both established seasons [24]. In other words, the representative month does not necessarily correspond to the hottest month in Season A (March to September) or the coldest month in Season B (January, February, October, November and December); but to the month that in each season reflected the behaviour of the whole season.

$$RD = (A_{dt} - A_{ds}) + (OSCT_{dt} - OSCT_{ds}) = 0, \quad (2)$$

where:

RD = Representative Day;

A_{dt} = Average daily dry – bulb temperature;

A_{ds} = Average season dry – bulb temperature;

$OSCT_{dt}$ = Average Oscillation daily dry – bulb temperature;

$OSCT_{ds}$ = Average Oscillation season dry – bulb temperature.

As a result, Table 5 shows for Season A the month of March as the representative month, and for Season B, the month of October.

TABLE 5. DRY-BULB TEMPERATURE, °C

Season A (Humid warm classification)								
Month	3	4	5	6	7	8	9	Average
Maximum Temperature	30.1	32.1	33.2	31.8	29.7	29.8	28.4	30.7
Average Temperature	21.3	23.6	24.7	24.5	23.2	23.1	22.0	23.1
Minimum temperature	12.5	14.7	16.2	17.2	16.6	16.4	15.7	15.6
Oscillation	17.6	17.4	17.0	14.6	13.1	13.4	12.7	15.1
Representative month	0.60	2.50	3.40	0.80	−1.90	−1.70	−3.50	
Season B (Sub-humid temperate classification)								
Month	10	11	12	01	02			
Maximum Temperature	27.3	27.2	25.2	24.8	26.9			
Average Temperature	20.4	19.2	16.9	16.6	18.3			
Minimum Temperature	13.5	11.2	8.60	8.30	9.60			
Oscillation	13.8	16.0	16.6	16.5	17.3			
Representative month	−0.10	0.80	−0.80	−1.20	1.20			

The representative day per season was estimated using Eq. (3) in the representative months indicated in each season. The following results were obtained:

- Season A – March 16;
- Season B – October 23.

The representative months and days were used to analyse and determine windows opening or closing hours during the two seasons that occur in a whole year for this locality.

3. RESULTS

Figure 3 shows the comfort hours in one year according to the simulation with *ow*, *cw* and *sa*. The results tended to keep open windows during the warm season from June to October. April and May presented similar comfort hours quantification between *cw* and *ow*. November presented greater comfort hours and the biggest difference between keeping *ow* and *cw* occurred in October.

Fig. 3. Comfort hours per month in sub-humid warm climate.

3.1. Windows opening schedule

According to the representative month results, the operative temperature behaviour (resulting from *sa*) for sub-humid warm climate varies not only throughout the same day, but also throughout the whole month. Due to the thermal characteristics, the analysis of schedules to keep *ow* or *cw* for the representative day was proposed, as well as for two additional days that represented the thermal needs of the entire season.

Season A. Due to the operative temperature behaviour in March, the analysis of this season was carried out on days 4, 16 and 31, as indicated in Fig. 4.

Day 4 represented the greatest heating needs according to the established comfort range while day 16 as a representative day, shows an intermediate behaviour; and finally, day 31 shows cooling needs. March showed cooling needs to a greater extent, and lower heating needs.

Fig. 4. Operative temperature behaviour in Season A.

March 4. In Fig. 5, the operative temperature behaviour for *ow*, *cw* and *sa* is indicated. According to the results, heating needs are observed from 3 h to 11 h, while the cooling needs appear between 17 h and 18 h. In order to stay more time in the comfort zone, the selective algorithm indicated a tendency to keep *ow* from 18 h to 3 h, while this trend is reversed to keep *cw* from 4 h to 11 h.

Fig. 5. Operative temperature analysis for March 4.

March 16. On March 16 a unified tendency to keep *ow* was observed; however, as the selective algorithm approaches the lower line of the comfort zone, it is recommended *cw* from 5 h to 9 h (Fig. 6).

Fig. 6. Operative temperature analysis for March 16.

March 31. It is not recommended to keep *cw* throughout the day and night at the end of Season A, as indicated in Fig. 7. During this representative day, a clear tendency to cool the indoor air volume was observed.

Fig. 7. Operative temperature analysis for March 31.

Finally, when analysing the three representative days for Season A, a tendency to keep *ow* on day 16 and 31 was observed. However, a heating task (*cw*) was performed at the beginning

of the season on day 4. It is recommended, at the beginning of Season A, to keep *cw* from 4 h to 11 h, as the season progresses, it is recommended to close the windows only from 5 h to 9 h and, finally to keep *ow* throughout the day and night at the end of the Season A. During *cw*, it is recommended to *ow* for at least 5 min every 2 hours to ensure air exchange and the minimum recommended ventilation rate [2].

Season B. In Fig. 8, the operative temperature behaviour in °C according to the representative day on October 23 corresponding to the coldest period (Season B) for a sub-humid warm climate is presented. To analyse this season, two more days were chosen: October 7 and 29 because this Season presented variations throughout the period.

Figure 8. Operative temperature for Season B.

During Season B, an inverse thermal behaviour in comparison to Season A was observed. At the beginning of this Season, a cooling need decreases until reaching the need for heating at the end of the season.

October 7. At the beginning of Season B, a clear trend toward cooling is observed, so it is recommended to keep ow day and night (Fig. 9).

Fig. 9. Operative temperature on October 7.

October 23. In this case, the cooling trend remained in a lower proportion than the observed in Fig. 9, and a tendency to increase the temperature was observed with cw (Fig. 10).

Fig. 10. Operative temperature on October 23.

October 29. On this day, there was a heating need from 4 h to 8 h, in this case, it is recommended to keep *cw* (Fig. 11).

Fig. 11. Operative temperature on October 29.

At the beginning of Season B, it is recommended to keep *ow* day and night, in an intermediate period of this Season, it is recommended to keep *ow* only from 13 h to 21 h and, finally to keep *cw* day and night at the end of Season B.

4. DISCUSSION

In the following discussion, perspectives of previous studies were interpreted according to the object of this study: natural ventilation and thermal comfort. Furthermore, directions for future investigations are recommended.

4.1. Natural ventilation

The current study analysed a low-income dwelling in the central region of Mexico with sub-humid warm climate to establish an algorithm with the main aim to control windows (open or closed) at hourly intervals and generate a strategy according to an adaptive comfort model. The adaptive comfort model correctly operates in dwellings with natural ventilation [21]–[24].

The main condition for using natural ventilation was the low occupancy in social housing due to the fact that users belong to the working class with 8-hour or more workdays. Carlton et al. found that in low-income urban houses, high ventilation rates are associated with increases in chronic cough, asthma and asthma-like symptoms [28]. It is recommended that one air change per Hour (ACH) during the occupancy time. ANSI/ASHRAE recommended 14 L/s using the Eq. (3).

$$Q_{tot} = 0.15A_{floor} + 3.5(N_{br} + 1), \quad (3)$$

where Q_{tot} = total required ventilation rate, L/s; A_{floor} = dwelling – unit floor area, m²; N_{br} = number of bedrooms.

This study showed limitations in the use of closed windows since there was a risk of non-compliance with the minimum ventilation rate of air change per Hour during the occupancy time. It is recommended to open windows periodically during the *cw* strategy if it indicates more than 2 h consecutively. However, it is recommended to expand the area of knowledge of the air change rates in sub-humid warm climate, as well as the variation of indoor air temperature when opening the windows to renew the air during the closed windows strategy.

4.2. Thermal comfort

Deng Xiang et al. [26] used the adaptive comfort model ASHRAE 55 [29] to analyse an advanced natural ventilation supplemented by a survey on the thermal sensation of the occupants carried out for the summer period, during the season with the greatest need for cooling. Knowledge on thermal comfort does not necessarily imply the implementation of mechanical controls, but rather having tools that allow the dwellers to expand the permanence of the comfort range and reduce the electrical consumption of active systems. It shows, in natural ventilation strategy, a possibility to save energy and increase the comfort hours.

The adaptive comfort model used by Bienvenido-Huertas et al. [25] was established in three ranges according to the metabolic rates of the occupants. The study used a comfort temperature with an amplitude range due to the user's adaptability in the selected location. Sung-Kyung Kim et al. found that temperature and humidity controlled by HVAC system usage may be reduced due to human ability to thermally adapt after reaching the thermal comfort range [30].

Utkucu et al. [31] analysed the window openings in two levels dwelling under four scenarios, and they found that the open windows scenario in both levels favoured the thermal comfort conditions, but the scenario with closed windows in the second level and open windows in the first level favoured energy consumption. Control of natural ventilation was dominant to maintain thermal comfort with an adaptive model, using residual active systems in summer [27].

Figure 12 shows the selective algorithm results for the month with the highest cooling requirement (May) and the month with the highest heating requirement (March) for Season A. The comfort range determined for each month is included. The cooling needs reach 4 °C during the month of May while in the month of March these needs are halved. The heating needs for the month of March were during the first days, while for the month of May they are practically null. There was a greater oscillation in the cooling needs during the month of May. Due to the temperature variation from March to May, and the variation of the oscillation, it is recommended to use night ventilation during the months of April, May and June and to decrease the opening of windows during the following months.

Figure 13 presents selective algorithm results for the month with the highest heating (January) and cooling (October) requirements for Season B. In contrast to Season A, and due to the temperature variation observed in Figs. 8–11, in Season B the cooling requirements decrease significantly from October to January. In mid-January, heating requirements of less than 2 °C were observed. It is recommended to reduce night ventilation, and to keep windows closed during November, December and January.

The selective algorithm is a tool for manual control of a natural ventilation system, aimed at users with social housing who cannot invest in their own thermal comfort.

Fig. 12. Selective algorithm, Season A.

Fig. 13. Selective algorithm Season B.

5. CONCLUSIONS

This study adheres to the effort of different authors to find natural ventilation control strategies that increase the permanence of the thermal comfort with the potential to reduce electricity consumption in houses.

Due to the characteristics of this study, it covers two types of contribution: 1) An adequate method was presented to users of low-income housing in the central region of Mexico with a sub-humid warm climate and 2) an adaptive comfort model was used due to the low occupancy of users of this type of housing.

However, the analysis was performed on an hourly basis because the possibility of using natural ventilation throughout the day was presented, and an algorithm that allowed manual selection between open or closed windows in sub-humid warm climate with possibilities to understand the indoor environmental performance of a social housing was also found.

The analysis of adaptive thermal comfort ranges for social housing occupants allows for insights the natural ventilation strategies with greater precision and their effect on the thermal environment.

In order to reach or stay longer in the comfort range, the selection algorithm between open or closed windows in sub-humid warm climate showed the following results: it is recommended during the months of February, March and April to close windows from 4 h to 11 h and during the months of May and June only from 5 h to 9 h. It is recommended to keep open windows day and night from July to October and to keep closed windows day and night during November, December and January. The selection algorithm allows low-income users to control their ventilation by passive systems. To enhance the findings, the following research directions are recommended:

- 1) to analyse the selective algorithm effect on humid and dry climates and determine the air rates and the indoor air quality according to international standards for social housing in developing countries;
- 2) to compare global simulation providers and compare results according to the National Climatological Service.

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