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THERMAL COMFORT STUDIES

TESIS

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Abstract

The improvement of energy efficiency in buildings is a key element in the combat against global warming. For this reason the use of passive and low energy consumption strategies for buildings has increased. However, it is important to evaluate the thermal comfort that these strategies provide to the buildings' occupants. This thesis addresses the evaluation of comfort in naturally ventilated buildings. It presents the thermal, acoustic and visual comfort backgrounds along with all the physical variables that influence them. The methods used to predict thermal comfort are also included. A description of the comfort assessment for buildings is also presented. It covers the recommendations made by international standards on the data acquisition for comfort studies and the elaboration of comfort questionnaires. This thesis likewise presents a literature review on comfort studies in the case of Mexico. Thermal simulations are the main tool for the comfort assessment during the design stage. In this work a methodology for the validation of thermal simulations is proposed. This methodology has been reported in an article that is published in an international journal. In this thesis the methodology to be followed for the thermal, acoustic and visual comfort assessment at the occupancy stage of the new IER building is proposed. The validation results show that the building model obtained from the calibration process is suitable to simulate the building in different seasonal, occupancy and ventilation conditions, and can be used with certainty to test strategies to improve thermal comfort in the building. This proposal includes the physical variables to be measured, the location where these measurements will be made and a comfort questionnaire. The types of data acquisition periods (which are divided into permanent and campaigns) and the analysis of data are also included. It is also proposed that at the design stage the thermal comfort evaluation of the new IER building be made using the extension of the predicted mean vote (PMVe) method. The methods suggested to be used for the occupancy stage are the PMVe and the adaptive predicted mean vote (aPMV). Additionally, it is proposed to obtain the comfort operative temperature using a linear correlation between the operative temperature and the thermal sensation votes so as to arrive at an adaptive model specific for the IER.

Abstract

La eficiencia energética en edificios es un factor clave en la lucha contra el cambio climático. Por esta razón el uso de estrategias pasivas y de bajo consumo de energía en edificios ha ido en aumento. Sin embargo, es importante evaluar el confort térmico que proveen dichas estrategias a los ocupantes. Esta tesis se enfoca en la evaluación del confort en edificios naturalmente ventilados. Se presentan los antecedentes de esta tesis con respecto al confort térmico, acústico y lumínico así como las variables que los afectan. También se presentan los métodos que se usan para predecir el confort térmico. Se incluyen las recomendaciones de los estándares internacionales para la adquisición de datos en estudios de confort y para la elaboración de los cuestionarios de confort. De igual manera, se presenta una revisión bibliográfica de los estudios de confort realizados en México. Las simulaciones térmicas de edificios son la principal herramienta usada durante la etapa de diseño de un edificio. En este trabajo se propone una metodología para la validación de simulaciones térmicas. Dicha metodología fue reportada en un artículo que está publicado en una revista internacional. Los resultados de la validación muestran que el modelo del edificio obtenido con el proceso de calibración es aplicable a distintas épocas del año, condiciones de ocupación y ventilación, así como obtener resultados precisos de evaluación del confort térmico usando diferentes estrategias. En esta tesis también se propone la metodología a seguir para la evaluación del confort térmico, acústico y lumínico en la etapa de diseño del nuevo edificio del IER. La propuesta incluye las variables físicas a medir, la localización de los instrumentos para dicha medición y el cuestionario de confort. Asimismo la propuesta incluye los tipos de periodo de medición, que están dividos en permanente y campañas, y el proceso de análisis de los datos. Para la etapa de diseño del nuevo edificio del IER se propone que la evaluación del confort térmico se haga mediate el método del voto medio predicho extendido (PMVe por sus siglas en inglés). Se sugiere que en la etapa de ocupación se utilicen los métodos PMVe y el voto medio predicho adaptativo (aPMV por sus siglas en inglés). Adicionalmente, se propone obtener la temperatura operativa de confort usando una regresión lineal entre la temperatura operativa y los votos de sensación térmica de los ocupantes, con el fin de establecer un modelo adaptativo específico para el IER.

Contents

Introduction

This thesis is part of the project Demonstration buildings of bioclimatic design in warm subhumid climate at the UNAM's Renewable Energy Institute (FES-2017-01-291600) sponsored by the Fund CONACYT - Secretariat of Energy- Energy Sustainability 2017-01 Collaboration Projects In Energy Efficiency - Cooperation with California University.

Energy efficiency in buildings can be achieved through the use of passive and low energy consumption strategies, based on bioclimatic design. For warm climates one of the main strategies is the use of natural ventilation. However, it is important to evaluate the thermal comfort that these strategies provide to the building occupants. This thesis adresses the evaluation of comfort in naturally ventilated buildings.

The general objective of this thesis is to propose the assessment of comfort for naturally ventilated buildings, specifically for the new IER building.

The specific objectives of this thesis are to provide a literature review of thermal, acoustic and visual comfort; to identify the thermal comfort methods designed for naturally ventilated buildings; to get information from international standards about the assessment and design of comfort questionnaires; to provide a methodology for the validation of thermal simulations and to provide the data acquisition methodology for the new IER building.

This thesis has six chapters. The first chapter presents the thermal, acoustic and visual comfort background that includes all the physical variables that influence each one of them. For the thermal comfort, the methods used to predict it are included. The second chapter describes the comfort assessment in buildings background which includes the recommendations made by international standards on the data acquisition for comfort studies and the elaboration of comfort questionnaires. The third chapter presents a literature review on the comfort studies in Mexico, this chapter includes only thermal comfort studies because this is the only type for Mexico that was reported in the literature. The fourth chapter contains the methodology proposed for the validation of thermal simulations which are used in the comfort assessment in the design stage. This methodology has been reported in an article published in an international journal. In this thesis the final draft of the article is presented. The fifth chapter describes the proposals of data acquisition for comfort assessment in the new IER building. This includes the physical variables to be measured, the occupants opinion gathering through a comfort questionnaire, the type of periods for the data acquisition and the analysis of the data obtained. The last chapter point out the conclusions and recommendations for future work.

Chapter 1

Thermal, acoustic and visual comfort background

In this chapter the background of thermal, acoustic and visual comfort is presented. The definition of thermal comfort, the physical variables that influence thermal comfort as well as the integrated temperatures that are commonly used are included. A review of the methods that have been developed over the years to predict thermal comfort, including methods for air-conditioned buildings and for naturally ventilated buildings is presented. The main phenomenons that cause local thermal discomfort and a description of each one of them are listed. The main aspects of acoustic and visual comfort are included.

1.1 Thermal comfort definition

ASHRAE 55 (ANSI/ASHRAE, 2017) defines thermal comfort as the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation. Another definition of thermal comfort is when the majority of the people in a certain space given a level of activity and clothing feel comfortable with the conditions of temperature, humidity, wind speed and radiation (Enescu, 2017).

1.2 Thermal comfort physical variables

ASHRAE 55 (ANSI/ASHRAE, 2017) states six factors that determine whether or not a person can be in thermal comfort, these are: metabolic rate, clothing insulation, air temperature, radiant temperature, air velocity and humidity. These physical variables are presented bellow:

- The metabolic rate or level of activity of a person: is the power delivered by a person due to his or her activity. It also depends on the weight, sex, age, health condition of the person. The met is used as the unit of measurement and corresponds to the power delivery by a sedentary typical person divided by the area of the surface of the skin (area of Du Bois), which is assumed as 1.8 m^2. One met is the equivalent heat lost of 58 W/m^2.

- The clothing insulation or level of clothing insulation: is the thermal resistance of the clothing. It was determined with studies in thermal mannequins. The clo is the unit of measurement and is equivalent to 0.155 $m^2\,{}^{\circ}C/W$ and corresponds to the typical business outfit. The value of the clothing insulation is calculated with the sum of all the clothes that the person is wearing, if the person is seated the furniture must also be consider.

- Air temperature (T_i): refers to the indoor air dry bulb temperature. In thermal comfort, the average air temperature that surrounds the occupants is used. The air temperature must be measured at three heights: ankle, waist and head. According to international standards, when the occupants are seated the heights correspond to 0.1, 0.6 and 1.1 m, while when they are standing the heights correspond to 0.1, 1.1 and 1.7 m. The time average, to calculate the air temperature, must be made in a period of more than 3 minutes and not more than 15 minutes (ANSI/ASHRAE, 2017).

- Mean radiant temperature (T_r): is the temperature of a uniform black (in the sense of black body) enclosure that exchanges the same amount of heat by radiation with the occupant as the actual surroundings. It is a single value for the entire body and accounts for both long-wave mean radiant temperature and short-wave mean radiant temperature (ANSI/ASHRAE, 2017).

- Air velocity (v_a): its refers to the average air velocity magnitude surrounding the occupants. As in the air temperature, the spacial average is made with the three heights mentioned before, ankle, waist and head. The average of air velocity must be made in intervals of not less than 1 and no more than 3 minutes (ANSI/ASHRAE, 2017).

- Relative humidity (H_r): refers to the indoor air relative humidity. The relative humidity is the ratio between the measured water vapour pressure in the air and the maximum quantity of water vapour pressure contained by the air (Enescu, 2017).

ASHRAE 55 (ANSI/ASHRAE, 2017) has tables for the values that correspond to different level of activity and clothing insulation.

1.3 Integrated temperatures for thermal comfort

Integrated temperatures are useful for some thermal comfort assessments. The integrated temperatures take into consideration two or more physical variables and are used to provide more information and to make the thermal comfort analysis easier. According to Enescu (2017) some of the most common used integrated temperatures are:

- Operative temperature (T_{op}): considers the T_i, T_r and implicitly v_a. It is defined by ASHRAE 55 (ANSI/ASHRAE, 2017) as the uniform temperature of an imaginary black enclosure that exchanges the same amount of heat by radiation and convection as in the actual nonuniform environment. This temperature can be calculated as

  $$T_{op} = \frac{T_r h_r + T_i h_c}{h_r + h_c}, \tag{1.1}$$

  where h_r is the radiative heat transfer coefficient in $[Wm^2/°C]$ and h_c is the convective heat transfer coefficient in $[Wm^2/°C]$. The last one depends on the air velocity.

- Effective temperature (ET): combines the influence of T_i, H_r and v_a. This temperature can be defined as the temperature of a thermal environment at 50% of relative humidity.

  $$ET = \frac{37 - (37 - T_i)}{0.68 - 0.0014H_r + \frac{1}{(1.76 + 1.4v_a^{0.75})}} + [-0.29T_i(1 - 0.01H_r)] \tag{1.2}$$

- Standard effective temperature (SET): combines the effect of T_i, H_r, v_a, and considers that $T_r = T_i$. Gives the air temperature of a hypothetical environment with 50% of the relative humidity, v_a<0.1 m/s and mean radiant temperature equal to the air temperature, which imaginary occupant has an activity level of 1.0 met and a clothing level of 0.6 clo, and has the same heat loss from the skin as a person in the actual environment with actual clothing and activity level. For its calculation method see ASHRAE 55 (ANSI/ASHRAE, 2017).

- Globe thermometer temperature (T_g): is the temperature measured by a globe thermometer. It depends on the T_i, v_a and T_r. According to Kazkaz and Pavelek (2013) the globe temperature is approximately the operative temperature ($|T_{op} - T_g| < 0.6K$) if the v_a is higher than $2m/s$ and $|T_r - T_i| < 10\ K$.

- Wet bulb globe temperature ($WBGT$): implicitly integrates the effect of T_i, H_r, v_a and T_r. It is calculate as

  $$WBGT = 0.7T_{wb} + 0.3T_g, \tag{1.3}$$

where T_{wb} is the wet bulb temperature.

1.4 Methods to predict thermal comfort

The methods to predict the thermal comfort can be divided into two main categories, the ones developed from chambers with controlled conditions and the adaptive methods. The first methods are used for air-conditioned buildings and the second ones take into account the adaptability of people to the climate, there are models for naturally ventilated buildings and for air-conditioned buildings. In this section a brief description of all the methods found in the literature review is presented.

1.4.1 Developed from studies in controlled condition chambers

The most famous and used method is the PMV-PPD developed by Fanger (1970). The predicted mean vote (PMV), is used to predict the mean value of the thermal sensation of a group of people in an environment. The scale used in this model is a 7-degree scale with 0 being the neutral, -3 very cold and 3 very hot. The advantage of this model is that it takes into consideration the six physical variables involved. The disadvantage is the ranges from each variable variables in which the model works. Another disadvantage is that it doesn't take into account the adaptability of the people. The predicted percentage of dissatisfaction depends on the value of PMV, it predicts the percentage of persons in thermal discomfort. ISO 7730 (ISO, 2005a) includes the equations to calculate the PMV, with an iterative method that can be programmed, and PPD values. The PMV can be calculated with the following equations:

$$\mathbf{PMV} = [0.303\exp(-0.036M)+0.028]\{(M-W)-3.0510^{-3}[5733-6.99(M-W)-P_a]$$

$$-0.42[(M-W)-58.15]-1.710^{-5}M(5867-P_a)$$

$$-0.0014M(34-T_i)-3.9610^{-8}f_{cl}[(t_{cl}+273)^4-(T_r+273)^4]-f_{cl}h_c(t_{cl}-T_i)\}, \quad (1.4)$$

$$\boldsymbol{t_{cl}} = 35.7-0.028(M-W)-I_{cl}\{3.9610^{-8}f_{cl}[(t_{cl}+273)^4-(\bar{t}_r+273)^4]+f_{cl}h_c(t_{cl}-T_i)\}, \quad (1.5)$$

$$h_c = \begin{cases} 2.38|t_{cl} - T_i|^{0.25} & \text{for } 2.38|t_{cl} - T_i|^{0.25} > 12.1\sqrt{v_a} \\ 12.1\sqrt{v_a} & \text{for } 2.38|t_{cl} - T_i|^{0.25} < 12.1\sqrt{v_a}, \end{cases} \tag{1.6}$$

$$f_{cl} = \begin{cases} 1.00 + 1.290 I_{cl} & \text{for } I_{cl} \leq 0.078 \\ 1.00 + 0.645 I_{cl} & \text{for } I_{cl} > 0.078, \end{cases} \tag{1.7}$$

where M is the metabolic rate $[W/m^2]$, W is the effective mechanical power of the person $[W/m^2]$, I_{cl} is the clothing insulation $[m^2K/W]$, f_{cl} is the clothing surface area factor [-], P_a is the water vapour partial pressure $[kPa]$, h_c is the convective heat transfer coefficient $[w/(m^2K)]$ and t_{cl} is the clothing surface temperature $[°C]$.

The PMV should only be used when the result obtained are in the range from -3 to 3 and that the six main parameters are within the next values

- $46 < M < 232\ W/m^2$ $(0.8 < met < 4)$
- $0 < I_{cl} < 0.310\ m^2K/W$ $(0 < clo < 2)$
- $10 < T_i < 30\ °C$
- $10 < T_r < 40\ °C$
- $0 < v_a < 1\ m/s$
- $0 < P_a < 2700\ kPa$

The equation to calculate the predicted percentage dissatisfied (PPD) is

$$PPD = 100 - 95 exp^{-0.03353 PMV^4 - 0.2179 PMV^2}. \tag{1.8}$$

1.4.2 Adaptive methods

These methods are developed from surveys in field studies.

- Adaptive models for comfort temperature (T_{comf}): These models calculate T_{comf}, also known as neutral temperature, as a linear function of a given temperature. ASHRAE 55 (ANSI/ASHRAE, 2017) is considered to be a global adaptive model because the data used for this study is from 160 buildings across 4 continents. These models also consider a comfort range. The slope in the adaptive model represents the level of adaptability of the people that participated in the study. A high slope value means a higher adaptability, as can be seen in the study of Nicol and Humphreys (2010), whereas a low slope means lower adaptability as in CIBSE (2006).

Table 1.1 Linear equations to calculate the comfort temperature T_{comf}.

Reference	Equation	Temperature index
EN15251 (2007)	$T_{comf} = 0.33T_{rm} + 18.8$	Daily running mean outdoor temperature
Rijal et al. (2009)	$T_{comf} = 0.52T_{rm} + 15.4$	Daily running mean outdoor temperature
Manu et al. (2016)	$T_{comf} = 0.28T_{rm} + 17.8$	Daily running mean outdoor temperature
CIBSE (2006)	$T_{comf} = 0.09T_{rm} + 22.6$	Daily running mean outdoor temperature
ASHRAE (2013)	$T_{comf} = 0.31T_{om} + 17.8$	Monthly mean outdoor temperature
de Dear and Brager (1998)	$T_{comf} = 0.25ET_{om} + 18.9$	Monthly mean outdoor effective temperature
Nicol and Humphreys (2002)	$T_{comf} = 0.54T_{om} + 13.5$	Monthly mean outdoor temperature

- Humidex index Ontario (Masterton and Richardson, 1979): Expresses through a value the effect of air temperature and humidity in the thermal sensation of the people for summer conditions in a scale of 20 to 45.

- Humidex index Colima (Gómez-Azpetia et al., 2006): Humidex index adaptation for the people and conditions in Colima, Mexico, it extended its use for all year.

- PMV_e (Fanger and Toftum, 2002): The extended PMV is a modification of the original PMV. The PMV overestimates the thermal sensation vote of people in naturally ventilated buildings in warm conditions. The modification decreases the metabolic rate by 6.7% of the metabolic rate associated to the activity for each positive point in the original PMV. As well as, multiply the new PMV value by a factor e. The factor e can have values between 0.5 and 1, depending on the warm weather period and if the people is used to HVAC systems or not.

- aPMV (Yao et al., 2009): The adaptive PMV is another modification of the PMV due to its overestimation of thermal sensation vote in naturally ventilated buildings in warm conditions. This modification takes into consideration the adaptation of the people to the weather, it can be obtained as:

$$aPMV = \frac{PMV}{1 + \lambda PMV} \tag{1.9}$$

λ is an adaptive coefficient with different values depending on the climate. This value can be calculate through experimental measurements.

1.4.3 Other methods

These methods also help in the selection of strategies like ventilation, humidification or air-conditioning to reach thermal comfort.

- Olgyay bioclimatic chart (Olgyay, 1963): Is based on a bioclimatic chart that shows the comfort zone in relation with the outdoor air temperature (T_o), humidity, radiant mean temperature, wind velocity, solar radiation. The first step is to gather the weather data. The second step is to build the chart showing the annual weather data. The third step is to plot the data from temperature and humidity. The fourth step is to plan the design strategies as the orientation, localization, size, the localization of doors and windows, ventilation and shadings. The advantage of this method is that it can be used in the design stage of a building. The disadvantage is that the strategies proposed to achieve comfort are few and that it only takes into consideration the outdoor conditions.
- Givoni's method (Givoni, 1969): First a weather analysis is carried out with the most extreme conditions in the cold season and in the hot season. The outdoor air temperature, vapor pressure and wind velocity are considered. The criteria used is the thermal stress index in the occupants, this index can be measured with the loss of weight through evaporation (normally 40-60 g/h if the person is in comfort). If strategies, as natural ventilation and evaporative cooling, do not provide thermal comfort then the use of air-conditioning is required. A thermal stress index is developed, it includes all heat transfer mechanisms between the human body and the environment. The advantage of this method compared with the one proposed by Olgyay is that it provides more strategies to achieve thermal comfort. The disadvantage is that it can not be used in the design stage due to measurements needed for this method. This index is valid in the ranges:
  - $20 < Air\ temperature < 50°C$
  - $5 < Vapour\ pressure < 40$ mm Hg
  - $0.1 < v_a < 3.5\ m/s$
  - $100 < Metabolic\ rate < 600\ kcal/h$ assuming a person with a weight of 70 kg the range is $0.2 < Metabolicrate < 1.4\ met$
  - Clothing [-]: semi naked, light summer clothes, industrial clothes or military

1.5 Local thermal discomfort

The local thermal discomfort is considered when a person has an annoyance in a specific part of the body but in general is in thermal comfort. The most common phenomenon are: vertical air temperature difference, warm and cool floors, draught and radiant asymmetry, ISO 7730 (ISO, 2005a).

ISO 7730 (ISO, 2005a) includes equations to calculate the percentage of people in discomfort due to the most common phenomena of local thermal discomfort that can be draught, vertical air difference, warm and cool floors and radiant asymmetry.

1. Draught: refers to the excessive air movement that can be uncomfortable. This model predicts the draught to neck height and thus can overestimate the sensation for other parts of the body like arms and legs. The overestimation of the percentage in discomfort can also occur if the metabolic rate is higher than 1.2 met and if the thermal sensation of people is warmer than neutral.

$$DR = (34 - T_i)(v_a - 0.05)^{0.62}(0.37 v_a T_u + 3.14), \tag{1.10}$$

$$For \quad v_a < 0.05\, m/s: \quad use \quad v_a = 0.05\, m/s,$$

$$For \quad DR > 100\%: \quad use \quad DR = 100\%,$$

   where $20°C < T_i < 26°C$, $v_a < 0.5\ m/s$, T_u is the local turbulence intensity, in percent, 10% to 60% (if unknown, 40% may be used).

2. Vertical air difference: refers to difference of air temperature between feet and head that can be annoying.

$$PD = \frac{100}{1 + \exp(5.76 - 0.856\Delta T_v)}, \tag{1.11}$$

   where ΔT_v is the air temperature difference between head and feet in $°C$. This equation can only be used when $0°C < \Delta T_v < 8°C$.

3. Warm and cool floors: refers to the difference between the air temperature and the surface temperature from floors that can be uncomfortable.

$$PD = 100 - 94\exp(-1.387 + 0.118 T_f - 0.0025 T_f^2), \tag{1.12}$$

   where T_f is the floor temperature in $°C$.

4. Radiant asymmetry: refers to difference in the mean radiant temperature of roofs, windows and walls that can cause discomfort.

   - Warm roof
   $$PD = \frac{100}{1+\exp(2.84-0.174\Delta T_{pr})} - 5.5, \tag{1.13}$$
     this equation is valid when $\Delta T_{pr} < 23°C$.
   - Cold roof
   $$PD = \frac{100}{1+\exp(9.93-0.5\Delta T_{pr})}, \tag{1.14}$$
     this equation is valid when $\Delta T_{pr} < 15°C$.
   - Warm wall
   $$PD = \frac{100}{1+\exp(3.72-0.052\Delta T_{pr})} - 3.5, \tag{1.15}$$
     this equation is valid when $\Delta T_{pr} < 35°C$.
   - Cold wall
   $$PD = \frac{100}{1+\exp(6.61-0.345\Delta T_{pr})}, \tag{1.16}$$
     this equation is valid when $\Delta T_{pr} < 15°C$.

   where ΔT_{pr} is the radiant asymmetry in $[°C]$.

1.6 Acoustic comfort

Acoustic comfort can be defined as the acoustic conditions that makes the people not to worry about them. The sound is a small pressure fluctuation that propagates through the air as a longitudinal wave. As all waves, it can be described by its amplitude, propagation speed, frequency and wavelength. When the amplitude of the sound wave increases, the loudness at which it is heard by the human ear is increased. The sound pressure level (L_p) is a logarithmic approximation of the human ear's response to the pressure amplitude or to the sound intensity. The sound intensity is the power in a sound wave per unit area of the medium perpendicular to the source of the sound. The L_p can be calculated with the equation

$$L_p = 10log_{10}\left(\frac{I}{I_0}\right) = 10log_{10}\left(\frac{\rho^2}{\rho_0^2}\right)\ [dB], \tag{1.17}$$

where I is the intensity $[W/m^2]$, I_0=10^{-12} is the minimum hearing intensity for humans $[W/m^2]$, ρ is the sound pressure [Pa], and $\rho_0 = 2\times10^{-5}$ is the minimum hearing sound pressure [Pa].

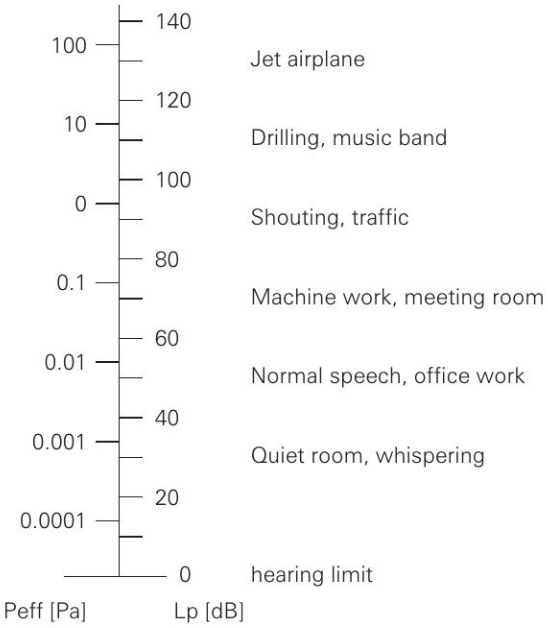

Figure 1.1 Typical sound pressure and sound pressure level produced by different sound sources.

The minimum level of hearing is 0 dB and the maximum level of hearing is 140 dB, which also is the pain limit. The frequency (f) of the wave gives the pitch of a sound. The human ear can perceive from 20 to 20,000 Hertz. The loudness level is a function of the frequency. A-, B- and C-weighted sound level filters are used in sound level meters to account for the loudness function in different sound conditions. The A-weighting is the most commonly used. Figure 1.1 show the typical sound pressure levels in dB (A) of different sound sources, (A) accounts for the A-weighting filter (Wagner et al., 2004).

Table 1.2 shows some of the sound pressure levels for different type spaces given by the Dutch standard NPR 3438 (NPR, 2007). It can be seen that the classrooms need a low sound pressure level since a higher level of concentration is required. For unoccupied classrooms the A-weighted sound pressure level should not exceed 35 dB (Acoustical Surfaces Inc., 2021).

Table 1.2 Optimal and maximum acceptable sound pressure level per type of activity (NPR, 2007).

Type of activity	Optimal sound pressure level [dB(A)]	Maximum acceptable sound pressure level [dB(A)]
Reception	55	65
Laboratory	45	55
Teaching/study	35	45

Other parameter important for acoustic comfort is the reverberation time. The reverberation time (T_r) is defined as the time it takes the sound level to decrease after the source of sound has been turned off. The reverberation time can be calculated as

$$T_r = \frac{V}{6A_s}[s], \tag{1.18}$$

where V is the volume of the space $[m^3]$ and A_s is the total absorption surface area in space $[m^2]$. The constant factor of 1/6 has units of s/m. The total absorption surface area is the sum of the product of the area of all objects in the room times its sound absorption coefficient, it can be calculated with the following equation

$$A_s = \sum_{i}^{N} \alpha_i A_i [m^2], \tag{1.19}$$

where A_i is the area of any surface in the room and α_i is the corresponding sound absorption coefficient of the material (Bluyssen, 2009) and N is the number of surfaces in the room.

Standards recommend to have at the mid-speech frequencies of 250, 500 and 1,000 Hertz a reverberation time up to 0.6 s for classrooms with a volume of approximately 300 m^3 and of up to 0.7 for classrooms with a volume of approximately 600 m^3 (Acoustical Surfaces Inc., 2021).

1.7 Visual comfort

Light is electromagnetic radiation, the human eye can perceive light with wavelengths between 380 nm and 760 nm, wavelength (or frequency) corresponds to the different colors.

The indoor lighting in buildings can be achieved by using artificial lighting or with daylight. The artificial lighting comes from bulbs, candles and lamps, while the daylight is provided by the sun and atmospheric light. The use of daylight is preferred to use than artificial light because it can be more comfortable for occupants (Bluyssen, 2009), not to mention the energy savings made. The new IER building, for which this work is made, is being designed to make the most of daylight. For this reason, this work addresses the variables that influence the lighting quality with daylight.

There are four physical variables that describe light and its effects. Luminous flux (ϕ), [lumen] is the amount of light per unit of time. The luminous intensity (I), [cd=lumen/steradian] measured the flux in a given direction. The luminance (L), [cd/m^2] indicates the lightness of an emitting surface for an observer (Serra, 1998). The illuminance (E), [lux=lumen/m^2] is the total luminous flux incident on a surface per unit area, illuminance is usually measured on working surfaces (Bluyssen, 2009).

NOM-025 (NOM, 2008) recommends a minimum illuminance of 300 lux in classrooms and 500 lux for drawing areas, computer labs and labs. Kellwood Lighting (2021) has gather information about illuminance needed by type of space from Chartered Institution of Building Services Engineers (CIBSE) and other sources, the recommendation is 300 lux for children's classrooms and 500 lux for adult classrooms, libraries, reading areas and auditoriums.

The distribution of luminance and that of illuminance are important for a good visibility. To measure the distribution, luminance and illuminance ratios are used. ANSI/IESNA RP-1-1993 (ANSI/IESNA, 1993) recommend that a luminance contrast ratio of 3:1 should be kept between the working area and its background. The NOM-025 NOM (2008) stated values for the illuminace contrast ratio between working area and its background, the ideal is 1:1 and the maximum acceptable is 3:1.

The glare is caused by high contrasts or irregular brightness luminance distribution and is a source of visual discomfort. Different metrics to predict the discomfort by glare are known, the most common ones are the Daylighting Glare Index (DGI) and Daylighting Glare Probability. The glare discomfort indexes can be calculated with the method described in Bellia et al. (2008), CLEAR (2021) and Radsite (2021).

The reflectance of surfaces also is important to the good quality of the visual environment. The reflectance is the ability of any surface to reflect the light. According to EN 12464–1 (CEN, 2002) the reflectance value should be for walls between 0.3 and 0.8 and for work surfaces between 0.2 and 0.6. In EN 12464-1 (CEN, 2002), ANSI/IESNA RP-1-1993 (ANSI/IESNA, 1993) and NOM-025 (NOM, 2008) measurement techniques and calculations for reflectance can be found.

Chapter 2

Comfort assessment in buildings background

The main considerations for comfort assessment are presented in this chapter. These include the considerations in the design and occupancy stages, and the recommendations made in the international standards.

2.1 Comfort assessment in the design stage

A thermal comfort assessment in the design stage can be made to evaluate the thermal comfort that passive and low energy consumption strategies proposed for a building can provide. Depending on the type of building, it is possible to use the PMV or some of the adaptive models mentioned in the previous chapter. This type of assessment is made performing building thermal simulations, these simulations will be addressed in the next chapter. The acoustic assessment at the design stage is commonly a qualitative analysis made to identify the places of the building where there is a higher probability to have noise problems and incorporate strategies to mitigate it. At this stage the acoustic assessment using software are made only for music halls or other buildings with special acoustic requirements. The available commercial software are Odeon (ODEON, 2021), EASE (AFMG, 2021) and CATT-acoustic (TUCT, 2021). A comfort visual assessment is possible as well through simulations in software like Radiance. The methodology followed and results for the new IER building can be consulted in the work by Betancourt García (2020).

2.2 Comfort assessment in the occupancy stage

Thermal, acoustic and visual comfort assessments are recommended to be made in the occupancy stage. ASHRAE 55 (ANSI/ASHRAE, 2017) provides the next guidelines for the comfort assessment in the occupancy stage. The occupants can point out any discomfort that they feel and that couldn't be predicted in the design stage comfort assessment. The surveys for the comfort assessment require two main parts: the experimental measurements of the physical variables that affect thermal, acoustic and visual environment and questionnaires to know the occupants opinion about the environment. These two parts are recommended to be made simultaneously to correlate the occupants opinion to the physical variables. If only one survey is possible throughout the day, it is recommended to conduct it at the time when the most discomfort is expected. In addition, observations can be made about the interaction of the occupants with the building to determine if their behaviour is affecting the predicted building's performance.

Surveys must be applied to mixed groups with different factors as age and gender to avoid biased results. If there are more than 45 occupants, the response percentage must be higher than 35%. If the number of occupants is between 20 and 45, at least 15 of them should answer the survey. For spaces with 20 or less occupants the response percentage must be of 80%. The surveys must be made in the spaces where each occupant spend most of their time. In the case there are similar spaces in the building, it is possible to select a space and evaluate it as a representative sample. If the distribution of the occupants cannot be observed or estimated, the measurements should be made at the center of the space. It is also recommended to take measurements in these spots: potentially occupied areas near windows, diffuser outlets, corners and entries. The measurement of T_i, H_r and v_a must be preferably made at ankle, waist and neck height. Standards mentioned that when the occupants are seated these heights are 0.1 m, 0.6 m and 1.1 m and when the occupants are standing these heights are 0.1 m, 1.1 m and 1.7 m. The period of measurement recommended is of 30 days or longer, for a minimum of two hours each day and the interval between measurements should not exceed 15 minutes.

To design the questionnaires the following must be taken into account: question specificity, language, clarity and leading questions. It is also important to avoid embarrassing questions, hypothetical questions and impersonal questions. Also, is important to avoid that the participants know their previous answers, their new answers can be affected because people tend to avoid extremes. As a recommendation, if the occupants of the building will be using the same questionnaires and scales multiple times, they should know so, to avoid undesired reactions.

In the case the building has an automation system (BAS), the temperature sensors should be protected from radiation and the accuracy should be $0.5°C$ or less. The relative humidity sensor should have an accuracy of $\pm 5\%$ ASHRAE 55 (ANSI/ASHRAE, 2017). In table 2.1 the recommended minimum precision of the instruments used for thermal comfort studies are presented.

Table 2.1 Recommended minimum precision of the instruments for thermal comfort studies.

Variable	Minimum precision	Reference	Recommended equipment
T_i	required: ±0.5°C, desirable: ±0.2°C	ISO (2012b)	see in ISO 7726
T_r	required: ±2°C, desirable: ±0.2°C	ISO (2012b)	see in ISO 7726
v_a	required: ±(0.05 +0.05 v_a) m/s, desirable: ±(0.02+0.07 v_a m/s	ISO (2012b)	hot-sphere anemometer y termistor
Absolute humidity	± 0.15 kPa this level should be guaranteed for $\lvert Tr - Ta \rvert <= 10C$	ISO (2012b)	psychrometer or lithium chloride hygrometer

2.3 Standards recommendations for surveys design

ISO 28802 (ISO, 2012a) and ISO 10551 (ISO, 2019) present recommendations of the questions that should be asked and the scales that are used to answer. Also, include recommendations on how each of the scales can be used to evaluate the thermal, visual, acoustic, air quality, vibration and other environments. They pointed the advantages of the subjective surveys, which are the simplicity to administer them and that are directly related to a psychological phenomenon. Also they pointed as disadvantage that there is no reason why a specific answer or response is provided.

If a person is conducting the survey, notes on the general impression of the environment, considering all the aspects that are contemplated in the survey like the thermal environment and local discomfort factors should be made. The strategies used for heating or cooling, are factors that can influence the behavior of the occupants and the adaptive actions. The acoustic environment should be noted, for instance, particular noises, their duration and their effect on the occupants activities. The visual environment must also be studied, for example, the lighting levels and their impact on occupants, particular sources of visual discomfort, all the sources of light and if they fit the particular needs of the occupants. The impression of the air quality and smells must be included in the observations. The inputs and outputs of air, the circulation patterns, stagnation regions and the type of ventilation system are also of interest. The pollution sources as well as their changes in any of the previous observations throughout the day and year should also be included. The tactile, aesthetics of the environment and the social interaction should also be taken into account because these can also influence the occupants' perception.

ISO 10551 (ISO, 2019) provides a guide on how to construct subjective scales. The main five types of scales can be divided into two categories, scales used for personal state and scales to describe the physical environment. The first three scales (perceptual, evaluative and perception) are for personal state and the last two (acceptability and satisfaction) are for the physical environment. The personal acceptability and the satisfaction scale give information of the opinion of the occupants about their surroundings. These two scales should always be applied after the three personal states. The main types of scales and the order they suggest to be applied in questionnaires are:

- Perceptual (How do you feel now?): this scale can be bipolar or unipolar. In the case of the unipolar scale a 4-degree scale that can be extended to 5 degrees is used. The point of origin is considered to be 0, the degrees of intensity are 1, 2, 3, (4).

  The bipolar scale is a 7-degree scale that can be extended to 9 degrees. The point of indifference is also 0 but this scale has a pole A and a pole B. The negative degrees of intensity are -1, -2, -3, -4 being -4 the one closest to pole A and -1 closest to 0. The positive degrees of intensity are 1, 2, 3, 4, being 4 the closest to pole B and 1 closest to 0. In both scales, 0 is the absence of sensation.

- Evaluative (How do you find it?): this scale is unipolar with 4 degrees that can be extended to 5 degrees. The 0 is comfort and the pole is extreme discomfort.
- Preference (How would you prefer to be?): has a bipolar scale with 7 degrees and is symmetrical. 0 is 'no change' preference.
- Acceptability
- Satisfaction

Table 2.2 shows a summary of the scales that are usually used in the surveys.

The different environments for which the surveys can be applied are listed below. The physical measurements and the scales used for each environment are included.

1. Measurement of the thermal environment: the physical variables to measure are T_i, T_r, v_a and humidity. To estimate the thermal sensation of people the physical variables are normally used along with estimates of the clothing insulation and the activity level of the people, which can be consulted in ISO 8996 (ISO, 2004) and ISO 9920 (ISO, 2007). For thermal environment the next scales are suggested in ISO 10551 (ISO, 2019):

   - Sensation scale. Question: Please rate on the following scale how you feel now. +3 hot, +2 warm, +1 slightly warm, 0 neutral, -1 slightly cool, -2 cool and -3

Table 2.2 Subjective scales used in the comfort surveys. The underline degrees are the ones most used in the literature, and they are used in the questionnaire proposed.

	1	2	3	4	5
Subject under judgement	Personal state			Physical environment	
Type of judgement	Perception	Evaluation	Preference	Personal acceptability	Personal satisfaction
Wording	"How do you feel (at this precise moment)?" 7 or 9 degrees	"Do you find it . . . ?" 4 or 5 degrees, from comfortable to very (or extremely), uncomfortable	"Please state how you would prefer to be now." 3 or 7 degrees	"How do you judge this environment on a personal level?" 2 degrees, generally acceptable, generally unacceptable	"In your opinion is the environment. . . ?" 5 degrees, from perfectly tolerable to intolerable

cold. It is preferable to use the conventional scales to compare with international standards and other studies. This question can be asked with only the numbers listed above or with a line giving the occupants the options to give a mark in between the rating given.

- Uncomfortable scale: 4 very uncomfortable, 3 uncomfortable, 2 slightly uncomfortable, 1 not uncomfortable.
- Preference scale. Question: please rate on the following scale how you would like to be now. 7 much warmer, 6 warmer, 5 slightly warmer, 4 no change, 3 slightly cooler, 2 cooler, 1 much cooler.
- Stickiness scale: 4 very sticky, 3 sticky, 2 slightly sticky, 1 not sticky.
- Draughtiness scale. 4 very draughty, 3 draughty, 2 slightly draughty, 1 not draughty.
- Dryness scale. 4 very dry, 3 dry, 2 slightly dry, 1 not dry.
- Satisfaction scale. Satisfied or not satisfied.
- Acceptability scale. Acceptable or nor acceptable.

2. Measurement of the acoustic environment: the physical variables must include the A-weighted sound pressure level. The instruments must be as specified in IEC 61672-1 (IEC, 2013). The evaluation method for occupants' sound exposure is specified in ISO 9612 (ISO, 2009). For the acoustic environment the next scales are used:

    - Annoyance scale: 4 very annoying, 3 annoying, 2 slightly annoying, 1 not annoying

- Preference scale. Question: Please rate on the following scale how you would like it to be now. 4 much quieter, 3 quieter, 2 slightly quieter, 1 no change.
- Acceptability scale: acceptable, no acceptable.
- Satisfaction scale: satisfied, not satisfied.
- Sources of noise. Question: Please indicate any sources of noise you can hear in your environment now.

3. Measurement of the visual environment: the physical variables should include the horizontal illuminance with the specifications in ISO/CIE 19476 (ISO/CIE, 2014). Measurements should be taken at different times of the day and year, different places in the room and when the occupants perform specific tasks. A general guidance in lighting in workplaces is in ISO 8995-1 (ISO, 2002). For visual environment the next scales are used:

   - Visual discomfort scale. Question: Please rate on the following scale your visual discomfort now. 4 much discomfort, 3 discomfort, 2 slight discomfort, 1 no discomfort.
   - Preference scale. Question: Please rate on the following scale how you would like your visual environment to be now. 7 much lighter, 6 lighter, 5 slightly lighter, 4 no change, 3 slightly darker, 2 darker, 1 much darker.
   - Acceptability scale: acceptable, no acceptable.
   - Satisfaction scale: satisfied, not satisfied.
   - Sources of glare. Question: Please indicate if you are experiencing any glare now.

4. Measurement of the air quality environment: the physical variables must include the level of CO_2. These measurements should be taken in the space and near doors and windows or any ventilation source, also throughout the day. In particular situations specific gases should also be measured like carbon monoxide, formaldehyde, particulates and other. For air quality environment the next scales are used:

   - Smelliness scale: 4 very smelly, 3 smelly, 2 slightly smelly, 1 not smelly.
   - Preference scale: more ventilated, no change, less ventilated.
   - Acceptability scale: acceptable, not acceptable.
   - Satisfaction scale: satisfied, not satisfied.

- Sources of smells. Question: Please indicate any sources of smell in your environment now.

5. Measurement of the vibration environment: the physical variables must include the acceleration in the vertical, horizontal and overall directions with respect to a person, sometimes also in roll, pitch and yaw. The instruments for the measurements are in ISO 8041 (ISO, 2005b). For vibration environment the next scales are used:

    - Uncomfortable scale: 6 extremely uncomfortable, 5 very uncomfortable, 4 uncomfortable, 3 fairly uncomfortable, 2 a little uncomfortable, 1 nor uncomfortable.
    - Annoyance scale: 4 very annoying, 3 annoying, 2 slightly annoying, 1 not annoying.
    - Acceptability scale: acceptable, not acceptable.
    - Satisfaction scale: satisfied, not satisfied.
    - Sources of vibration. Question: Please indicate any sources of vibration in your environment now.

Chapter 3

Comfort studies in Mexico

In Mexico the comfort studies are scarce and have been limited to thermal comfort studies. Acoustic nor visual comfort studies have been found in the literature. In this chapter six papers addressing thermal comfort methods are presented. Other studies of thermal comfort in Mexico were found such as Marincic et al. (2009), Griego et al. (2012) and Medrano-Gómez and Escobedo Izquierdo (2017) in which bioclimatic strategies are proposed to achieve thermal comfort.

Becerra-Santacruz and Lawrence (2016) aim to establish the thermal comfort boundaries of housing located in Morelia Michoacán, with temperate climate. They considered one study case over two seasons: cold season (from the 17th of December 2008 to the 27th of January 2009) and in warm season (from the 11th of May to the 21st of June 2009). The study case was a social house with different main facade orientations (north, east, south and west), three houses per orientation were analysed. T_i and H_r were measured at 1.8 m height in the living room and in one bedroom. Thermal sensation votes (TSV) of the occupants were obtained through a questionnaire with 440 responses. T_{comf} obtained for the cold season was 22.4°C and for the warm season was 24.8°C. The results obtained show that in cold season the houses can reach 68% of thermal acceptability and 33% in the warm season.

Oropeza-Perez et al. (2017) present adaptive thermal comfort models for four climate regions of Mexico, in cold and warm seasons, for air-conditioned houses that can be also naturally ventilated. They divided the country into four climatic regions: arid, dry, temperate and humid. The study is conducted in the 2015 Christmas vacations and in the 2016 summer vacations. 74 voluntary students of a university in Puebla were asked to answer the questionnaire while they were back to their houses in other states. For the test, they were asked to be dressed with 0.5 to 2 clo, to have activity with 1.0 to 1.5 met and being on a proper distance from radiative heat sources. A linear regression to obtain T_{comf}, merging data from air-conditioning and naturally ventilated condition, was made, for each region and each season. Results are shown in table 3.1.

Table 3.1 Adaptive comfort models for different climatic regions in Mexico.

MX-region-season	Adaptive comfort model
MX-arid-cold season	$T_{comf} = 0.48T_o + 13.9$
MX-arid-warm season	$T_{comf} = 0.59T_o + 9.6$
MX-dry tropic-cold season	$T_{comf} = 0.84T_o + 5.3$
MX-dry topic- warm season	$T_{comf} = 0.96T_o - 3.6$
MX-temperate-cold season	$T_{comf} = 0.27T_o + 17.9$
MX-temperate-warm season	$T_{comf} = 0.53T_o + 10.3$
MX-humid tropic-cold season	$T_{comf} = 0.38T_o + 15.7$
MX-humid tropic-warm season	$T_{comf} = 0.47T_o + 9.07$

López-Pérez et al. (2019) made a study in Tuxtla Gutiérrez Chiapas, with hot semi-humid climate, in buildings of the National Institute of Technology of Mexico. The field data were recorded between the 27th of February to 31st of May 2017 in working days from 10:00-18:00. The physical variables measured were T_i, T_g, H_r and v_a. The study was made with 496 occupants, 335 men and 139 women, in air-conditioned buildings and naturally ventilated buildings. The occupants were asked about their TSV through a thermal comfort questionnaire. They reported a linear regression of the TSV as a function of T_{op} expressed in °C, for air-conditioned buildings

$$TSV = 0.405T_{op} - 10.64 \tag{3.1}$$

and for naturally ventilated buildings

$$TSV = 0.324T_{op} - 8.30 \tag{3.2}$$

T_{comf} for air-conditioned buildings was of 26.4°C and for naturally ventilated buildings was of 25.6°C. A linear regression for the comfort temperature as a function of the outdoor running mean temperature (T_{rm}), both given in °C, was made. The result equation for air-conditioned buildings was

$$T_{comf} = 0.13T_{rm} + 22.7 \tag{3.3}$$

and for naturally ventilated buildings was

$$T_{comf} = 0.32T_{rm} + 18.45 \tag{3.4}$$

Rincón-Martínez et al. (2019) present a thermal comfort study for Pachuca, Hidalgo, with semicold dry climate. Physical data were obtained for cold and warm seasons. These conditions were recreated in a test cell of the Autonomous Metropolitan University (UAM) Iztapalapa. The study was made with undergraduate students from 15 to 24 years old with a sedentary activity of 1.2 met and clothing level of 1 clo, who are used to naturally ventilated buildings. The data correlation was made with 917 observations. The results show that the values obtained from the field studies previously made and the test cell studies are close in T_{comf} but have a difference in the comfort range.

Rincón-Martínez et al. (2020) made a study in Ensenada, Baja California, with temperate dry climate, in naturally ventilated buildings of the Autonomous University of Baja California. The study was conducted from the 20th of October to the 24th of November 2016. Students were ask to respond a questionnaire, 818 answered questionnaires were obtained. The physical variables measured were T_i, H_r and v_a at 0.1, 0.6, and 1.1 m height in classrooms and 0.1, 0.85, and 1,4 m height in laboratories and workshops. A linear regression was made with TSV as a function of T_i. The results gave T_{comf}=23.7°C and an adaptive comfort model of $T_{comf} = 0.61T_i - 9.78$.

Cetz and Azpeitia (2018) present a thermal comfort study for Merida, Yucatan, with a hot semi-humid climate, in a school for naturally ventilated spaces as well as air-conditioning spaces. The study was conducted in two periods, from March to May and from September to November, in which 3,369 data sets were obtained. The physical variables measured were T_i, T_g, H_r, v_a and CO_2 levels at a heigh of 0.6 m in the central corridor of the classrooms. A linear regression was made for both type of spaces, naturally ventilated and air-conditioning. The results have a $T_{comf} = 0.79T_o$+6.58 for naturally ventilated spaces and $T_{comf} = 0.026 + 27.61$ for air-condioning spaces.

Chapter 4

Comfort assessment by thermal simulations of non-air conditioning buildings

In this chapter a methodology for the validation of thermal simulations of non-air conditioning buildings is presented. Brief introductions to the importance of building thermal simulation validation and the thermal comfort method used for this work are given. The methodology proposed is presented in an article published in the Journal of Building Engineering. The final draft is included here.

The accuracy of the thermal simulations is key to improve the energy efficiency in buildings. The validation of building thermal simulations can help to understand the thermal behaviour of buildings and how the interaction with the occupants can improve or worsen the thermal performance. Moreover, the validation can be useful in the design stage of buildings to make sure the strategies used are adequate to ensure thermal comfort to the occupants. Eventually after the validation, strategies can be used to improve and propose refurbishments in the occupancy stage to enhance the thermal comfort of occupants.

In this study the ePMV is used as a method to predict and compare the impact of different strategies in the thermal comfort. The ePMV method proposed by Fanger and Toftum (2002) is selected because it was developed for naturally ventilated buildings in warm climates. This method use an adaptive coefficient (e) related to how accustomed occupants are to air conditioned spaces. The aPMV method (Yao et al., 2009), also developed for naturally ventilated buildings for warm climates has the disadvantage that it requires a field study to determine the value of the coefficient, that is the reason it has not been used for this study.

4.1 Validation of thermal simulations of non-air conditioning buildings

Validation of thermal simulations of a non-air-conditioned office building in different seasonal, occupancy and ventilation conditions

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Abstract

In this work, a methodology for the validation of non-air-conditioned building thermal simulations is proposed. Having certainty in these simulations can give confidence to building designers on the possibility to avoid the use of mechanical air-conditioned systems or to reduce the period of their use, thus increasing the building's energy efficiency. The main features of the proposed methodology that differentiate it from the previous ones are: i) the separation of data inputs which values are known with uncertainty into those that have more influence on indoor air temperature and those with more impact on surface temperatures; ii) to carry out the calibration process in two stages having as comparison variables indoor air temperature in the first stage and adding surface temperatures in the second stage; and iii) to carry out the validation process in different seasonal, occupancy and ventilation conditions. The case study is an office building, simulations are performed in EnergyPlus employing the Airflow Network model for infiltration and ventilation. Quantitative comparisons are made using eight metrics. The results show the advantages of carrying out the second stage of validation proposed in this work. The validation results show that the building model obtained from the calibration process is suitable to simulate the building in different seasonal, occupancy and ventilation conditions, and can be used with certainty to test strategies to improve thermal comfort in the building. For the case study, two strategies are tested showing important reductions in thermal discomfort on occupancy hours during the critical hot season.

Keywords: Building thermal simulation; non-air-conditioned; validation; calibration; EnergyPlus; experimental data

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Nomenclature

AE	Absolute error [%]
ACH	Air changes per hour [1/h]
b	Intercept [°C]
CVRMSE	Coefficient of variation of the root mean square error [%]
DE	Defect error [%]
Δdf	Difference between simulated and experimental decrement factor [-]
Δlg	Difference between simulated and experimental lag time [h]
ΔT_{max}	Average of the difference between simulated and experimental daily maximum temperature [°C]
ΔT_{mean}	Average of the difference between simulated and experimental daily mean temperature [°C]
ΔT_{min}	Average of the difference between simulated and experimental daily minimum temperature [°C]
EE	Excess error [%]
GOF	Goodness of fit [-]
m	Slope [-]
MBE	Mean bias error [°C]
ME	Mean error [%]
NMBE	Normalised mean bias error [%]
r	Pearson's index [-]
RMSE	Root mean square error [°C]
R^2	Correlation coefficient [-]
T_i	Indoor air temperature [°C]
$\overline{T_i}$	Time average of T_i [°C]
T_{si}	Inside surface temperature [°C]
T_{si_s}	Inside surface temperature of the South wall [°C]
T_{si_w}	Inside surface temperature of the West wall [°C]
T_{si_r}	Inside surface temperature of the roof wall [°C]
T_{so}	Outside surface temperature [°C]
T_{so_s}	Outside surface temperature of the South wall [°C]
TE	Total error [%]
$_{exp}$	Subindex indicating quantity from experiments
$_{sim}$	Subindex indicating quantity from simulations

Acronyms

AFN	Airflow Network model
PMVe	Extended Predicted Mean Value
NO	Unoccupied
O	Occupied

1. Introduction

About 30% of total worldwide energy consumption and carbon emissions into the atmosphere correspond to the building sector [1]. Thus, it is of great importance to reduce the energy consumed by buildings.

1.1. Bulding's thermal and energy modeling and simulation

The modeling and simulation of building's thermal and energy performance is an important element in the design of energy efficient buildings. Three reviews of building modeling and energy performance prediction were recently published [2, 3, 4]. In [2], the modeling types are classified into physical models, statistical methods and hybrid models. The physical models are divided in turn into computational fluid mechanics (CFD) approach, zonal approach and multizone or nodal approach; the fundamentals, advantages, application area and limitations for each one were presented in the review. In [3], the classification is similar but employs different names: forward approach, data driven approach and gray box approach. In [4], the focus is on the zonal modeling for large space buildings. In the multizone or nodal approach each building zone is considered a homogeneous volume characterized by uniform state variables and is approximated to a node, which generally represents a room [2]. This approach is useful to simulate buildings with many rooms. It is used to identify new strategies to improve energy efficiency in new or existing buildings. EnergyPlus is one of the most popular softwares using the nodal approach and is likewise an open source software. It is comprised by a collection of many program modules that take into account weather, thermal and mass loads in spaces, heat transfer through walls, roofs, floors and windows and also accounts for heat and mass transfer into buildings due to infiltration and ventilation [5].

1.2. Validation of thermal and energy building simulations

The validation of thermal and energy building simulations of existing buildings with their corresponding experimental measurements are undertaken so as to have reliable identification of energy savings or thermal comfort measures in an existing building and also to improve simulation skills of personnel with the aim of increasing the confidence in building simulations during the design stage of new buildings.

A literature review on calibration of building energy simulation programs was published in 2005 [6]. In this review, the uses, problems, procedures, uncertainty and tools of the calibration of building energy simulation programs were addressed, only air-conditioned building were considered. Most of the studies analyzed model errors using monthly data. Particular attention was paid to the calibration of the program DOE-2, which is the precursor of EnergyPlus. Raftery et al. [7] reported a review of case studies and methods for calibrating building energy models with measured data. They proposed an evidence-based methodology for the calibration of air-conditioned buildings using hourly data. Pernetti et al. [8] gave guidelines for the calibration of building simulations with the aim to reduce the discrepancies between simulated and actual building energy behavior. In these guidelines, the validation process consists of the calibration of the building model divided into five steps, and the validation over a different time period. The five steps are: 1) definition of the aim and the validation criteria; 2) general data gathering and base model definition; 3) sensitivity analysis; 4) second data gathering campaign and simulations runs; and 5) calibration criteria. Detailed information is given concerning the five steps of calibration using either one of two study cases, a non-air-conditioned historical building that was unoccupied and without internal heat gains, and an occupied air-conditioned house. In the case of the non-air-conditioned building, one space was instrumented with air temperature and surface temperature sensors and was used as the control thermal zone. Comparisons between simulated and measured temperatures were made qualitatively and quantitatively, the latter employing three metrics. Results for the final building model are within the following ranges for both the indoor air and the surface temperatures: 0.5 to 1.0 °C for the mean bias error (MBE), 0.9 to 1.0 °C for the root mean square error (RMSE) and 0.99 to 1.00 for Pearson's index (r). The simulations were made using TRNSYS.

1.3. Comparison of EnergyPlus results with experimental results

EnergyPlus is being constantly used by both professionals and researchers. Nearly 2,000 scientific articles can be found that report the use of this program. However, there are only eight articles that report on the comparison of EnergyPlus simulated results with experimental results, most of which are focused on a specific problem and do not report the validation process. All of these articles include a description of the studied building, information of the measured weather variables as well as the variables used for the comparison between simulations and measurements. A brief description of the building and the main results of the comparison between simulations and measurements are presented for each case.

Sang et al. [9] studied a full-scale non-air-conditioned test room which included a wall with a phase change material. The comparison variables were T_i and T_{si}. A qualitative comparison of T_{si} for the four walls was made by plotting each during one full day.

Raftery et al. [10] studied the effect of vertical greenery systems (VGS) on the building's thermal performance. The comparison variables were T_i, T_{so} and T_{si}. The cases of study were: A) a test cell with a VGS on the west wall and B) two residential flats on a thirty-three story building, one with VGS and the second without VGS. R^2, the cosine and the norm were used as metrics for the comparison between simulations and measurements. The norm is zero and the cosine is one for a perfect agreement. The metric results for T_i are: R^2 equals 0.97 and 0.81, in the case A) and B), respectively. The norm was between 0.02 and 0.09 and the cosine from 0.60 to 0.95, for both cases.

Andelković et al. [11] modeled a double skin façade (DSF) of a five story air-conditioned building. The variables compared were: indoor air temperature (T_i), inside surface temperature (T_{si}), outside surface temperature (T_{so}), and air velocity in the DSF. The metric results for T_i were: $R^2 = 0.93$, MBE=-2.25 °C, RMSE=2.58 °C, the coefficient of variation of the root mean square error CVRMSE=12.29%, ΔT_{imax}=5.54 °C and ΔT_{imin}=0.01 °C.

Simá et al. [12] studied the shading effect of both a tree and neighboring buildings on the thermal performance of a closed and unoccupied house. Simulations on the shading effect with and without the tree were carried out and validated with the experimental measurements. The variables of comparison were T_i, T_{si} and T_{so} of one thermal zone. The metrics were the differences of decrement factor (Δdf), lag time (Δlg) and discomfort hours.

Yang et al. [13] evaluated three different heat balance algorithms: conduction transfer functions, combined heat and moisture transfer model and effective moisture penetration depth. A full-scale air-conditioned test room with 2 occupants was used. Three different climates were simulated: hot humid, temperate and hot dry. T_i simulated and T_i measured were qualitatively compared by plotting them.

Barrios et al. [14] validated the equivalent-homogeneous-layers-set method (EHLS) implemented into EnergyPlus. The validation was made for a full-scale test room. Maximum differences are ΔT_{imax}= -0.9 °C, Δdf=0.1 and Δlg=1.9 h.

Barbaresi et al. [15] studied an air-conditioned wine storage building. Two models were simulated: A) considering a single thermal zone and B) considering two thermal zones. The comparison variable was T_i and the metrics were r, slope (m), and intercept (b) of the linear regression, mean error (ME), RMSE, total error (TE), excess error (EE), defect error (DE), and absolute error (AE). The results for model A were: r=0.994, m=1.013, b=-0.5 °C and RMSE=0.705 °C. The results for model B were: r=0.994, m=0.994, b= -0.1 °C and RMSE=0.684 °C. As expected the results obtained in the simulation with two thermal zones were more accurate.

Belleri et al. [16] described an analysis of the predicted and measured ventilation performance of an non-air-conditioned office in California, using the air changes per hour (ACH) as a comparison variable. At first the office was modeled as if it had not yet been constructed, considering values for some input variables derived from the literature. Wind-pressure coefficients were measured in wind-tunnel experiments. Measurements of T_i, and the window opening factors of the windows and doors were conducted in the office. The model was incrementally improved by changing the following parameters: alignment of T_i to the measured value by adjusting the heating and cooling set-points of an EnergyPlus ideal air-conditioning system; window control from the ASHRAE-55-Adaptive to the Temperature method; weather data frequency from 1 hour to 5 minutes; window control as measured; and wind-pressure coefficients from measurements. The authors pointed out that the process highlighted the limitations of the occupant-driven window control models of EnergyPlus.

Raftery et al. [17] described the calibration process of an air-conditioned office building using the method proposed in [7]. The metrics for the comparison were the MBE and CVRMSE for the HVAC electric consumption. The results for the final model were: MBE=4.1% and CVRMSE=7.8%.

Coakley et al. [18] described the simulation calibration process of a library building with mixed-mode ventilation. The input data was divided into different classes each with a different range of variation (0 to 50%) as related to the certainty of the data. One hundred simulations with random input data were performed. The metrics for the comparison were the normalized mean bias error (NMBE), CVRMSE and goodness of fit (GOF), for electric energy consumption and for T_i. They compared metrics derived from monthly and hourly data, pointing out that monthly data masks model discrepancies.

1.4. Simulations for non-air conditioned office buildings

In Mexico there are regions of the country where designing buildings with a bioclimatic approach, which includes the use of natural ventilation, can provide thermal comfort to its occupants without the use of air-conditioning systems. Nevertheless, the use of air-conditioning is increasing specially the case of office buildings. Accurate thermal building simulations of non-air-conditioned buildings can give confidence to building designers on the possibility to avoid the use of mechanical air-conditioned systems or to likewise help reduce their time of usage, increasing the building's overall energy efficiency.

EnergyPlus simulations have been used to study the thermal performance of non-air-conditioned office buildings. Some examples of these studies are: the evaluation of different ventilation strategies for space cooling, where EnergyPlus simulations were complemented with computational fluid dynamics (CFD) simulations [19]; the impact of climate change on thermal comfort [20]; the impact of outdoor airborne particulate matter with an aerodynamic diameter below 2.5 μm (PM2.5) on natural ventilation usability in California [21]; and the suitability of phase change materials coupled with night ventilation in Western China [22].

1.5. Scope of the present work

In summary, previous building model validation studies were mainly focused on air-conditioned buildings. Only two works were found that reported the calibration process in non-air conditioned buildings. The first one employed, as example for some steps, a closed unoccupied building without internal heat gains. For this example, results of the calibration period are shown, but non are presented for the validation period [8]. The second work carried out the entire calibration process for a naturally ventilated occupied building, but the final simulation model included a fictitious air-conditioned system to match T_i with the aim of improving the simulation prediction of ACH [16]. Among the studies that reported quantitative comparisons between simulated and measured values of T_i, range of the metrics or value (when only one work reported a metric) for the acceptance of simulation results are: for ΔT_{imax} and ΔT_{imin} 0.0 to 5.5 °C; for RMSE 0.7 to 2.6 °C; for m 1.0; for b 0.0 to 0.1 °C; for R^2 0.81 to 0.97 and for r 0.99 to 1.00.

The aim of the present work is to propose a methodology for the validation of thermal simulations of occupied and naturally ventilated non-air-conditioned buildings and to present results of the validation of a study case using eight metrics of T_i. The methodology consists of the calibration process and the validation process. The later is performed in different seasonal, occupancy and ventilation conditions. The calibration process is divided into six steps: 1) definition of the comparison variables; 2) data gathering; 3) base building model definition (divide model inputs and control variables); 4) sensitivity analysis of the control variables on T_i and on T_{si} and T_{so} (definition of control variables for first and second stages); 5) first stage of the calibration - T_i as comparison variable; and 6) second stage of the calibration - T_{si} and T_{so} as comparison variables. The study case is an office building built in Temixco, Morelos, Mexico, a hot climate region. Additionally, the building validated model is used to evaluate two strategies so as to improve thermal comfort in the building.

The paper is organized as follows. The building used as study case is described in section 2. Section 3 presents the experimental measurements. Section 4 describes the methodology of the building thermal simulations calibration. Section 5 presents the comparison between simulated and experimental results for five periods. The evaluation of the strategies to improve thermal comfort is show in section 6. The conclusions are given in section 7.

2. Building description

The building used as study case is a five story building located in Temixco, Morelos, Mexico. It is used by postgraduate students, postdoctoral researchers and administrative staff. For this study, only the two upper levels were simulated, these two stories will be called the simulated building. The building has a rectangular base with large façades oriented to the North and South with a 6.8 ° angle facing towards the Northeast and Southwest (Figure 1(a)). Initially the simulated building was considered to be at ground level with a wind speed profile correction to equal the wind speed at the height of the simulated building. However, the view factors with ground, air and sky for radiative heat exchange are not the same at ground level than at an 18 m height, which is the height of the base of the simulated building. The simulations here reported are made considering the simulated building at the real height and using an adiabatic condition at the simulated building floor.

The two simulated levels are occupied by offices and are connected by a central space, which has its roof at a higher level than the roof on the offices at the second level, with natural ventilation being produced by wind and thermal effects. The openings are comprised by the main door in the first level, the vents located between the roof of the second level offices and the roof of the central space, as well as all office windows and doors. The simulated building has vertical solar protections on the North and South façades, the solar protections are two stories tall, covering the height of the simulated building. The solar protections on the South façade (Figure 1(b)) are equally spaced at 60 cm from each other. On the North façade the separation of solar protections varies, being that of 60 cm on the corners of the building, increasing towards the center (Figure 1(c)).

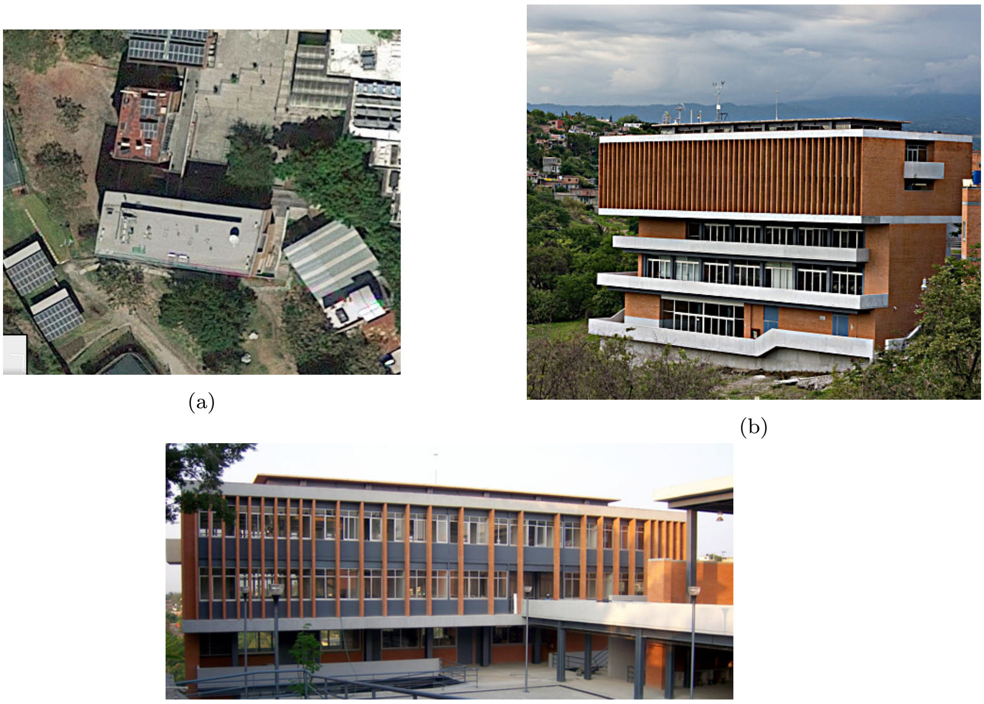
For the validation, the Coordination Office, located on the Southwest corner of the second level is used as the control thermal zone, thus all measurements were performed in this space. The high temperature caused by the Coordination Office's orientation is the main reason why this space was selected.

3. Experimental measurements

The variables measured to create annual weather files (epw) are: direct and diffuse solar radiation, outdoor air temperature and relative humidity, atmospheric pressure, wind speed and wind direction. The outdoor variables were measured during 2018 and 2019. The indoor air temperature (T_i) was measured during different periods of October and December of 2018, as well as February, April and May of 2019. Inside surface temperature (T_{si}) and outside surface temperature (T_{so}) were measured only during the period of April, 2019.

The weather data were taken from a weather station at a 10 m height from the roof of a next building, except for the diffuse solar radiation which was taken from the weather station at a 3 m height from the roof of the simulated building. Both weather stations were at a 33 m height from the ground of the studied building. The weather variables, equipment and their uncertainty are shown in Table 1.

T_i was measured in the center of the room at a 0.9 m height. T_{si} was measured for three surfaces, the roof, and the South and East walls. T_{so} was only measured for one surface, the South wall. All T_{si} and T_{so} measurement were taken from the center



(a)

(b)

(c)

Figure 1: Views of the building. (a) Aerial view, (b) view of the South façade and (c) view of the North façade.

of the surface. The instrument used for the measurement of T_i was a heat stress monitor QUESTemp, with an uncertainty of ±0.5 °C. Thermocouples type T wre used for the measurements of T_{si} and T_{so}, with an uncertainty of ±0.3 °C. Weather and temperature measurements were carried out every minute and the average values during 10 minutes were used to generate the epw files and to compare results.

Table 1: Equipment and uncertainty for each weather variable.

Variable	Equipment	Uncertainty
Beam radiation	Pyrheliometer EKO MS-56/ISO 9060 first class	$< 1W/m^2$
Diffuse radiation	Pyranometer Kipp & Zonen CMP11/Iso 9060 class A	$< 10W/m^2$
Wind speed	Wind sonic anemometer Gill instrument option 4	±2% (at 12m/s)
Wind direction	Wind sonic anemometer Gill instrument option 4	±3 ° (at 20m/s)
Temperature	1000 Ω PRT IEC 75 1/3 class B	$\pm 0.3\ ^\circ C$
Humidity	HMP45C HUMICAP 180	±3% $(10-90\%)$ and ±6% $(90-100\%)$

4. Calibration of the building's thermal simulations

In this work, a methodology for the validation of thermal simulations of non-air-conditioned buildings is proposed. The validation methodology consists of a calibration process and a validation process, a flow chart is presented in Figure 2. Simulations were performed using EnergyPlus 9.1.0.

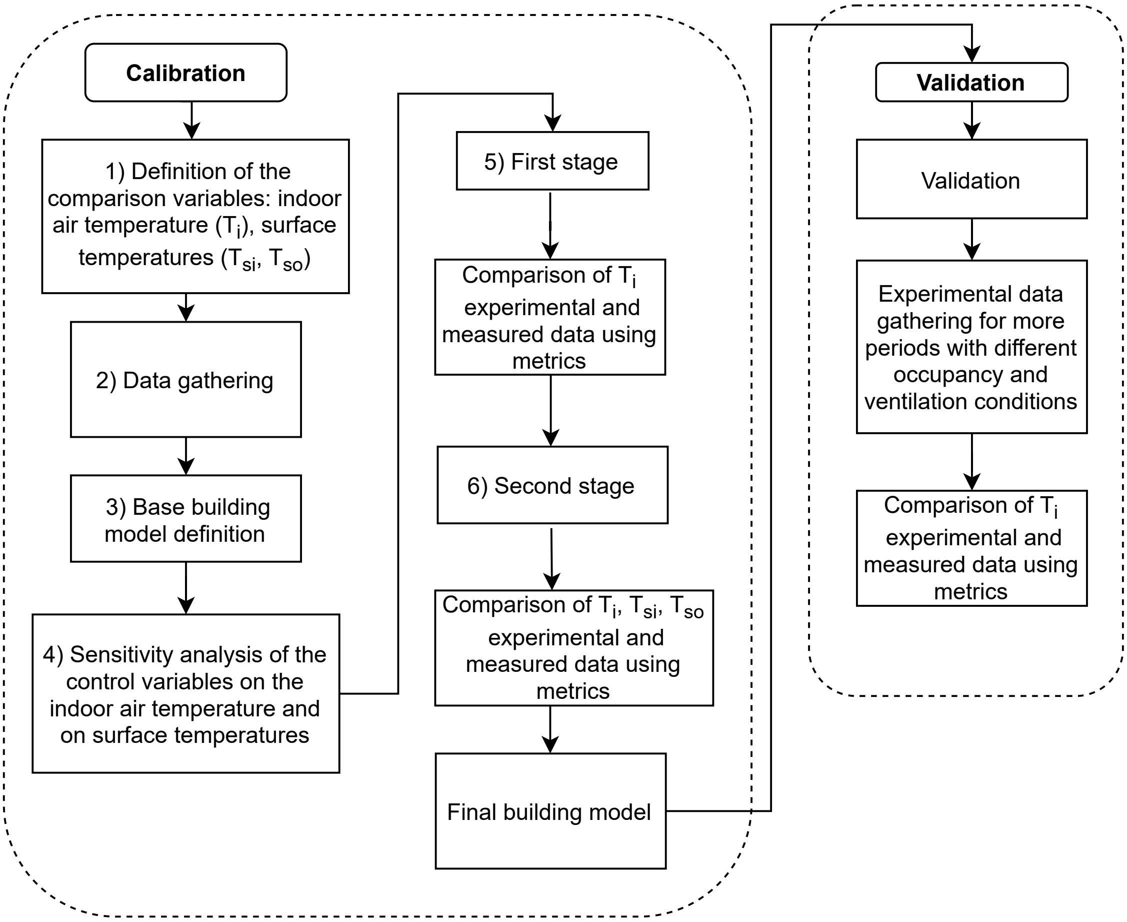


Figure 2: Flowchart of calibration and validation processes.

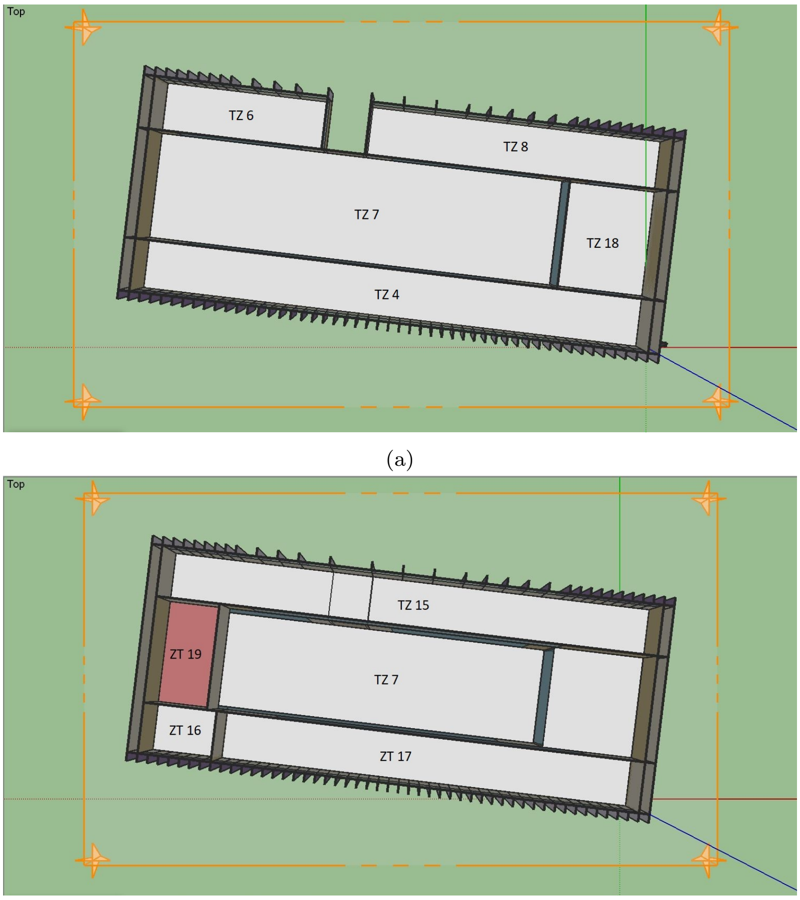
The calibration process was divided into six steps:

Step 1) Definition of the comparison variables. The selected comparison variables are T_i, T_{si} and T_{so}.

Step 2) Data gathering. Weather and control zone temperature data were taken as described in Section 3. The geometry and dimensions of the building and the construction properties of floors, walls and roofs were taken from the building's plans. The thermal properties of each material were taken from Ener-Habitat [23] and OpenStudio [24], their values are within the range given by [25]. Table 2 shows the construction properties used for the base building model. The walls are classified both into envelope and internal walls. There were three types of internal walls: A) separates a thermal zone from the central thermal zone, B) separates the meeting room (thermal zone 19) from other thermal zones, and C) are within a given thermal zone (see Figure 3). Occupancy and all window and door openings in the Coordination Office were registered in a logbook. A building occupants survey was made to set the occupancy and openings schedules. An audit of the use of lamps and electric equipment was made. Likewise, an audit of the furniture and internal partitions inside each thermal zone was carried out.

Table 2: Properties of the simulated building constructions. Layers are listed from the outside to inside of the construction. Values of thickness and properties changed in the second stage of the calibration process are in parenthesis. These values are used in the final building model.

Element	Construction	Layer material	Thickness [cm]	Thermal conductivity [W/m K]	Density [kg/m^3]	Specific heat [J/ kg K]	Reference
Floors	Floor	High density concrete	13.0	1.35	1800	1000	[26]
Walls	Envelope North/South	High density concrete	8.0	1.35 (2.00)	1800 (2400)	1000	[26]
	Envelope East/West	Hollow brick	12.0	0.70	1970	600	[26]
	Internal type A	Aluminum	7.0	160.00	2700	1213	[27]
	Internal type B	Hollow brick	12.0	0.70	1970	600	[26]
	Internal type C	Gypsum	1.9	0.16	785	830	[27]
		Air	0.3	0.02	-	-	[28]
		Gypsum	1.9	0.16	785	830	[27]
Roofs	First level	High density concrete	24.0	1.35	1800	1000	[26]
	Second level	High density concrete	4.0	1.35	1800	1000	[26]
		Tezontle	15.0 (9.0)	0.16 (0.50)	400 (720)	1000	[29, 30]
		High density concrete	8.0	1.35	1800	1000	[26]



(a)

(b)

Figure 3: Plan views from SketchUp divided by thermal zones. (a) First level and (b) second level.

Step 3) Base building model definition. According to the uncertainty of the gathered data, the input data were divided into model inputs and control variables. The control variables were the ones with larger uncertainty and were varied in the sensitivity analysis.

The considerations made for the base building model were the following: the simulated building was divided into nine thermal zones, shown in Figure 3. There were four thermal zones in the first level, four thermal zones in the second level (TZ 16 corresponds to the Coordination Office) and one double height thermal zone in the center of the simulated building (TZ 7). The wind speed profile characteristics were the same for the weather station as for the building, corresponding to urban terrain. Natural ventilation and infiltration were simulated using the Airflow Network model (AFN) from EnergyPlus. Openings schedule, wind pressure coefficients and discharge coefficients were considered as model inputs. Openings schedule were taken from the survey. Wind pressure coefficients were taken from the program calculations. Because they were large openings the discharge coefficient was set at 0.6 for all openings in the detailed opening component [31, 32]. Internal loads produced by lights were considered as model inputs. They were calculated taking into account the power consumption of each type of lamp and the number of lamps in each space. Internal loads by electrical equipment were also considered model inputs, and were estimated taking into account that on average, the administrative staff and professors each used a PC with a power consumption of 300 W, and that each student used a laptop with a consumption of 70 W. An extra 10% in the amount of power was added to take into account cellphones and other electrical equipment not previously taken into consideration. A fraction of the internal loads generated by both lights and electrical equipment were considered in the schedule for weekdays and weekends according to user information. The activity level of all occupants was set to 120 W with a 0.3 radiant fraction and a 0.7 sensible fraction. The internal mass was considered a model input calculated considering the furniture and internal partitions inside each thermal zone. For the occupancy condition setting, the simulated building was divided into two: the Coordination Office and the rest of the simulated building. The Coordination Office was unoccupied and all openings were closed. The weekday schedules for occupancy and all window and door openings for natural ventilation in the rest of the simulated building were considered from 07:00 to 21:00, with different percentages of maximum office occupancy during these hours, which remained the same during the five weekdays and form month to month, according to the survey data. During weekends, the building was unoccupied and windows and doors remained closed.

The infiltration in the building was an unknown data. Although the number of occupants for the rest of the offices was known from the survey carried out for this study, there were other people who entered the building during short periods of time. This number was an unknown data, and it was considered to be a percentage of all occupants. Thus, infiltration and internal loads by people who entered the building during short periods were used as control variables.

The West and East walls were double walls, each of them constructed with hollow bricks and separated by 60 cm. The air gap was simulated as a thermal zone and each brick wall was simulated with the EHLS method proposed in [14].

Among all construction properties the ones that showed the largest uncertainty were: the roughness of all walls and roofs, the thermal conductivity and density of the South and North walls, as well as the thermal conductivity, density and thickness of a layer on the second level roof. This layer was used as lightweight aggregate with variable thickness to form a slope for rain drainage. In the simulations the thickness of this layer, made of tezontle, was considered the same for the entire building. All former variables were considered as control variables. The properties of the materials were varied within the ranges given by [25], and the thickness of the tezontle layer was varied within the range given in the architectural plans.

Step 4) Sensitivity analysis. A sensitivity analysis of the control variables on T_i and on T_{si} and T_{so} was undertaken to define the control variables for the first and second stages. The sensitivity analysis was made by varying the control variables within their uncertainty range, during a given time period in October. The results showed that the infiltration and the internal loads by people who entered the building during short periods were the variables with the most impact on T_i, while the construction properties mainly affected T_{si} and T_{so}.

Step 5) First stage of calibration. In this stage, T_i was used as a comparison variable and the infiltration and internal loads by people were used as control variables. The infiltration mainly impacted the amplitude of T_i, while the internal loads by people mainly affected the average of T_i. The values of infiltration and internal loads by people who entered the building during short periods that reduce the metrics of T_i were used as model inputs in the second stage.

Step 6) Second stage of calibration. In this stage, T_{si}, T_{so}, as well as T_i, were used as comparison variables. The control variables for this stage were the roughness, thermal conductivity and density of the South and North walls to match T_{si} and T_{so} for the South wall; the roughness of the West wall to match this wall T_{si}; the roughness of the outside layer and the thermal conductivity, density and thickness of the roof tezontle layer to match T_{si} of the roof. The values for these construction properties that enhanced the metrics for the comparison variables were used for the final building model employed in the validation process.

Eight metrics were used for the comparison between simulations and experimental results in the two calibration stages and the validation process: the average of the difference between simulated and experimental daily maximum temperature (ΔT_{max}); the average of the difference between simulated and experimental daily minimum temperature (ΔT_{min}); the average of the difference between simulated and experimental daily mean temperature (ΔT_{mean}); the root mean square error (RMSE) that provides the average of the absolute value of the difference between simulated and experimental temperature at each time-step; the slope (m), the intercept (b) and the correlation coefficient (R^2) of the linear fit of the simulated temperature as a function of the experimental temperature, both temperatures minus the experimental mean value; and the Pearson's index (r) that provides a direct correlation between simulated and experimental results [8].

4.1. First stage results

The period in October was the first to be measured during this work, and was used for the first stage simulations. During this period, the Coordination Office was unoccupied, its windows and door were remained closed. The rest of the simulated building was occupied during work hours of weekdays, its windows and doors were opened during occupancy, and remained closed when it was unoccupied.

In AFN, the infiltration was controlled by the air mass flow coefficient, so that this coefficient was varied to match T_i amplitude with experimental results. Best results were obtained with a value of 0.02, which produced an average of ACH=0.4 1/h. The number of people who entered the building for short periods was considered proportional to the number of occupants for each hour given by the schedule. The number of people who entered the building for short periods that minimize the difference between simulated and measured averages of T_i was 25% of the building's occupants.

Figure 4 presents the qualitative comparison between simulated and experimental results of T_i as a function of time, as well as the simulated T_i with respect to the experimental T_i. Table 3 presents the results of the metrics for T_i for the period in October. From these results, it can be seen that the maximum difference between simulated and experimental T_i is 0.7 $^{\circ}C$ for both ΔT_{max} and RMSE; and that the values of R^2 and r are over 0.75, which is the minimum acceptable value according to [11].

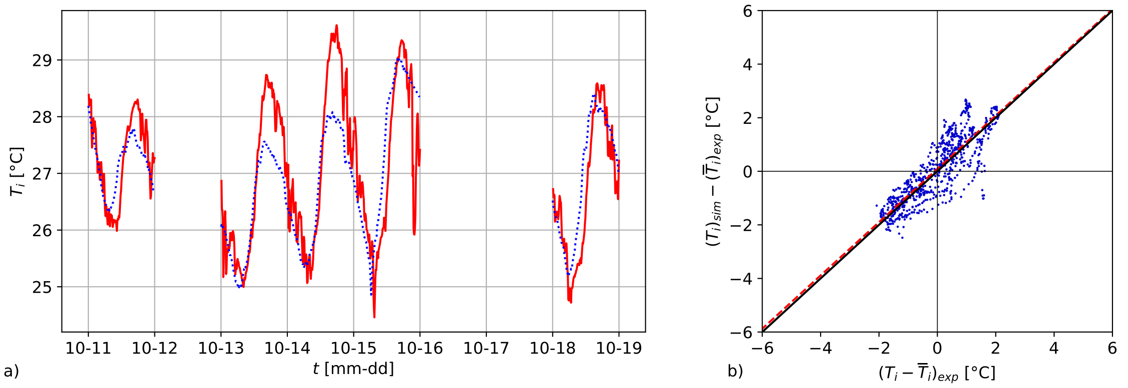


Figure 4: Comparison between simulated and experimental results during the period of October. a) T_i as a function of time. Red and blue lines represent the simulated and experimental data, respectively, b) the simulated T_i with respect to the experimental T_i, subtracting the time average of the experimental T_i, $(\overline{T_i})_{exp}$ from both.

Red and black lines are the linear fit to the data and the ideal linear fit, respectively.

Table 3: Results of the T_i metrics for the period of October.

Comparison variable	$\Delta T_{max}[°C]$	$\Delta T_{min}[°C]$	$\Delta T_{mean}[°C]$	RMSE $[°C]$	m [-]	$b[°C]$	R^2 [-]	r [-]
T_i	0.7	-0.3	0.1	0.7	1.0	0.1	0.84	0.84

4.2. Second stage results

The period in April was used for the second stage of calibration. The months of April and May are the hottest months of the year in Temixco, Morelos, Mexico, and thus represent the critical hot condition for the building. The period in April was selected for the second stage since for this period the simulated building was unoccupied and remained closed, this means that only-infiltration was considered. This condition increased the impact of heat transfer through the envelope mainly affecting surface temperatures that were used as comparison variables in this second stage. The change in the roughness of all outside layer materials belonging to the constructions, from ‘smooth’ (the default in EnergyPlus and used in the first stage) to ‘rough’, improved all metrics for all temperatures, specially for T_{so_s} and T_{si_w}, the sub-indexes s and w specify the South and West walls, respectively. Changing the materials’ properties generally improved the metrics. The largest improvement was obtained for ΔT_{mean} which changed from $4.5°C$ to $2.5°C$. The changes in the properties’ values from the base building model to the final building model can be seen in Table 2. Note that the increase in thermal conductivity for the high density concrete and that of the tezontle were accompanied by an increase to their respective densities, which is the expected relationship between these properties in this type of materials.

Figures 5 and 6 present the qualitative comparison between simulated and experimental results of temperature as a function of time and the simulated temperature with respect to the experimental temperature for T_i, T_{si_s}, T_{so_s}, T_{si_w} and T_{si_r} (sub-index r is for roof), respectively. The simulated results reported here were obtained once the changes to the roughness and material properties were made. The metric results are presented in Table 4, in it, it can be seen that for all temperatures, R^2 is over 0.75. The temperature with the largest value of ΔT_{mean} is T_{si_w}. This can be due to the difficulty in simulating the double wall on the West façade which also receives the highest amount of solar radiation. It seems that the overestimation in T_{si_w} is compensated with the underestimation of T_{si_r} in the effect that both exerted on T_i, which also has an overestimation, yet lower than that of T_{si_w}. It can be noted that during the period in April, R^2 and r for T_i were larger than those obtained in the first stage for the period in October (Table 3).

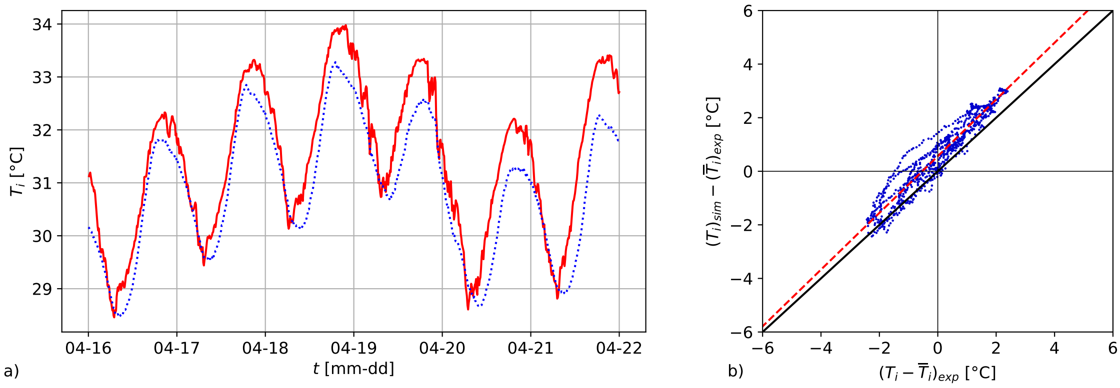


Figure 5: Comparison between simulated and experimental results in the period of April. a) T_i as a function of time. Red and blue lines represent the simulated and experimental data, respectively, b) the simulated T_i with respect to the experimental T_i, subtracting the time average of the experimental T_i, $(\overline{T_i})_{exp}$ from both. Red and black lines represent the linear fit to the data and the ideal linear fit, respectively.

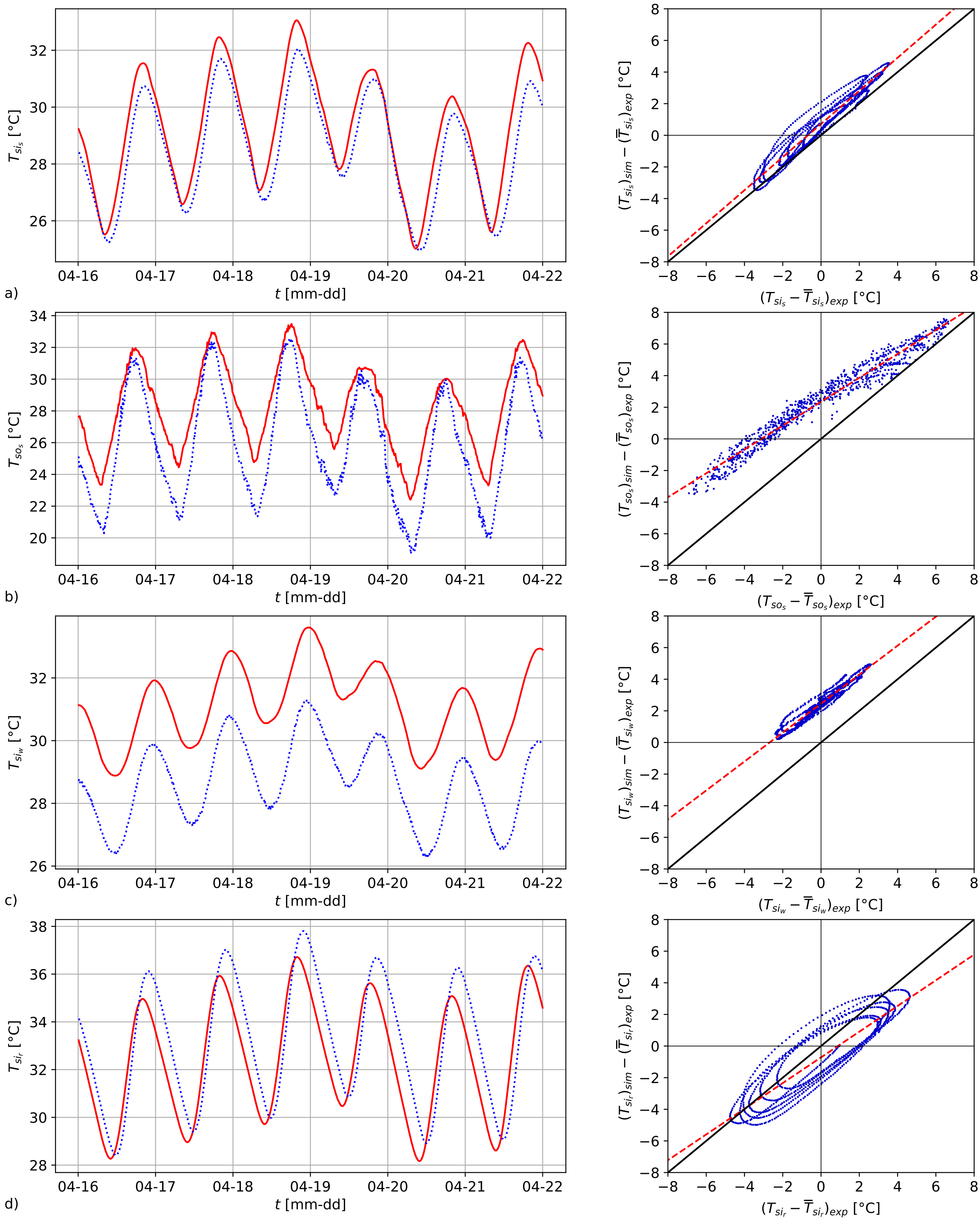


Figure 6: Comparison between simulated and experimental results. Left side T_{si} and T_{so} as a function of time. Red and blue lines represent the simulated and experimental data, respectively. Right side the simulated T_{si} and T_{so} with respect to the experimental T_{si} and T_{so}, for all temperatures, the values are given subtracting the time average of the experimental value. Red and black lines are the linear fit to the data and the ideal linear fit, respectively. For a) T_{si_s}, b) T_{so_s}, c) T_{si_w}, d) T_{si_r}.

Table 4: Temperature metrics results for the period in April.

Comparison variable	$\Delta T_{max}[^{\circ}C]$	$\Delta T_{min}[^{\circ}C]$	$\Delta T_{mean}[^{\circ}C]$	RMSE $[^{\circ}C]$	m [-]	$b[^{\circ}C]$	R^2 [-]	r [-]
T_{si_s}	0.8	0.2	0.7	0.9	1.0	0.7	0.96	0.96
T_{so_s}	0.0	1.4	1.1	0.9	0.8	2.4	0.98	0.98
T_{si_w}	2.4	2.7	2.5	2.5	0.9	2.5	0.97	0.97
T_{si_r}	-1.1	-0.4	-0.7	1.5	0.8	-0.7	0.87	0.87
T_i	0.7	0.0	0.6	0.7	1.1	0.6	0.96	0.96

5. Validation

For the validation process five time periods with different seasonal, occupancy and ventilation conditions were tested. The seasonal, as well as the occupancy condition for the Coordination Office and for the rest of the simulated building are specified for each period in Table 5. When the space was occupied there was natural ventilation, while when it was unoccupied there was only infiltration.

Qualitative comparisons between simulated and experimental results of T_i as a function of time and the simulated T_i with respect to the experimental T_i, for the periods in October, December, February and May are shown in Figure 7. The simulated T_i in October had better results than that obtained in the first stage (fig. 4), the difference between simulated and experimental temperature amplitude was reduced. In December, the simulated T_i had a similar behavior to that of the experimental, with a small difference in temperature amplitude. In February, the behavior of simulated T_i was similar to the experimental one, showing a small delay and an overestimation lower than 1 °C. The simulated T_i in May, showed the best qualitative agreement with experimental T_i.

Table 5 shows the results of the metrics for T_i during all periods. It can be observed that for all periods all metrics with temperature units have positive values (except ΔT_{min} in May), indicating an overestimation less or equal to 0.7 $^{\circ}C$. In all periods, m is equal to 1.0±0.1, and in most, b is 0.0 °C reaching a maximum of 0.3 °C. R^2 and r are over 0.85, which indicates a good correlation between experimental and simulated T_i. The metrics for the period in October improved with respect to the corresponding values from the first stage simulations (table 3), indicating the convenience in carrying out the second stage. The period in May showed the best RMSE, R^2 and r results.

The values of ΔT_{max} and ΔT_{min} are smaller than the maximum accepted value reported in the literature, 5.5 °C. Also, the values of RMSE are smaller than the maximum reported in the literature, 2.6 °C. The values of R^2 are larger than the minimum accepted value in the literature, 0.81.

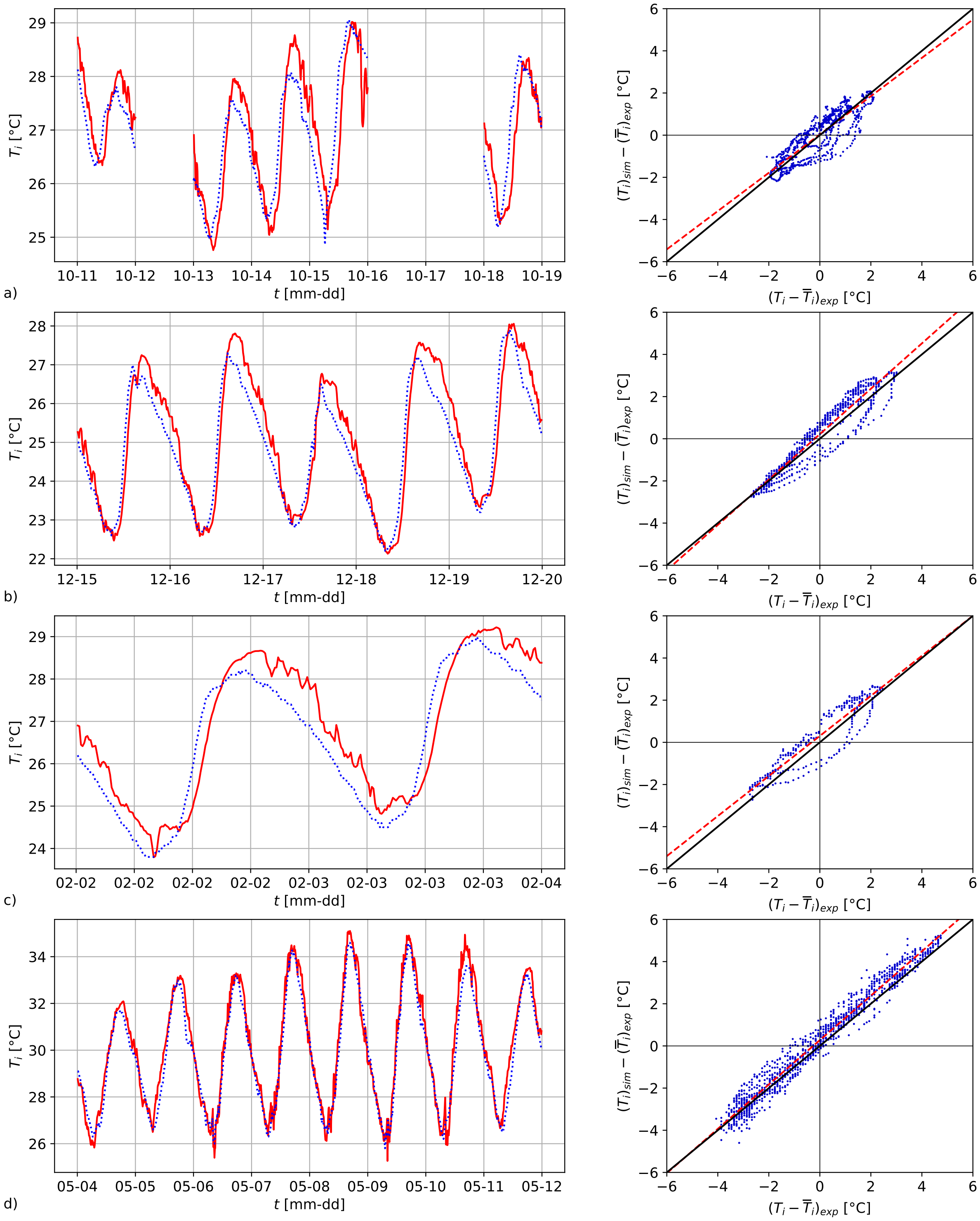


Figure 7: Comparison between simulated and experimental results. Left side T_i as a function of time. Red and blue lines represent the simulated and experimental data, respectively. Right side the simulated T_i with respect to the experimental T_i, for all temperatures, the values are given subtracting the time average of the experimental value.

Red and black lines are the linear fit to the data and the ideal linear fit, respectively. For the periods in a) October, b) December, c) February, d) May.

Table 5: Metrics for T_i for the five periods. The season and occupancy conditions are included. The occupancy condition is shown as occupied (O) and unoccupied (NO), in the Coordination Office - in the rest of the simulated building.

Period	Season	Occupancy	$\Delta T_{max}[°C]$	$\Delta T_{min}[°C]$	$\Delta T_{mean}[°C]$	RMSE $[°C]$	m [-]	$b[°C]$	R^2 [-]	r [-]
October	Transition	NO - O	0.3	0.0	0.0	0.6	0.9	0.0	0.86	0.86
December	Semi-cold	NO - NO	0.3	0.0	0.2	0.6	1.1	0.2	0.95	0.95
February	Transition	NO - O	0.3	0.2	0.3	0.6	0.9	0.3	0.94	0.94
April	Hot	NO - NO	0.7	0.0	0.6	0.7	1.1	0.0	0.96	0.96
May	Hot	O - O	0.4	-0.3	0.3	0.5	1.1	0.0	0.98	0.98

6. Strategies to improve thermal comfort

In this section two strategies to improve the thermal comfort of the building are tested by performing simulations using the validated final building model. The first strategy is the use of night ventilation (NV). NV implies that when the Coordination Office and the rest of the building are unoccupied, they remain closed (only with infiltration), and that when they are unoccupied, windows remain open and doors be closed. The second strategy is that of changing to the color white (W) all exterior surfaces of the building envelope.

Figure 8 shows a qualitative comparison of T_i in the Coordination Office between the base case (B), NV case and NV-W case, during three days of May. The B case corresponds to the building as it is actually colored and used, *i.e.* with natural ventilation when it is occupied, and infiltration when it is unoccupied. It can be seen that the NV case reduces the maximum T_i, in approximately 2 $°C$, and the NV-W case in more than 3 $°C$, when both are compared to the B case. During the initial hours of occupation, the NV and NV-W cases have slightly higher values of T_i than the B case because at that time the outdoor air temperature is lower than T_i and can reduced the T_i value when windows are opened, as in the B case. The case W is not shown in the figure because its impact on T_i is not significant.

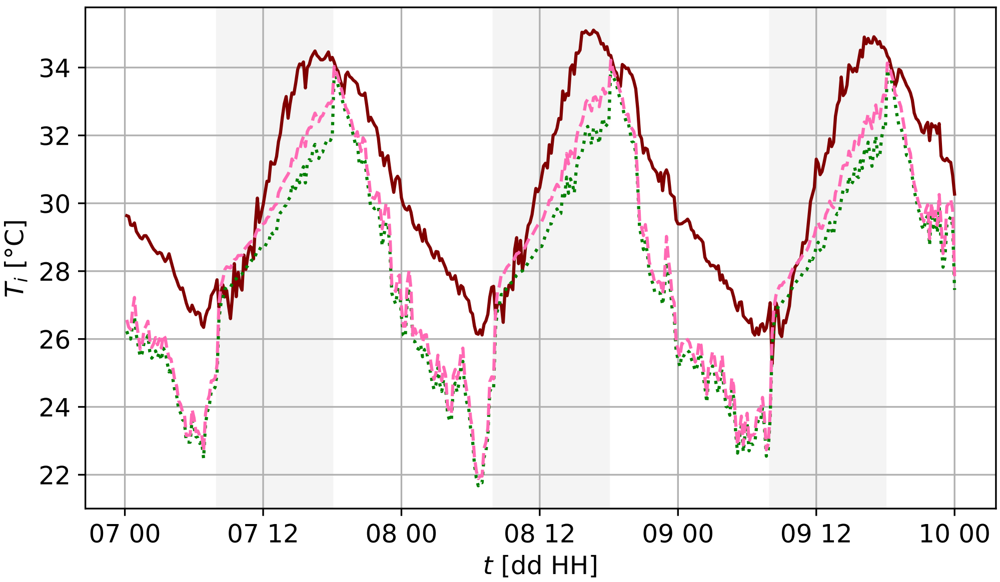


Figure 8: Impact of strategies on the Coordination Office T_i for three days during May. Base case (B) - dark brown solid line, night ventilation case (NV) - dashed pink line, and night ventilation with white colored outside building envelope (NV-W) - dotted green line. Vertical gray areas represent occupancy hours in the Coordination Office.

To evaluate the impact of the strategies proposed for the building an evaluation of the thermal comfort was made. The thermal comfort was evaluated employing the extended Predicted Mean Value (PMVe) proposed in [33], which is specifically designed for non-air-conditioned buildings in hot climates. Here, $e = 0.5$ is used. The comfort range of PMVe is considered as in the standard ASHRAE-55, *i.e.* [-0.5,+0.5] [34]. Figure 9 shows the PMVe for the same three days during May showed in Figure 8. It can be observed that the NV-W case reduces the value of PMVe as well as the amount of discomfort hours.

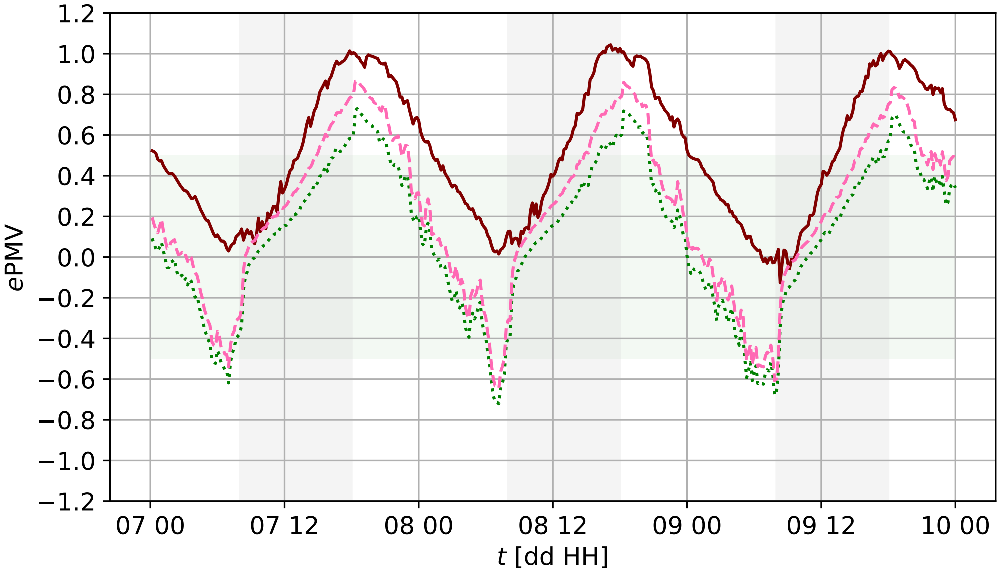


Figure 9: Impact of strategies on the PMVe of the Coordination Office for three days in May. Base case (B) - dark brown solid line, night ventilation case (NV) - dashed pink line and night ventilation with white colored outside building envelope (NV-W) - dotted green line. The vertical gray areas represent the occupancy hours in the Coordination Office and the green horizontal area represents the comfort zone.

For a quantitative comparison the period between the 1st and 17th of May is used. This period was selected because the vacation period was still into effect before the 1st of May, and the rainy season starts after the 17th of May, ending the critical hot season. The maximum values for the PMVe are 1.1 for the B case, 0.9 for the NV case and 0.7 for the NV-W case. The percentage of discomfort hours during occupancy time are 44.8% for the B case, 32.8% for the NV case and 16.9% for the NV-W case. These results show that a significant reduction in discomfort during occupancy hours can be achieved by a change in ventilation habits, from day ventilation to night ventilation, as well as a change to white color for the outside surface of the building envelope.

7. Conclusions

In this work a methodology for the validation of thermal simulations of non-air-conditioned buildings is proposed. It consists of a calibration process and a validation process.

The main differences in this methodology which contrast from the two previously reported for non-air-conditioned buildings are: i) the separation of data inputs which values are known with uncertainties into those that have more influence on the indoor air temperature of the control zone from those with more impact on the surface temperatures of the control zone; ii) to carry out the calibration process into two stages, the first one using as the comparison variable the indoor air temperature, and the second one adding as comparison variables the surface temperatures; and iii) to carry out the validation process in different seasonal, occupancy and ventilation conditions. Identifying which control variables have more influence over the indoor air temperature and which exert more influence over surface temperatures allows for the calibration to be divided into two stages: one to match the indoor air temperature and one to match the surface temperatures of each wall and roof varying only their corresponding properties. This significantly reduces the number of simulations that have to be done in order to find the values for the control variables that minimize the metrics for the comparison variables. As it was done in the present work for the study case, it is recommended that the second stage is made during the hottest season when the high solar radiation and outdoor temperature produce the highest possible effect of the construction properties on surface temperatures.

Results show that the metrics of the indoor air temperature improve values in the second stage when compared to those obtained in the first stage. And that inside surface temperatures change up to 2 $°C$, which impacts on thermal comfort predictions.

The validation results show that the building model obtained from the calibration process is suitable to simulate the building in different seasonal, occupancy and ventilation conditions, and can likewise be used with confidence to test strategies used to improve thermal comfort for the building.

Two simple strategies to improve thermal comfort in the case study building were tested: a change in ventilation habits consisting of switching from ventilation during occupancy to night ventilation and the change to white for the building facade color. When these two strategies are combined the percentage of discomfort hours during occupancy time is significantly reduced with respect to the actual building conditions from 44.8% to 16.9%.

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Chapter 5

Data acquisition for comfort assessment of the new IER building

In this chapter the proposal of data to be measured and gathered, the period types of the data acquisition and the analysis of data for the comfort assessment of the building are presented.

5.1 Data for comfort assessment

In this section, the variables needed for the comfort assessment are presented. The variables can be divided in physical variables that will be measured in the building and occupants opinion that depend from person to person. In physical variables are considered all the variables for the comfort assessment of thermal, acoustic and visual environment. In the occupants opinion, information such as age, gender, location of the occupants within the building, clothing insulation, activity of the occupants and the sensation votes can be found.

5.1.1 Physical variables

The physical variables that are going to be measured for the evaluation of comfort are presented for each environment. For thermal comfort: T_i, v_a, H_r and T_r; for acoustic comfort: A-weighted sound pressure level and reverberation time; and for visual comfort: illuminance on the work surface, distribution of illuminance, and daylight glare probability.

5.1.2 Occupants opinion

The occupants opinion is considered and will be obtained through a comfort questionnaire. The thermal environment and visual environment include scales regarding sensation, comfort, preference, and acceptance. The thermal environment section includes as well clothing insulation and activity level related questions. The acoustic environment includes questions regarding sensation, preference, and acceptance votes. A section where the occupants can write any source of discomfort they might find and a questionnaire's opinion section are also included. The questionnaire also includes the date and time at which it was sent in order to correlate the TSV with the physical variables measured. The questions within the questionnaire are presented below in Spanish as it will be presented to the building occupants, followed by its English version. The questionnaire has been elaborated in the platform Google Forms and it is available for the IER community. A copy is available here.

Comfort questionnaire

- Encuesta general

  1. Indica tu sexo.
     Femenino, Masculino
  2. Indica con número tu edad en años cumplidos.
  3. Selecciona la opción que más se acerca a tu complexión física.
     a, b, c
  4. ¿Cuánto tiempo has vivido en Morelos?
     0 a 6 meses, Entre 6 meses y un año, Entre 1 año y 2 años, Más de 2 años
  5. Si contestaste 0 a 6 meses en la pregunta anterior ¿en qué ciudad vivías?
  6. Normalmente ¿eres usuario de aire acondicionado?
     Sí, No
  7. Si contestaste que sí a la pregunta anterior ¿cuál es la temperatura objetivo en grados Celsius del equipo que normalmente usas?
  8. Indica en qué espacio te encuentras ahora.
     Comedor, Área de trabajo grupal, Área de cómputo, Impresión 3D, Laboratorio de mecánica y electricidad, Aula 1, Aula 2, Aula 3, Aula 4, Aula 5, Aula 6, Aula 7, Aula 8, Aula 9, Aula 10, Laboratorio de química, Laboratorio de termódinamica, Área de trabajo individual 1, Área de trabajo individual 2
  9. Dentro del espacio que señalaste en la pregunta anterior ¿en qué zona te encuentras?
     NO, NC, NE, CO, C, CE, SO, SC, SE

10. Si hay dispositivos de campaña instalados en el espacio en el que te encuentras, indica con número el que se encuentre más cerca de ti.

- Encuesta de comfort térmico

  1. Indica todos los elementos de vestimenta que se acercan más a los que estás usando.
     Brasier, Calzones, Trusas, Calcetas o medias, Sandalias, Zapatos, Botas, Playera sin mangas, Playera tipo polo, Camisa manga corta, Camisa manga larga, Camisa de franela o sudadera, Shorts, Pantalón, Pants, Overol, Falda, Vestido sin mangas, Vestido manga corta, Vestido de manga larga, Chaleco, Suéter, Traje
  2. Indica la opción que más se acerca a la actividad que has estado realizando los últimos 30 minutos.
     Sentado reposando, Sentado en silencio, leyendo, escribiendo o hablando, Sentado tecleando, Parado, Caminando
  3. ¿Cuál es tu sensación térmica general en este momento?
     Fría, Fresca, Ligeramente fresca, Neutral, Ligeramente cálida, Cálida, Calurosa
  4. ¿Cómo te sientes con la sensación térmica?
     Confortable, Ligeramente en disconfort, Disconfort, Muy en disconfort
  5. ¿Cómo preferirías que fuera la sensación térmica?
     Más fría, Más fresca, Ligeramente más fresca, Sin cambios, Ligeramente más cálida, Más cálida, Más calurosa
  6. ¿Cómo consideras el ambiente térmico?
     Aceptable, No aceptable

- Encuesta de confort acústico

  1. Consideras que el ruido en el espacio en que te encuentras es...
     No molesto, Ligeramente molesto, Molesto, Muy molesto
  2. ¿Cómo preferirías que fuera el ambiente acústico?
     Sin cambios, Ligeramente más silencioso, Más silencioso, Mucho más silencioso
  3. ¿Cómo consideras el ambiente acústico?
     Aceptable, No aceptable

- Encuesta de comfort lumínico

1. En este momento el ambiente lumínico en el espacio en que te encuentras es...
   Extremadamente oscuro, Oscuro, Ligeramente oscuro, Neutral, Ligeramente claro, Claro, Extremadamente claro
2. ¿Cómo te sientes con la iluminación?
   Confortable, Ligeramente en disconfort, Disconfort, Muy en disconfort
3. ¿Cómo preferirías que fuera la iluminación?
   Mucho más oscura, Más oscura, Ligeramente más oscura, Sin cambios, Ligeramente más clara, Más clara, Mucho más clara
4. ¿Cómo consideras el ambiente lumínico?
   Aceptable, No aceptable

- Observaciones generales. Describe cualquier tipo de disconfort o comentarios que tengas (olores, movimiento del aire, humedad, etcétera.)Sugerencias y comentarios del edificio
- Opinión de encuesta. Por favor ayúdanos a mejorar la encuesta con tus comentarios.

English version

- General survey

1. Indicate your sex.
   Feminine, Masculine
2. Indicate with number your age in completed years.
3. Select the option which reflects best your body composition.
   a, b, c
4. ¿How long have you been living in Morelos?
   0 to 6 months, Between 6 months to a year, Between 1 year and 2 years, More than 2 years
5. If your answer was 0 to 6 months in the previous question, where did you lived?
6. Normally, are you an air-conditioning user?
   Yes, No
7. If your answer in the previous question was yes ¿which is the target temperature in Celsius degrees for the air conditioning system that you normally use?

8. Indicate the space where you are currently.
   Cafeteria, Group work area, Computer area, 3D Impression, Mechanics and electricity lab, Classroom 1, Classroom 2, Classroom 3, Classroom 4, Classroom 5, Classroom 6, Classroom 7, Classroom 8, Classroom 9, Classroom 10, Chemistry lab, Thermodynamics lab, Individual work area 1, Individual work area 2
9. Within the space that you select on the previous question, in which zone are you in?
   NW, NC, NE, CW, C, CE, SW, SC, SE
10. If there is any campaign data acquisition system in the space you are at, indicate with number the one closest to you.

- Thermal comfort survey

  1. Indicate all the elements of clothing that approach the most to what you are wearing.
     Brassier, Panties, Men's briefs, Socks or panty hose, Sandals, Shoes, Boots, Sleeveless shirt, Short-sleeve knit sport shirt, Short-sleeve dress shirt, Long-sleeve dress shirt, Long-sleeve flannel shirt or long-sleeve sweatshirt, Shorts, Trousers, Pants, Overall, Skirt, sleeveless dress, Short-sleeve dress, Long-sleeve dress , Vest, Sweater, Suit
  2. Indicate the option that resembles most to the activity you have been doing in the last 30 minutes.
     Seated reclining, Seated quiet, reading, writing or speaking, Seated typing, Standing, Walking
  3. How is your general thermal sensation in this moment?
     Cold, Cool, Slightly cool, Neutral, Slightly warm, Warm, Hot
  4. Do you find the thermal sensation
     Comfortable, Slightly uncomfortable, Uncomfortable, Very uncomfortable
  5. How would you prefer to be you thermal sensation?
     Much cooler, Cooler, Slightly cooler, No changes, Slightly warmer, warmer, much warmer
  6. How do you judge the thermal environment?
     Acceptable, Unacceptable

- Acoustic comfort survey

   1. Do you consider the noise in the space where you are at is...
      Not annoying, Slightly annoying, Annoying, Very annoying
   2. How would you prefer to be the acoustic environment?
      No change, Slightly quieter, Quieter, Much quieter
   3. How do you judge the acoustic environment?
      Acceptable, Unacceptable

- Visual comfort survey

   In this moment the visual environment in the space where you are at is...
   Very dark, Dark, Slightly dark, Neutral, Slightly light, Light, Very lightHow do you feel with the lighting?
   Comfortable, Slightly in discomfort, Discomfort, Very in discomfort How would you prefer to be the lighting?
   Much darker, Darker, Slightly darker, No change, Slightly lighter, Lighter, Much lighter How do you judge the visual environment?
   Acceptable, Unacceptable

- General observations. Describe any type of discomfort or comments that you have (smells, air movement, humidity, etc.) Suggestions and comments on the building.
- Opinion survey. Please help us improve this survey with your comments.

5.2 Data acquisition period types

The data acquisition will be made with two approaches, the first type of data acquisition will be made through a permanent measurement and the second will be campaigns. This section presents the physical variables that will be used in each type of data acquisition period. The comfort questionnaires will be available permanently so the occupants can register their thermal sensation votes when ever they feel any type of discomfort. For the campaigns the occupants will be asked to answer the questionnaire. When the campaigns are running the results of the questionnaires will be correlated with the physical variables measured closest to the person. In the case of the permanent measurement the answers to the questionnaire will be correlated with the single data acquisition system, in the middle of the room.

5.2.1 Permanent

The permanent measurements will be made using a system developed within the CONACYT-SENER project. The system is named DTHIS (Dispositivo para medir temperature, humedad, iluminación y sonido). The DTHIS will be hang from the ceiling, close to it in the center of the classrooms. Measurements will include T_i, H_r, L_p and luminance map. Since the measurements will be taken close to the ceiling height a correlation will have to be made with the results from the campaigns in order to use the permanent measurements to calculate T_i and H_r at the occupancy heights.

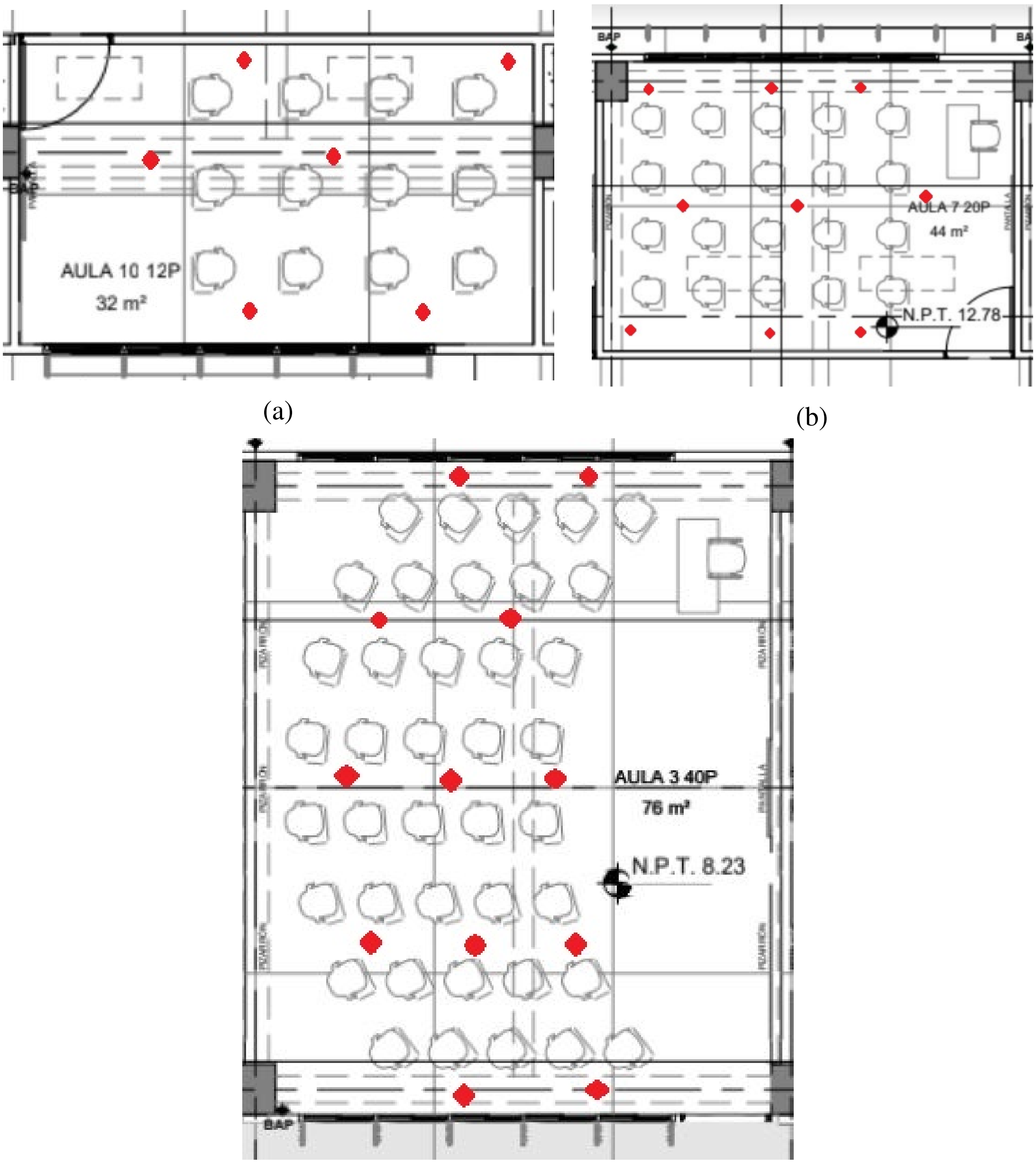
5.2.2 Campaigns

The campaigns will be made in different periods along the different seasons of the year. The measurements will include T_i, T_r, H_r, v_a, L_p, maps of L and E. The height at which T_i, T_r, H_r and v_a measurements should be made according to ASHRAE 55 (ANSI/ASHRAE, 2017) is considering that the average occupant height is of 1.8 m. In this study, a consideration is made regarding the height of occupants, the average height of the Mexicans is of 1.6 m, the recommendation is to take the measurements at a height of 0.1 m for the ankle, 1.1 m for the waist and 1.5 m for the neck in laboratories, that correspond to standing occupants, because the activities developed there require the occupants to be standing. In the case of classrooms, the dinning room, computer lab and study areas the height will correspond to seating heights, the following are proposed 0.1 m for the ankle, 0.6 m for the waist and 1.1 m for the neck. If there would be limitations in the number of measurements the recommendation is to take them at the neck level.

The spaces in the new IER building can be divided by their capacity, there are spaces for 40 people, 20 people and for 10 people. The measurements should be taken differently in each type of space, the recommendations are the following: for the 40 people spaces 12 spots, for the 20 people spaces 9 spots and for the 10 people spaces 6 spots. Figure 5.1 shows the different spaces by capacity and the recommended spots for the measurements. In case less acquisition systems are available, they should be distributed uniformly in the space depending on their number.

5.3 Analysis of data

The information obtained in the data acquisition will be used to evaluate the thermal, acoustic and visual environment. The proposal is to use the PMVe method Fanger and Toftum (2002) for the design stage because the value of the adaptive coefficient can be selected according to



(a)

(b)

(c)

Figure 5.1 Floor plans of the spaces in the new IER building, the red diamonds show the recommended spots where the measurements should be taken. (a) 10 people space, (b) 20 people space and (c) 40 people space.

the use of air-conditioning in the surrounding buildings as well to use the PMVe and aPMV for the occupancy stage. At occupancy stage in both methods the adaptive coefficients must be calculated correlating the physical variables measured data with the thermal sensation votes.

Chapter 6

Conclusions and recommendations for future work

In this chapter the conclusions and recommendations for the comfort assessment for the new IER building are presented.

This work contributes to people interested in the assessment of the thermal, acoustic and visual comfort by presenting a summary of the main aspects for their evaluation.

Building simulations are recommended for the comfort assessment in the design stage and experimental measurements are recommended in the occupancy stage. The experimental measurements include the acquisition of physical variables and occupants opinion.

From the international literature review it is found that there are few comfort studies in Mexico. Most of them are focused on finding the comfort temperature using adaptive models that only consider the temperature for the comfort assessment.

A methodology for the validation of building thermal simulations for non-air conditioning buildings is proposed in this thesis. This methodology is recommended to be followed to ensure the accuracy in these simulations to perform a comfort assessment.

During the process of simulations validation it is found that surface roughness has a large impact on the convective coefficient and also on the indoor air temperature.

The air mass flow coefficient value which gives an accurate value of infiltration in the IER building simulated as a case study for the simulation validation carried out in this thesis can be used in the simulations of the new IER building in the design stage.

This thesis proposes the methodology to be followed for the thermal, acoustic and visual comfort assessment at the occupancy stage of the new IER building. This proposal includes the physical variables to be measured, the height and the plan distribution and a comfort questionnaire. The types of data acquisition period, divided in permanent and campaigns and the analysis of data are also included.

It is also proposed that at the design stage, the thermal comfort evaluation of the new IER building be made using the extension of the predicted mean vote (PMVe) method. In the occupancy stage the methods PMVe and the adaptive predicted mean vote (aPMV) are suggested to be used. Both adaptive coefficients should be calculated correlating the physical variables measured data with the thermal sensation votes.

Additionally it is proposed to obtain the comfort operative temperature using a linear correlation between the operative temperature and the thermal sensation votes to obtain an adaptive model specific for the IER.

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