UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO

INSTITUTO DE ENERGÍAS RENOVABLES

INSTITUTO DE INGENIERÍA

Methodology for the validation of thermal simulations of a real building

TESIS

Que para obtener el título de

Ingeniera en Energías Renovables

P R E S E N T A

Veronica Ivette Calixto Aguirre

DIRECTORES DE TESIS

Dra. Guadalupe Huelsz Lesbros, Dr. Guillermo Barrios del Valle

IER Instituto de Energías Renovables

INSTITUTO DE INGENIERÍA UNAM

Temixco, Mor., a 11 de marzo 2019

I would like to dedicate this thesis to my parents and sister that listened to me for the past 6 months about this works and the obstacles that have to face. To my dearest Carlos, for always being my support and cheering me up when nothing has any sense. To my aunts Estela and Manuela because they were always my inspiration and the reason I knew of the existence of this degree. To my uncle Jesus for the funding and all the help. To my grandparents Crimilda, Servando, Petra and Salvador because they have always believed in me. To my aunts and uncles Aguirre Cruz and Calixto Rodríguez.

To my friends, Ronzimios group because for being the ones that take me back to earth, for believing in me but most importantly for showing me that life can change but friends are always there.

To the LIER's 4th generation: Carlos, Caro, Memo, Eros, Itzelita, Eira, Juanico, Juanca, Darinka, Anita, Sam, Gesú, Migue, Ade, Fer, Julio, Sebas, Sergio and Clarisa for being my family for the past years and for teaching me that you can go as far as you want.

To my tutors, Guadalupe and Memo for inspiring from the first day of class and for always supporting me through all the process. To the GEE because I know this thesis can help to make greater works.

To all my teachers because without the lessons and the exigence I wouldn't be here.

I would like to thank the National Autonomous University of Mexico for the opportunity and for showing me we can always do better. To the Renewable Energies Institute for the knowledge I have acquired from you and for letting me be part of this great community.

To 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.

To José Antonio Castillo Torres and Miriam Veronica Cruz Salas from the GEE, for working extra hours and helping me with some issues with this thesis.

To Miguel Robles because he was very patient and understanding and for letting us use his office as the space to validate this methodology.

To my thesis committee Jorge Rojas, Norma Alejandra Rodríguez Muñoz, Guadalupe H., Miriam Veronica Cruz Salas and María Guadalupe Alpuche Cruz for helping me even though all of you had a lot of work and for the advisory.

Abstract

The buildings simulations are a milestone to achieve energy efficiency, for this reason, to develop a methodology to simulate buildings is very important. In this thesis, a literature review of the comparison between experimental measurements and simulations in EnergyPlus is presented. A review of the procedure to simulate buildings proposed in a book found in the literature was made. The description of metrics used in the literature and tolerance ranges are included in this thesis. The indoor air temperature was used as comparison variable for the validation process, because the simulated building has no air conditioning systems. Based on the procedure reviewed, a methodology to simulate buildings is proposed, where EnergyPlus input data are divided into model inputs and control variables. For this building, a model input is, for example the materials. This methodology is applied to simulate a building in the Renewable Energies Institute (IER), for this building the internal gains from people and infiltration are used as control variables. The base case for the simulation is the case where only model inputs are considered. Case 1 is the case where variations of the control variables give the best qualitative results. Due to the underestimation of the temperature at hours with solar radiation by case 1, a simulation case 2 was proposed. The case 1 includes the solar protections existing in the building as shading group. Case 2 has no solar protections. When the solar protections are modeled as shading group two considerations are done, one is that these elements do not count on the heat transfer and the second one is that they do not have materials or constructions. The solar protections in reality are red hollow bricks and thus the heat transfer by radiation and conduction have to be considered. The results include plots for qualitative comparison of the measurements and the two cases simulated. Quantitative comparison using the most common metrics described in the literature review was done. In both comparisons, the results obtained for case 2 are better than for case 1, this suggests that the solar protections in the building are absorbing heat, due to their red color, and are transmitting heat by conduction and radiation to the building indoor. The accuracy of the cases 1 and 2, given by the metrics values, are compared with similar studies reported on the literature and with tolerance ranges recommended in the literature. In this thesis, the temperature is underestimated in the simulations, as it is in most of the studies reported in the literature.

Table of contents

Symbols

Acronyms

ach air changes per hour

ae absolute error

CEN European Committee for Standardization

CFD Conduction Finite Difference

CTF Conduction Transfer Function

cvrmse coefficient of variation of the root mean square error

de defect error

drms differences root mean square

DSF double skin façade

ee excess error

EHLS equivalent-homogeneous-layers-set method

EMPD Effective Moisture Penetration Depth

EP EnergyPlus

GOF Goodness of fit

HAMT Combined Heat and Moisture Transfer model

IPMVP International Performance Measurement and verification Protocol

M&V Measurement and Verification

mbe mean bias error

me mean error

nmbe normalised mean bias error

rmse root mean square error

te total error

VGS vertical greenery systems

WMO World Meteorological Organization

Variables

Δx Average difference of the simulated value and measured value of variable x [$^{\circ}C$]

δx standard deviation of the variable x

dt_s Superficial decrement factor

E_{ec} electrical energy consumption [kWh]

E_{hc} heat energy consumption [kWh]

H_o Outdoor air relative humidity [%]

I_s Solar irradiance [W/m^2]

lg_s Superficial lag time [h]

P Precipitation [mm]

P_a Atmospheric pressure [kPa]

R^2 correlation coefficient

T_{dp} Dew point temperature [°C]

T_f Floor temperature [°C]

T_{imax} Daily maximum indoor air temperature [°C]

T_{imin} Daily minimum indoor air temperature [°C]

T_{is} Indoor surface temperature [°C]

T_i	Indoor air temperature [°C]
T_{os}	Outdoor surface temperature [°C]
T_o	Outdoor air temperature [°C]
W_d	Wind direction [°]
W_s	Wind speed [m/s]
b	intercept
dt	Decrement factor
lg	Lag time [h]
m	slope
r	Pearson's index

Introduction

Building energy all over the world is a significant part of the final energy consumption. According to the International Energy Agency (International Energy Agency and International Partnership for Energy Efficiency Cooperation, 2015), the energy consumption in buildings per capita in the world in 2012 was of 4,700 kWh, the largest consumer was Canada with 20,000 kWh and India the lowest consumer with 2,000 kWh, Mexico had a consumption of 2,500 kWh. The electrical consumption in buildings per capita in the world was 1,400 kWh which means that less than 50% of the total energy consumption in buildings in the world corresponds to electrical energy. The electrical consumption in buildings per capita in Canada was 8,500 kWh, India 200 kWh and Mexico 700 kWh. The energy consumption in the world in buildings per unit area was 170 kWh/m^2 and in Mexico 50 kWh/m^2 .

In Mexico, the National Energy Balance for 2016 (SENER, 2017) reported that the energy consumption in buildings represents 18.1% (266,571,324 kWh) of the annual final energy consumption. For the same year, the electric energy use intensity in buildings of the Federal Government in Mexico was estimated in 63 kWh/m^2. In buildings without air conditioning this quantity was 41 kWh/m^2 and in buildings with cooling air conditioning was 73 kWh/m^2, which means that the 44% of the total electrical consumption is due to air conditioning systems (Calixto-Aguirre and Huelsz, 2018). This significant consumption for cooling air conditioning in Mexico is crucial to have more efficient buildings based on bioclimatic design.

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. One of the objectives in this project is to design with bioclimatic criteria a new building for the IER, in warm subhumid climate. Also to apply different strategies and low energy cooling systems.

For the design stage, whole building thermal and energy simulations are a milestone to achieve a thermally comfortable and energy efficient building. Some of the strategies proposed to be incorporated in the building are quite complex to model in the a whole building thermal and energy simulation's program, such as EnergyPlus.

The general objective of the thesis is to provide a guide to simulate the building and contribute to a deeper knowledge of the participants in the project about Energyplus.

The specific objectives of this thesis are to provide the literature review about studies of the comparison of EnergyPlus and experimental results; to get information from those comparisons to provide a frame for the accuracy of the simulations; to develop a methodology to simulate buildings without air conditioning that can be applied to the new building and to anticipate the problems that might have to be face in the simulations of the new building.

This thesis has five chapters. The first chapter is a description of the literature review of the work that has been made in the world regarding experimental data and EnergyPlus simulations comparison. The second chapter is based in a book that propose a procedure to simulate real buildings, it also includes metrics of comparison between the simulation and the experimental data and the explanation of the ones used in the articles of the previous chapter. The third chapter is the description of the space that has been simulated and the methodology followed for both, the experimental data and the simulation. In the fourth chapter the results of the simulations and the experimental measurements are presented and compared. The last chapter has the conclusions of the thesis. The appendix included are to provide more information about specific issues. The first appendix is a quick guide to use the QUESTemp. The second appendix presents the calculation of the building orientation. The third appendix shows the calculations of the wind speed profile for the simulation model.

Chapter 1

Literature review

In this chapter, a literature review about studies of the comparison of EnergyPlus (EP) and experimental results is presented. The articles provide information that could be useful for this work, a total of eight articles were found. In all the articles, the simulations were validated with experimental data obtained by the authors or from the literature. Most of the articles focus on finding a solution for specific problems (phase change materials (Sang et al., 2017), vertical greenery systems (Dahanayake and Chow, 2017), double skin façades (Andelković et al., 2016) and comparisons of different heat balance algorithms (Yang et al., 2015)) rather than providing a methodology to simulate real buildings. The general description of the building was included in all of the articles, however not all of them mentioned if the building simulated had air conditioning or not, the information about the occupancy was neither included in some of the articles. In regard to the variables measured as input for the simulation, all the articles included the weather data. However, most of the articles did not mention the sensors or the equipment used to measure the involve variables. The heat balance algorithm used in the simulation was mentioned in just a few articles. The comparison parameters between the simulations and the experimental data in most cases were indoor air temperature (T_i) and indoor surface temperature (T_{is}) and the outdoor surface temperature (T_{os}), usually compared using as metric the correlation coefficient (R^2), and in some cases also using the slope (m). Some others presented just a qualitative comparison where T_i, T_{is} and T_{os} were plotted. Simá et al. (2015) also used the decrement factor (df), lag time (lg) and discomfort hours for the comparison of results. Some articles used, the following metrics for the comparison, the mean bias error (mbe), the root mean square error (rmse) and the Pearson's index (r). The most usually used metrics are explained in Chapter 2. In the following paragraphs, a brief description of each article is presented.

Sang et al. (2017) studied a full scale test room with a wall with a phase change material without air conditioning. The EP simulation used the Conduction Finite Difference

(CFD) algorithm, with a step time of 1 min and the space discretization constant of 0.3, as recommended in the EP manual. The test room was instrumented with 8 heat flux sensors and 20 temperature sensors on the walls and roof surfaces. They report the enthalpy and the thermal conductivity of the phase change material. Solar irradiance (I_s), outdoor air temperature (T_o), T_i, T_{is} and outdoor air relative humidity (H_o) were measured with the TR-72U Thermo Recorder. The validation of the simulation was done from the 2^{nd} of March 2014 to the 13^{th} of March 2014. A qualitative comparison of T_{is} was plotted for one of the days.

Dahanayake and Chow (2017) studied the effect of vertical greenery systems (VGS) in the building thermal performance. For the simulation of the VGS three models were combined, the green roof module's heat balance equations, ArmyCorps of Engineers' FASST vegetation models and green wall hydrothermal model. The variables measured were T_o, I_s, wind speed (W_s) and dew point temperature (T_{dp}). For the validation, T_i, T_{os} and T_{is} of the VGS were compared to the values measured. The validation was done considering two cases of study, the case A is a test cell with a VGS in the west wall and the case B were two residential flats in a thirty three story building, one with VGS and the second without VGS. For case A, six thermocouples type T and a weather station were used, and in case B, three thermocouples type T were used. In both cases data loggers and a single-phase electronic system energy meter were used. Case A has a validation period that starts from the 25^{th} of July of 2012 and for the rest of the summer and natural ventilation was considered from 19:00 to 7:00. The case B considered one residential flat in the 4^{th} story with VGS and a second residential flat in the 5^{th} story, in this case the total energy consumption was also measured and the period of validation was from June to September. The model had T_o and H_o schedules. The R^2, the cosine and the norm were used as metrics for the comparison of the measured temperatures. For good results, the norm should approach zero and the cosine should approach one. The results of the comparison for R^2 were 0.90, 0.88 and 0.97 for T_{is}, T_{os} and T_i respectively, the norm was between 0.02 and 0.09 and the cosine from 0.64 to 0.95.

Andelković et al. (2016) modeled a double skin façade (DSF) building with five storys and HVAC systems. The simulation was made with the Airflow Network Algorithm for the natural ventilation, EP version 8.2 and Design Builder as interface. Some data that were taken into account for the simulation were: the number of occupants per room, the effect of lighting and internal equipment, accurate data of shadowing and infiltration and user's schedules. The validation was done in three different seasons: winter, transient and summer. The transitional season refers to the spring period. The variables measured were T_o, H_o, I_s, W_s and wind direction (W_d). The variables compared were T_{is}, T_{os}, T_i and air velocity in the DSF. The metrics of comparison used in this work are mbe, rmse, coefficient of variation of the root mean square error (cvrmse), R^2, temperature minimum difference (ΔT_{min}) and temperature maximum difference (ΔT_{max}) between experimental and numerical results. The results of the comparison showed that $R^2 = 0.90$, the mbe is negative which means that the simulation under predicted the results, the rsme is very close to zero, the cvrsme is between 7% and 15% which were being considered as normal by the authors, ΔT_{imin} is close to 0°C and ΔT_{imax} is -7.2°C.

Simá et al. (2015) studied the effect of shading of a tree and of the neighbor buildings in the thermal performance of a closed and inhabited house. Simulations with the effect of shading with the tree and without the tree were carried out and validated with the experimental measurements. The experimental measurements were done from the 1^{st} of April 2011 until 30^{th} of April 2012, but the comparison was made for 2 months, April 2011 and April 2012. Thermocouples were used to measure T_i, T_o, T_{is}, T_{os} in 5 of the 8 zones of the house, additionally the floor temperature (T_f) was measured. From a weather station the variables T_o, H_o, I_s, W_s, W_d, atmospheric pressure (P_a) and precipitation (P) were recorded and used for the model. The program used to draw the geometry for this simulation was Design Builder. The simulations used the measured average monthly T_f, infiltration was considered as 0.7 air changes per hour (ach). The variables used for the validation were T_i, T_{is} and T_{os}. Their monthly average were qualitatively compared, as metrics of comparison the Δdf, Δlg and the difference of discomfort hours were used. For the validation only one thermal zone was used.

Yang et al. (2015) evaluated three different heat balance algorithms (conduction transfer functions (CTF), combined heat and moisture transfer model (HAMT) and effective moisture penetration depth (EMPD)) to know the accuracy and applicability of each one of them. The HAMT method is not suitable for the building energy simulation before the building is already done or in the architecture design due to the time of computing, the complexity to obtain some parameters needed and the cost of the analysis involving moisture effect. The EMPD is the most precise and quick method to simulate moisture transfer. A full scale test room was used to observe the accuracy of the models. Three different climates were simulated (Hot humid, temperate and hot dry), 2 occupants were assumed sleeping inside the test room for 10 hours. The infiltration was assumed as 0.5, 1, 2 and 5 ach. The air-conditioner was set at 26°C and the dehumidification system to be turned on when the humidity is higher than 65% and the test room is occupied. T_i simulated and measured were qualitatively compared by plotting them.

Coakley et al. (2012) described the calibration of a whole-building energy consumption simulation with natural ventilation. The EP model is calibrated with measured data of energy consumption and zone temperatures. The variables measured were T_i, CO_2 levels, electrical energy consumption (E_{ec}) and heat energy consumption (E_{hc}). A weather station measured:

T_o, H_o, P_a, W_s, W_d and I_s. A building audit was performed, where information like electrical equipment and the consumption of each one of them (lighting, cameras, general services and sub-distribution elevator) was obtained. The occupancy was also studied with random surveys. Over 60 individual sensors in the building were used. Due to the enormous amount of data from the building a data cleaning had to be made, if there were less than 6 hours of missing data an interpolation was used and if there were more than 6 hours, that period of time was excluded. To clean the data from the weather station MySQL was used, a software to manage databases. The input data was divided into different classes which had different range of variation (0 to 50%) related to the certainty on the data. To determine the Goodness of fit (GOF) based in a weighted combination of two metrics, a weight of 1:3 cvrmse to the normalized mean bias error (nmbe) were used. One hundred simulations with input data randomly chosen according to their correspondent deviation were performed from May to December of 2011. The metrics for the comparison are nmbe, cvrmse and GOF, for energy (E_{ec} and E_{hc}) and for temperatures.

Huelsz et al. (2017) validated the equivalent-homogeneous-layers-set method (EHLS) implemented into EP. The validation was made for one full scale test room, the measured data were from April 2010 to March 2011. The climatic conditions were recorded using a Davis Vantage Pro2 weather station which measured T_o, H_o, W_s, W_d, P_a, P and I_s. T_{is}, T_i, T_{os} and T_f were measured with thermocouples (T-type). All data were registered every ten minutes by a Campbell Scientific data acquisition device. The heat balance algorithm used in this study was CFD with a value of 0.15 for the space discretization constant. The comparison of results was done in one week of the hottest month (June) and one week of the coldest month (January). A qualitative comparison of the T_i plot and a quantitative comparison of the monthly averages of Δdf and of Δlg were carried out. The results showed that ΔT_{imax} was -0.9°C, the maximum differences were for Δdf 0.1 and for Δlg 1.9 hours.

Barbaresi et al. (2015) looked for the identification of an effective and efficient approach to model wine storage buildings. The building has an air conditioning system. T_i at different heights was measured using twelve sensors (PCE-HT71) from the 12^{th} of June 2014 to 17^{th} of June 2014. A weather station (model PCE-FMS20) recorded data of T_o, H_o, P_a, W_d and W_s. T_f was measured at 100 m depth. The information of the weather stations was used to create three weather files (2012, 2013 and 2014). Information gaps were completed with data from a weather station located at 32km from the building. For the simulation two models were considered, the first has a single thermal zone and the second has 2 thermal zones, one over the other separated by an air wall. Infiltration of 0.5 ach was considered. The metrics used for the comparison were r, calculation of linear regression (m and intercept (b)), mean error (me), rmse, total error (te), excess error (ee), defect error (de) and absolute error (ae).

The total analyzed period were six months, the results of the comparison showed r=0.9944, m=1.013, b=0.4649 and for all the errors, the average difference was less than 1°C. The results obtained in the simulation with two thermal zones were more accurate.

A summary of the general information of the simulations performed in the articles mentioned above can be found in table 1.1. It can be observed that most of the eight articles give information about the use or not of air conditioning and half of them do use air conditioning. More than half of the articles have information about the occupancy but only two of them are actually occupied. Most of the articles have information about the measured outdoors variables T_o, T_{os}, W_s and W_d but in general do not give information about the equipment used. In regard to the indoor variables, most of the articles give information about them, the most used are T_i and T_{is}. Half of the articles mentioned the equipment used to measure the indoor variables. Only half of the articles give information about the heat balance algorithm used. The ventilation is not usually mentioned in the articles, in one of them a fan is used, another one mentioned the use of natural ventilation but give no information about the simulation of it. The period of validation is mentioned in most of the cases, it ranges from six days to six months.

Table 1.1 Review of articles

Reference	AC	Building	Occupancy	Outdoor variables	Equipment outdoor variables	Indoor variables	Equipment indoor variables	Heat Balance Algorithm	Ventilation	Period	Comparison variables	Metric	Observations.
Andelkovicć et al. (2016)	Yes	5-storey building	Not specified	T_o, H_o, I_s, W_s and W_d	Not specified	T_i, T_{is}	Not specified	Not specified	Not specified	Three seasons: winter, transient and summer	T_{is} of the DSF, T_i in the DSF and W_s in the DSF	mbe=negative, rmse∼0, cvrmse=7-15% , R^2 = 0.9, ΔT_{imin} ∼0°C and ΔT_{imax}= -7.2°C	# occupants per room, lighting, internal equipment, shadowing, infiltration and user's schedules
Coakley et al. (2012)	Yes	3-storey building	Yes, random surveys were conducted	T_o, H_r, P_a, W_s, W_d and I_s	Not specified	T_i, T_{is}, CO_2, E_{elec} and E_{heat}	Not specified	Not specified	Not specified	May to December of 2011	E_{ec} and T_i	nmbe, cvrmse, GOF	60 individual sensors
Simá et al. (2015)	No	2-storey house	No	T_{os}, T_o, H_r, I_s, W_s, W_d, P_a and P	Not specified	T_i, T_{is}	T-type thermocouple 30 AWG	Not specified	No	April 2011 and April 2012 for only one zone	T_i, T_{is}, T_{os}	Qualitative comparison (plot monthly average of the T_{is}, T_{os} and T_i) DF, LT and discomfort hours	Measured average monthly T_f, infiltration of 0.7 ach, internal gains and ventilation are not considered thermocouple
Dahanayake and Chow (2017)	Not specified	Residential flat in 33-storey building with green wall and full scale test room	Not specified	T_{os}	Weather station	T_i, T_{is}	3 T-type thermocouples for the flat and 6 T-type thermocouples, data loggers and single-phase electronic energy meter	Three models for VGS: Green roof module's heat balance equations, FASST vegetation models and green wall hydrothermal model	Not specified	June-September	T_i and T_{is}, T_{os}	R^2=0.97, 0.88 and 0.97, the norm 0.02-0.09 and the cosine 0.64-0.95	Hourly T_o profile schedule and H_r schedule
Barbaresi et al. (2015)	Yes	1-storey wine storage building	No	T_o, H_o, P_a, W_d and W_s	Weather station (model PCE-FMS20)	T_i	PCE-HT71 logger no.12, no. 18 and no.30	Not specified	Not specified	Six months	T_i	r=0.994, m=1.013, b=-0.465, me=-0.234, rmse=0.705, te=-987, ee=810, de=-1701 and ae=2511	0.5 ach, the ground temperature was measured with a sensor at 100 m depth
Huelsz et al. (2017)	No	Full scale test room	No	T_o, T_{os}, H_o, W_s W_d, P_a, P, I_s	Davis Vantage Pro2, Campbell Scientific, CR800, AM16/32B, RF400 radios and NL100	T_i, T_{is}	T-type thermocouple	CFD	Not specified	One week of the hottest month (June) and one week of the coldest month (January)	T_i	T_{imax}= -0.9° C, monthly averages Δdf_s=0.07 and Δlg_s=1.9 with δ.	The measured data from April 2010 to March 2011
Sang et al. (2017)	No	Full scale test room	Not specified	T_o, I_s and H_o	Wireless Vantage Pro2 Plus	T_i, T_{is}	TR-72U Thermo Recorders, SWP-L816, Rlog-7730	CFD	Fan	2^{nd} of March to 13^{th} of March 2014	T_{is}	Qualitative comparison (plot)	Step time: 1 min and space discretization constant: 0.3
Yang et al. (2015)	Yes, set at 26°C when the room is occupied	Full scale test room	2 occupants sleeping for 10 hours	Does not apply	Does not apply	Does not apply	Does not apply	CTF, HAMT and EMPD	No	3 different climates (Hot/humid, temperate and hot/dry)	T_i	Qualitative comparison (plot)	Dehumidification system on if $>$65% and the test room is occupied

Chapter 2

Procedure to simulate buildings

This chapter is based on the book Building refurbishment for energy, specifically of the chapter 5 of the authors Pernetti et al. (2014), which includes a process to simulate real buildings. The book includes the steps that have to be followed before the simulation starts, a methodology for the treatment for the data obtained, recommendations to obtain the properties of the materials, equipment commonly used to measure the experimental data and the model validation. This chapter also includes the explanation of some metrics used in the articles reviewed in Chapter 1.

2.1 The calibration process of building energy models

In chapter 5 of Pernetti et al. (2014) a calibration procedure for the simulation of buildings is proposed, this includes a list of the works and protocols that exist for the simulation model calibration and metrics for the comparison. The European Committee for Standardization (CEN) Technical Committee 89 (Working Group 14) is working on the standardization for the simulations in Europe, the work includes strategies for the calibration and measurements of post-processing procedures. Currently three protocols exist, that define the criteria and tolerance range for the calibration for building energy models, the International Performance Measurement and Verification Protocol (IPMVP), Measurement and Verification (M&V) and ASHRAE Guideline 14/2002: Measure of energy and demand savings (Pernetti et al., 2014).

The calibration operative procedure can be divided into six steps.

1. Selection of comparison variables
   The variables of comparison for the simulation and the experimental data are selected.

The book recommends the energy consumption for buildings with HVAC systems (BAC) and the temperature for buildings without these systems (BnAC). The most used variables of comparison are:

- For BAC: actual energy consumption, that can be calculated with two different methods, the indirect using energy bills and the direct using measurements.
- For BnAC: indoor air temperature, and can be complemented with surface temperature, these variables are commonly measured with resistance thermometers, thermocouples or thermistors. The sensors should not be located in places near a heat source or direct sunlight, avoid the edges and thermal bridge effect. If possible thermography should be used to locate non-homogeneous areas.

2. Comparison variables data gathering
   For BAC, determine the consumption of energy and fuel. For BnAC, select the places where the temperature sensors are going to be set and make measurements.

3. Building data gathering and simplifications
   Search for information related to the geometry, materials, the HVAC systems, the internal gains, infiltration and the weather data in order to determine if there is going to be any simplifications in the model.

4. Sensitivity analysis
   Determine the variation of the dependent variables with respect to the variation of input data due to the uncertainty of them. Predict how these variables will affect the output of the model. The sensitivity analysis methods for building simulations can be divided into two categories.

   - External methods: a sample of inputs are generated and the deterministic numerical model is executed for each input.
     - Local $\Rightarrow$ evaluates the uncertainty of the output with respect to the variation of a parameter. For example, to variate the values of internal mass and compare the results from before and after the change was made.
     - Global $\Rightarrow$ evaluates the uncertainty of the output on a range of variability of the input data. This could be made by a program that gives the probability distribution function of each parameter.
   - Internal methods: directly evaluate the output distribution from the uncertain inputs and from the differential equations of the mathematical model.

5. Input data gathering campaign and data selection
Once the important variables are selected with the sensitivity analysis, the data are classified into two categories: the model inputs and the control variables for calibration.

The Guideline ASHRAE 14 has a hierarchy of the type of sources where data can be found, according to the type of source the data have a specific range of variation.

- Direct sources
  - Long-term monitoring ⇒ more than 6 months
  - Short-term monitoring
  - Spot measurements
  - Use of building permanent measurements
  - User interview
- Indirect sources
  - Design project and documentation
  - Technical sheet of materials and operating manual of the HVAC system
- Standard sources
  - Technical standards
  - Standard guidelines and reference catalogs

In the case of indirect and standard sources any value used in the simulation should be verified, this type of source is the one that can be adjusted to calibrate the simulation.

The next steps are usually followed for the calibration process.

(a) Thermal conductance measures
This step is crucial in constructions where materials and their properties are unknown. The steps for the experimental approach can be found in the ISO 9869:1994 and applies especially for opaque elements. The ISO 9869 specifies the equipment, methods for the measurement, quality and post-processing techniques. The measurements should be made with a heat flow meter pasted to the wall with thin silicon and 2 thermometers in both internal and external surfaces. The time of measurement should be more than 72 hours and can be extended as long as 7 days. The international standard proposed two different techniques for the post-processing, the average method and the dynamic analysis method.

(b) Weather data
The weather data are major variables that will control the behavior of the simulation. In order to have data that are reliable, the next steps should be followed.

i. Quality assurance ⇒ Verifies the data consistency, the quality, ensure there are no outliers or unphysical data. For this purpose the World Meteorological Organization (WMO) propose the next test.
   - values exceeding more than 50 % the 1st and 99th percentile are deleted
   - temperature derivatives higher than 4 K/h are not physical
   - values repeated for more than five times for temperature, solar radiation and wind velocity are anomalous data for data with a time frequency of 10-15 min
   - values repeated for more than five times for relative humidity are anomalous if lower than the 75th percentile for data with a time frequency of 10-15 min
   - values of global solar radiation higher than solar constant are eliminated as well as radiation before sunrise or after sunset
   - negative values of wind velocity, solar radiation and relative humidity as well as relative humidity higher than 100 % are nonphysical

ii. Quality control ⇒ Detection of missing data, errors and the solution to these errors to provide accurate data. Interpolation of data is accepted if there is no more than 25% of the data missing. Linear interpolation is accepted for short periods of time and only for temperature, relative humidity and wind velocity. Interpolation for long periods and solar radiation, the cyclic interpolation is recommended.

iii. For the infiltration, the recommended value is 0.5 ach when there are no HVAC systems.

6. Comparison for the model validation
   This step is to ensure that the model has a similar behavior to the real building. The comparison between simulated results and measurements of the selected comparison variables can be qualitative and quantitative.

   For a qualitative comparison, plots of the comparison variables are used.

   For a quantitative comparison, the following metrics are used. In the literature, some metrics have different names that change from author to author, the name used in this work is the most commonly found.

   - For electrical consumption and temperature

- From the linear adjustment to the data in the plane M, S, where M is the measured result and S is the simulated result. The following metrics are defined.
  * Slope (m): The best value that could be obtained is 1.
  * Intercept (b): The best value that could be obtained is 0.
  * Correlation coefficient (R^2): The best value that could be obtained is 1.
- Pearson's index (r): is the correlation between two variables, in this case the simulated and measured results.

$$r = \frac{\sum(M_i S_i) - \sum M_i \frac{\sum S_i}{N}}{\sqrt{\left(\sum M_i^2 - \frac{(\sum M_i)^2}{N}\right)\left(\sum S_i^2 - \frac{(\sum S_i)^2}{N}\right)}} \tag{2.1}$$

where S_i is the ith simulated result and M_i is the corresponding measured result, N is the total number of data.The results can be interpreted the next way.

$$If \begin{cases} r < 0 & \text{opposite correlation: the model is not representative} \\ r = 0 & \text{no correlation between variables} \\ r > 0 & \text{direct correlation if } r > 0.5 \text{ significant correlation between variables} \end{cases}$$

- Total error per time unit (te): the algebraic sum of the difference between the simulation and the measurements divided by the time period (Barbaresi et al., 2015).
- Excess error (ee): the sum of all the positive values of the difference between the simulation and the measurements divided by the time period (Barbaresi et al., 2015).
- Defect error (de): the sum of all the negative values of the difference between the simulation and the measurements divided by the time period (Barbaresi et al., 2015).
- Absolute error (ae): the sum of all absolute values of the difference between the simulation and the measurements divided by the time period (Barbaresi et al., 2015).

• For electrical consumption

- Mean bias error (mbe): provides information about the resemblance of the simulation with respect to the measured data for a given period

$$mbe = \left[\frac{1}{N} \sum_{i=1}^{N} \frac{(S_i - M_i)}{M_i} \right] \tag{2.2}$$

The results can be interpreted the next way.

$$If\ mbe\ is \begin{cases} positive & \text{simulation overestimates measurements} \\ negative & \text{simulation underestimates measurements} \end{cases}$$

- Root mean square error (rmse): provides the absolute value of the differences between the measured and simulated temperatures.

$$rmse = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left(\frac{S_i - M_i}{M_i} \right)^2} \tag{2.3}$$

• For temperature

- Differences root mean square (drms): provides the absolute value of the differences between the measured and simulated temperatures.

$$drms = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left(S_i - M_i \right)^2} \tag{2.4}$$

- ΔT_i: The average difference of the simulated and measured value of the indoor air temperature.
- ΔT_{imax}: The average difference of the simulated value and measured value of the daily maximum indoor air temperature.
- ΔT_{imin}: The average difference of the simulated value and measured value of the daily minimum indoor air temperature.

2.2 Tolerance ranges of some metrics for model validation

The tolerance ranges proposed in three documents, International Performance Measurement and Verification Protocol (IPMVP), Measurement and Verification (M&V) and ASHRAE Guideline 14/2002: Measure of energy and demand savings (Pernetti et al., 2014), for mbe and cvrmse for electrical consumption are shown in table 2.1 for monthly data and for hourly and subhourly data.

Table 2.1 Tolerance ranges for monthly data and for hourly and subhourly data for electrical consumption.

	IPMVP	M&V	ASHRAE 14
$mbe_{month}[\%]$	± 20	± 15	± 5
$cvrmse_{month}[\%]$	5	10	15
$mbe_{hour}[\%]$	-	-	± 10
$cvrmse_{hour}[\%]$	-	-	30

Andelković et al. (2016) recommended that R^2 must be equal or greater than 0.75.

2.3 Variable and metrics of comparison for this thesis

The comparison variable that is suitable for this work is temperature because the simulated space that will be used for the simulation validation had the air conditioning turned off in the period of validation. The indoor air temperature (T_i), outdoor air temperature (T_o), solar radiation (I_s), wind speed (W_s), wind direction (W_d), outdoor air relative humidity (H_o) and atmospheric pressure (P_a) have been measured. The following metrics of comparison are suggested, m, b, R^2, r, drms, ΔT_i, ΔT_{imax}, ΔT_{imin}, Δdf and Δlg.

Chapter 3

Methodology

This chapter gives a general description of the studied building and describes the methodology followed for the experimental measurements, for the simulations and for the validation process.

3.1 Building general description

The studied building is located in Temixco, Morelos, Mexico. The building has five stories, as can be seen in figure 3.1, but only the two upper stories were simulated. In the following, these two stories will be called the simulated building. The two stories are connected by a central space with natural ventilation. The building has a rectangular base with large façades to the North and South with an angle of 6.8° to the East-West, the calculation of this angle can be found in Appendix B. The building has solar vertical protections for the North and South façades with the same vertical length. In the South, they are equally spaced but in the North they have different spacing, as can be seen in figure 3.1 (photo) and 3.3 (simulation view). On the roof the central space has an elevation with respect to the rest of the roof level, this elevation has mostly windows as walls. On the roof there are two solar collectors and a platform with the weather station that recorded the data for this study. The East and West walls are double walls. The North and South façades are half windows and half walls. The interior walls that face the central space are mostly windows.

The simulated building is used for the master's and Ph.D. students as workspace, as offices of the Postgraduate's and Bachelor's coordinators and as cubicles for some researchers.

The space used to validate the model of the simulated building is an office in the second story. The office was chosen because it has high temperatures compared with the rest of the building due to its location in the Southwest corner of the building. The office has air

(a)

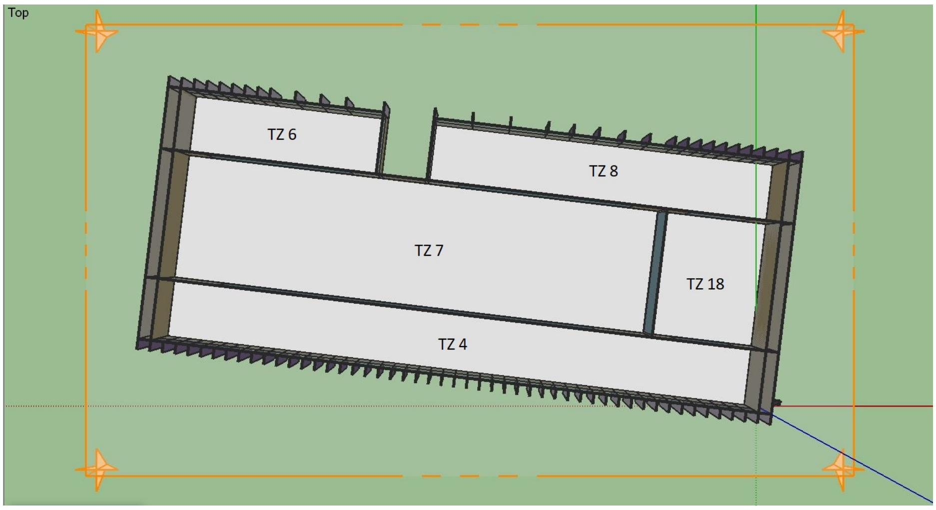
(b)

Fig. 3.1 Real building views. (a) South perspective. (b) North perspective.

conditioning but it was turned off, inhabited and closed during the measured period. Not using air conditioning is the reason to use T_i as variable for the validation.

Figure 3.2 shows the thermal zones (TZ) in which the building was divided. The thermal zone studied in this thesis is the number 16, which can be found in figure 3.2b as TZ 16.

(a)



(b)

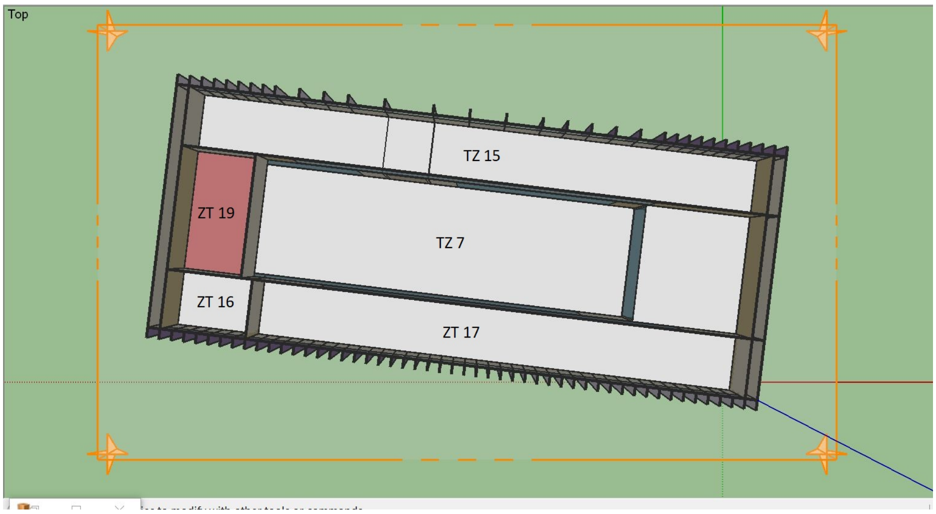


Fig. 3.2 Plan views from SketchUp divided by thermal zones. (a) Lower plan view. (b) Upper plan view.

3.2 Experimental measurements

The weather data to create the weather file (epw) were obtained from the weather station of the IER, that is a direct source of information, and can be found in IER-UNAM (2010). The weather station is located just in the roof of the simulated building. The measured variables are I_s, T_o, H_o, P_a, W_s and W_d. The weather data used were verified with all the steps in the quality assurance process. Then the quality control steps were followed, 2 data were missing, for which linear interpolation was used. The epw file used data from the 26^{th} of September to the 19^{th} of October 2018.

In order to obtain the data for the validation, a direct source of information was used, the temperature sensor of a QUESTemp 34 heat stress monitor, located in the center of the room at a 0.9 m of height, was used. In Appendix A a brief guide on how to use the QUESTemp 34 is presented. The measurement period was from 10^{th} to the 19^{th} of October 2018, this is the period of data used for validation. However, this period has an interruption of approximately eight hours the 12^{th} and a second interruption of a day and a half from the 15^{th} to the 17^{th}.

3.3 EnergyPlus simulation

In this section the procedure followed for the simulation is presented. The first section describes the general considerations made for the simulation. The second section presents the materials and the constructions used in the simulation. The third section describes the method used to simulate the natural ventilation. The fourth and fifth section describe the procedure followed to simulate the lights and electrical consumption respectively. The base case, that includes all the model inputs, is considered to be the simulation with all the information described in this section.

3.3.1 General considerations

The simulated building was divided into 19 thermal zones. The boundary condition in the building floor are considered adiabatic, supposing that there are the same conditions in the classrooms below the simulated building thus there are no heat transfer between the two spaces. The internal walls in the zones are considered as internal mass. The solar protections were drawn with the same geometry of the real ones and were simulated as shading surfaces. The solar protections generated a warning in the simulation that was discarded with a numerical experiment that showed that the simulation was working correctly. The numerical experiment consisted in visually confirming in SketchUp that the incident solar radiation in the walls, where the solar protections were located, starting and ending at

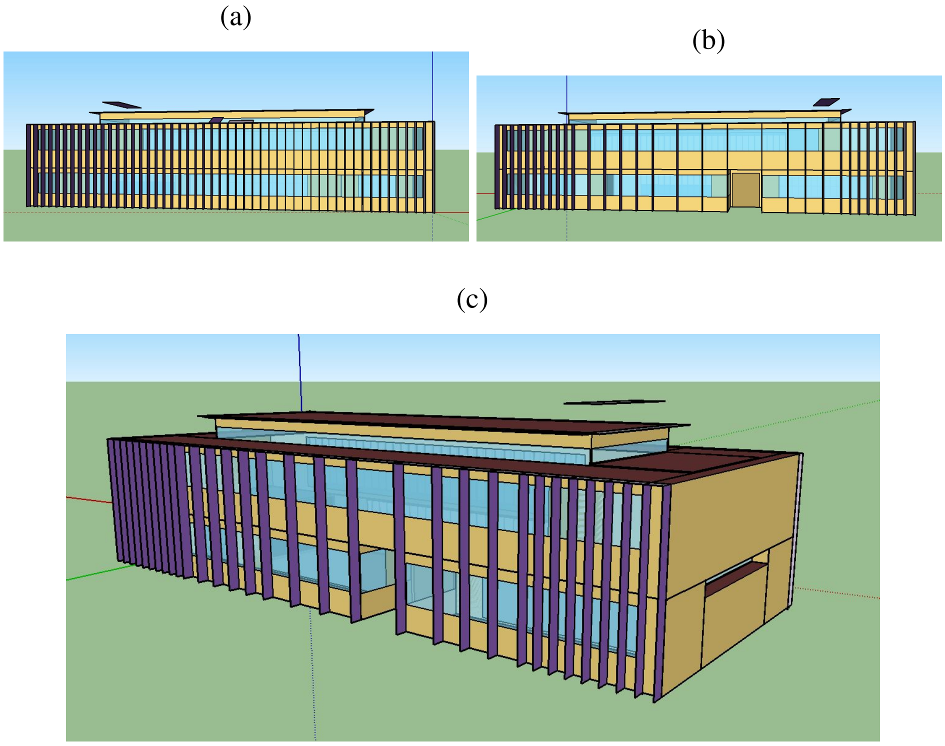


Fig. 3.3 Simulated building views in SketchUp. (a) South. (b) North. (c) Perspective.

hours corresponded to the hour that appeared in the EP results. To complete the experiment another simulation without the solar protections was made. The peak value for the solar radiation had to correspond in both simulations, because the solar protection are just lines and there is no shading at solar noon, which was confirmed with the simulation. The solar collectors and the platform for the weather station were considered as shading surfaces. For the properties of the materials indirect and standard sources of information were used, the information of the building and planes were taken from (ST-IER-UNAM, 2005). A simplification was made with the doors and walls that face the central area, an equivalent area was used to simulate these objects. One of the materials that compose the roof is scoria rock, commonly known as tezontle, it is used in different thickness that variate from 5 cm to 30 cm. In this case a simplification was made by calculating the volume of this material and obtaining a uniform thickness which is 15 cm. A correction in the wind speed profile had to be made because the simulated building has only two stories and the real one has five, this correction can be consulted in Appendix C.

3.3.2 Materials

All the materials used in the constructions are known (ST-IER-UNAM, 2005), thus thermal conductance measurements were not needed. Most of the properties of the materials were taken from the database of Ener-Habitat (IER-UNAM et al., 2014), the rest were taken from the database of OpenStudio (NREL et al., 2013). Table 3.1 shows the constructions of opaque elements of the simulated building such as walls and columns. In the case of the windows the material used was glass with a thickness of 0.3 cm. The constructions used for the simulation are presented on table 3.1 from the exterior to interior layers and are divided according to the type of element (floor, wall, roof) and location. The construction used for the internal walls that face the central zone is named Internal to central zone, while the Internal partition is the construction that divides the cubicles. In the case of the construction Internal to central zone a simplification was made, the aluminum of the frames for the windows was not considered in the construction, the original construction has iron columns but most of the area for those walls is covered by windows. The construction Office refers to an office that is at the East, in the first story. The roofs of the building have a steel deck which is not considered in the simulation because of the very low thickness of this material. The East and West walls are made of hollow brick, to simulate these walls a simplification of the EHLS method proposed by Huelsz et al. (2017) was used. The simplification consists on the used of a constant thermal conductivity instead of temperature dependent thermal conductivity by Aguilar Mier (2018). A program to calculate the thermal properties of the equivalent homogeneous layer that correspond to air in the hollow brick was used (Barrios, 2017). The resulting values are, thickness 7.81 cm, thermal conductivity 0.305 W/m K, density 1000 kg/m^3 and specific heat 467.125 J/kg K.

3.3.3 Natural ventilation

The natural ventilation in the central zone was simulated with the model AirflowNetwork in EnergyPlus. Four openings were considered for the central zone, the first one is the door which is open from 7 to 21 hours in the working days, the second opening is a window in the first story in the West wall, the third and fourth openings are windows, one facing North and one facing South, in the second level (with area equal to the sum of all corresponding open windows).

The wind pressure coefficients calculation were made by the program with the option surface average calculation. To simulate the openings in the building the object:DetailedOpening is used with a discharge coefficient equal to 1, with the consideration that the windows work as entrance and exit.

Table 3.1 Constructions and thickness

Element	Construction	Material	Thickness [cm]	Thermal conductivity [W/m K]	Density [kg/m^3]	Specific heat [J/ kg K]	Reference
Floors	Floor	High density concrete	13	1.35	1800	1000	IER-UNAM et al. (2014)
Walls	North/South	High density concrete	8	1.35	1800	1000	IER-UNAM et al. (2014)
	Internal to central zone	Iron	50				NREL et al. (2013)
	Internal partition	Gypsum	1.9	0.16	784.9	830	NREL et al. (2013)
		Air	-	-	-	-	-
		Gypsum	1.9	0.16	784.9	830	NREL et al. (2013)
	Office	Aluminum	7	160	2700	1213	NREL et al. (2013)
	East/west	Hollow brick	12	0.7	1970	600	IER-UNAM et al. (2014)
Roofs	Roof second story	High density concrete	4	1.35	1800	1000	IER-UNAM et al. (2014)
		Tezontle	15	0.16	400	1000	Cedeño Valdeviezo (2010) and Cortés Portillo (2008)
		High density concrete	8	1.35	1800	1000	IER-UNAM et al. (2014)
	Roof	High density concrete	24	1.35	1800	1000	IER-UNAM et al. (2014)

3.3.4 Lights

The calculations of the power consumption of the lights were made for each of type of lamp in the building times the number of lamps in each space. Once the power consumption in each thermal zone was determined, the return air fraction, the fraction radiant, the fraction visible and the fraction replaceable were determined using the values of the most similar lamp model in the list of LBNL (2018) to the more common one in the building, that is a lamp with two fluorescent tubes. The return air fraction refers to the heat that goes to the return air, in the case where the zone has no return air system the air is introduced into the zone. The fraction radiant is the long-wave radiation that receives the zone from lights. The fraction visible is the short wave radiation that receives the zone from lights. The fraction replaceable is used to turn on/off the daylight controls when the building has them. Considering this approximation, the value for the return air fraction was 0.56, for fraction radiant 0.12, for fraction visible 0.20 and for fraction replaceable 0.

3.3.5 Electrical equipment

The power consumption by the electrical equipment in the office used for the validation and in the closer zones to it was accurately audited and entered in the simulation. For the electrical equipment of the other zones an approximation is made, assuming for staff use a PC with power consumption of 300 W, for students a laptop with power consumption of 70 W and for all zones a 10% extra of power consumption of cellphones.

3.3.6 Internal mass

The internal walls in the zones were considered as internal mass, as was mentioned in the general considerations. The construction used for these walls was Internal partition that can be found in table 3.1. The furniture in the building are mostly wood desks and shelves, this type of furniture is the only one considered for the internal mass. To simulate this furniture a new construction was created, the construction is of wood of 5 cm of thickness. For the calculations of the area that is covered by this construction it was considered that the area of a desk is approximately of 1.5 m^2 and for the area of the shelves a value of 1.75 m^2. Those areas were multiplied by the number of people in the zone. For detailed information about the internal mass calculations see Appendix 4.

All the model inputs described in this section are included in the base case of the simulation. In figure 3.4, the comparison of the base case with the measurement is presented. It can be observed that in the base case of the simulation the indoor temperature in the office is underestimated. The next step for the calibration process is to add the control variables to the simulation, which will be the one that provides accuracy to the model.

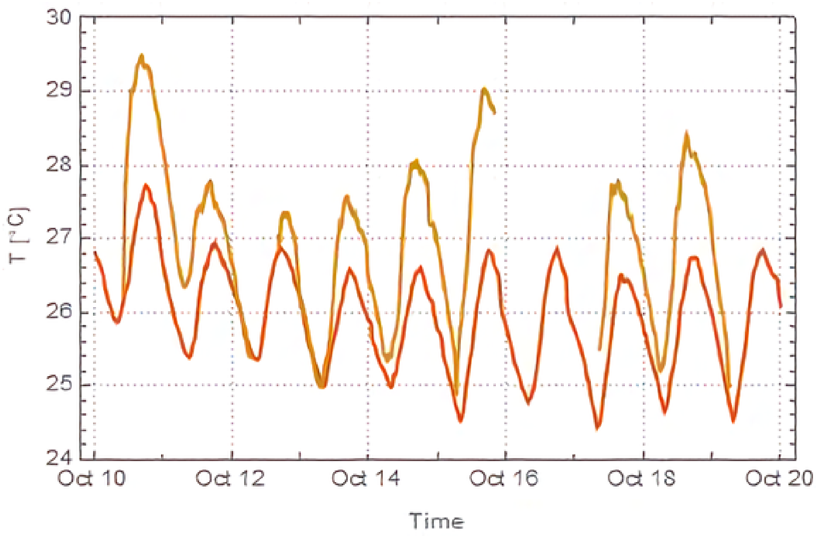


Fig. 3.4 Comparison of the base case with the measurement. The orange line represents the base case of the simulation. The yellow line represents the measurement.

3.4 Validation process

The variables that are used as control variables, for which the sensitivity analysis was made with external local method, are the people and the infiltration. The external local method consisted of a qualitative comparison, a plot, of the results with different values on the activity of people and the air flow mass coefficient for infiltration.

3.4.1 Internal gains of people

The building occupancy is difficult to know because there are a lot of students that enter the building but only stay for a few minutes and because the postgraduate students are intermittent in their workspace. The people with short stays were not considered. The first step was to know the number of people assigned in each of the cubicles. The second was to make the schedules for the cubicles near to the office, asking the users. The number of people calculation method was number of people. The control variable in this case is the level of activity per person, that can be between 100 W and 150 W (LBNL, 2018) correspondent to office related activities. The level of activity was varied until the simulation showed the best results with a value of 150 W.

3.4.2 Infiltration

The way to simulate infiltration is via the crack object in the zone and by using an air mass flow coefficient, the value for this coefficient is usually considered between 0.0001 and 0.003 according to Gudnason and Scherer (2012). In this case the air mass flow coefficient is assumed to be bigger because doors and windows in Mexico are less airtight than EEUU and European countries. The infiltration was considered for the validated office, the zones next to it and the zone below it. The air mass flow coefficient was modified until the amplitude of the oscillation of T_i from simulations was as large as the measured one, an air mass flow coefficient of 0.02 was the best value. The mean air changes per hour in the validated office is of 0.2 which is a low value considering that Pernetti et al. (2014) propose a value of 0.5 ach when the infiltration is unknown. In figure 3.5 can be observed the air changes per hour in the validated office, it can be seen that most of the time the value of the infiltration is below 0.5 ach and that in only a time step the value reaches 2.2 ach. In a study made by Asociación de Empresas para el Ahorro de Energía en la Edificacaión, North America Insulation Manufactrers Association and Environment Canada (AEAEE et al., 2012) the mean value of infiltration in houses in Mexico is of 5 ach.

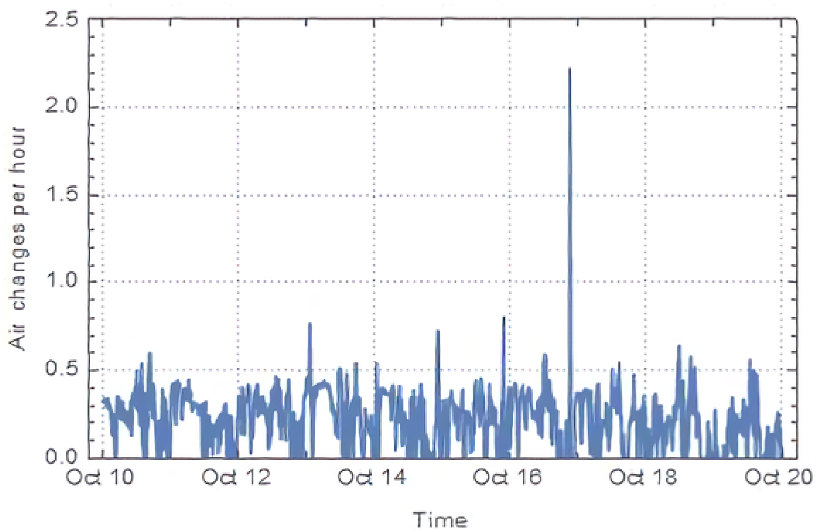


Fig. 3.5 Air changes per hour in the validated office, calculated with an air mass flow coefficient of 0.02.

Chapter 4

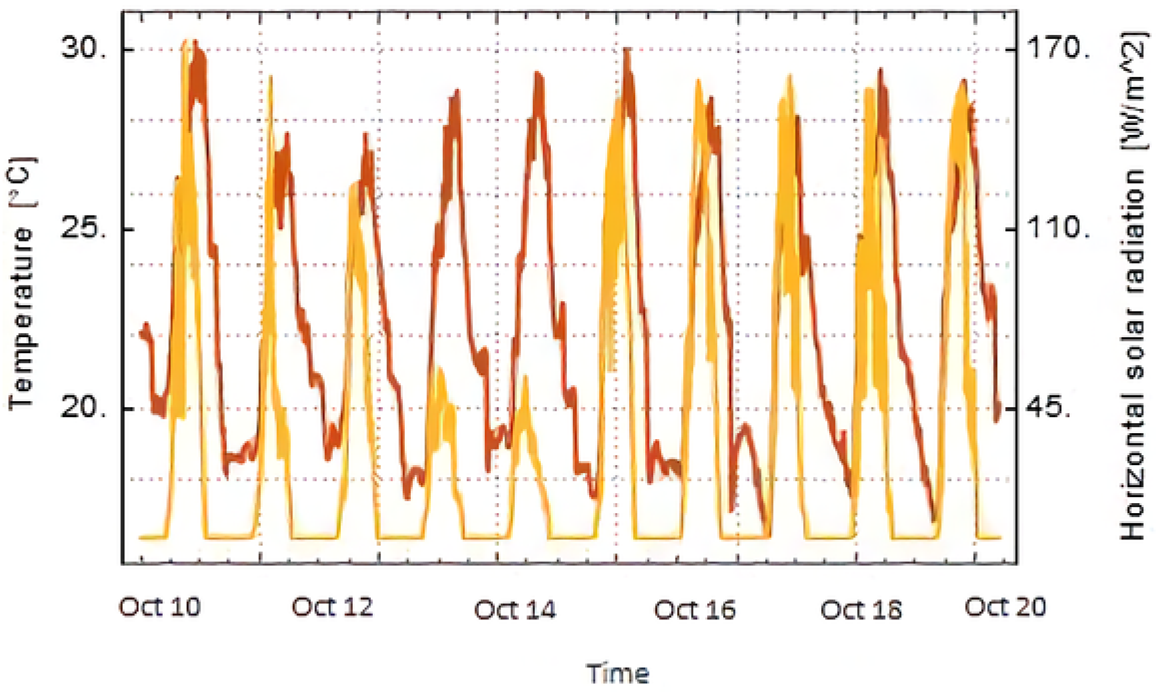
Results comparison

In this section the results of the simulation are presented and compared to experimental data. For the results of simulation two cases are presented. The case 1 is the base case with the internal gains from people and the infiltration values from the validation process, that is the simulated building has the solar protections drawn in SketchUp as shading group, and the case 2 is the simulated building without any solar protections. The results presented are qualitative comparisons of the mean, minimum and maximum of the T_i, decrement factor and lag time and quantitative comparisons of T_i using as metrics m, b, R^2, r, drms, ΔT_i, ΔT_{imax}, ΔT_{imin}, Δdf and Δlg.

Figure 4.1a presents the outdoor air temperature and the solar radiation in the period of validation. Figure 4.1b presents T_i from measurements and from simulations. In figure 4.1b can be observed that the results of the case 1 of the simulations follow very well the behavior of the measurements. However, the simulation doesn't reach the maximum temperatures measured but in most of the days the minimum obtained by the simulation is very near to the measurement. For this reason the case 2 was decided to be created, the case 2 considers that the solar protections don't exist. In this figure can be observed that when the protections are not drawn the minimums change almost nothing but in the maximums there is an important change and are closer to the measurements. It can be observed that in the days were radiation is lower the simulations presents better behavior than in days with higher solar radiation. This would indicate that the solar protections in the building are providing heat to the building. Due to the consideration of simulating these elements as shading surfaces without materials and the consideration of EP that these elements are not taken into account to the heat transfer, the assumption is that long-wave radiation is provided by these elements.

The figure 4.2 presents the average of the daily mean temperature for the days in which the measurement is complete, eleven, thirteen, fourteen and eighteen of October 2018. It can be observed that case 1 presents lower mean temperatures and that the mean temperature

(a)



(b)

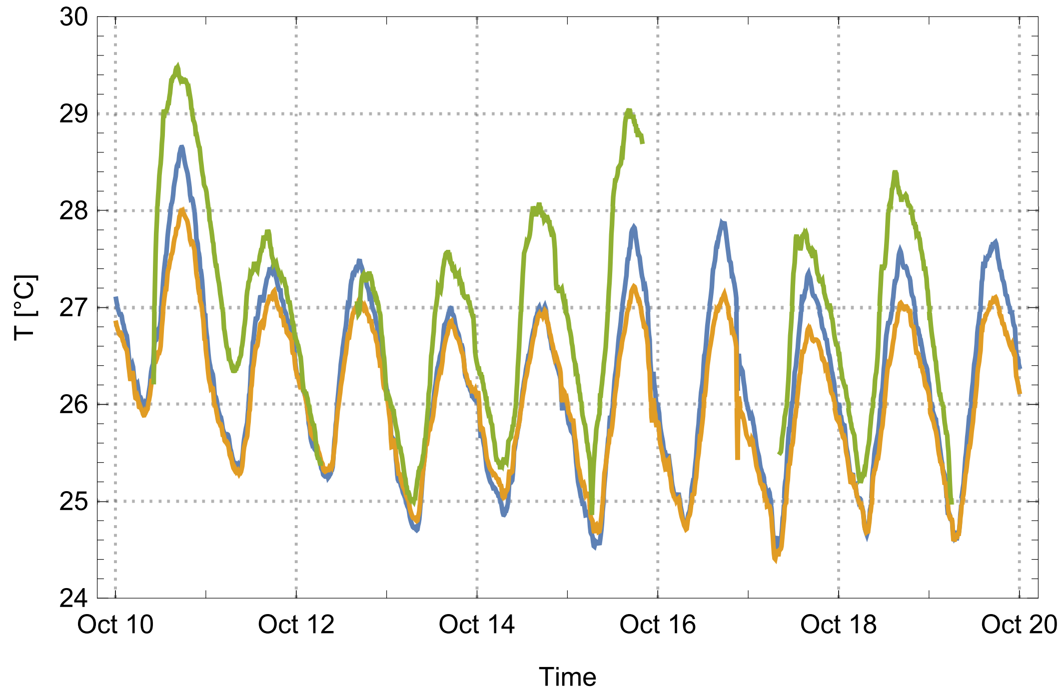


Fig. 4.1 Results. (a) Radiation and outdoor air temperature. The orange line represents the outdoor air temperature and the yellow line represents the solar radiation. (b) Temperatures measured and simulated. The green line represents the measurements, the yellow line represents the case 1 simulated and the blue line represents the case 2 simulated.

for this case, barely change from day to day. The daily mean temperature from case 2 is higher and there is a bigger change from day to day. Although neither case is equal to the measurements, it can be observed that the differences are less than $1°C$.

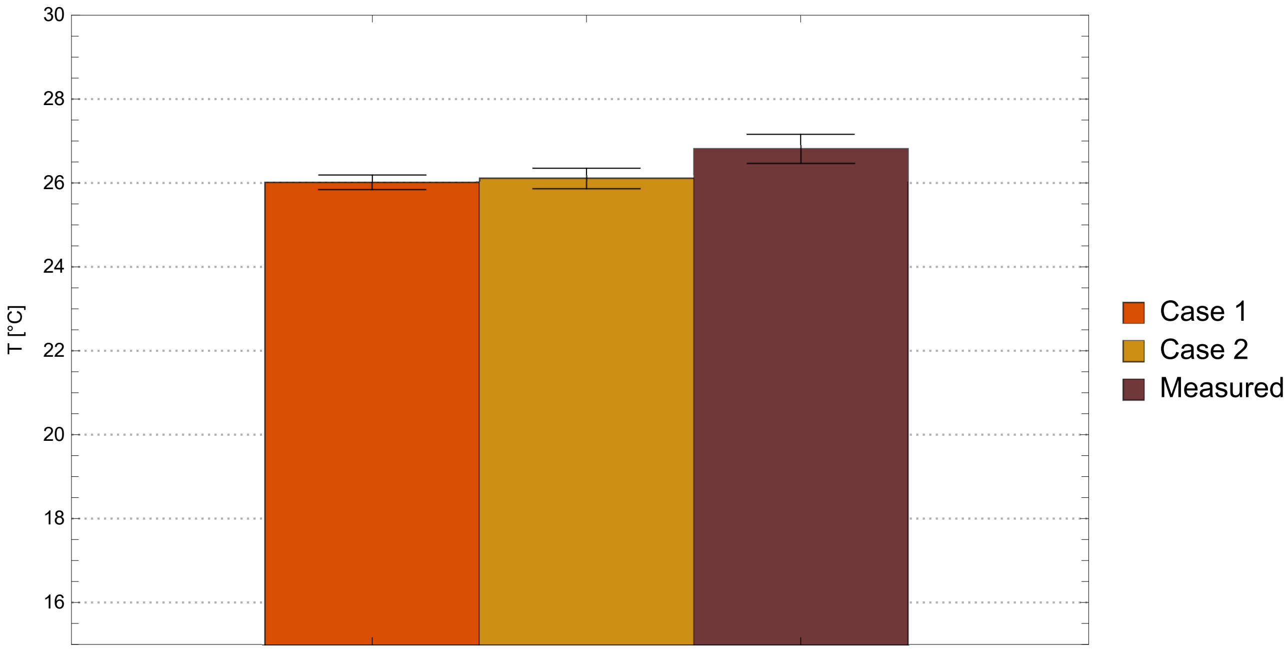


Fig. 4.2 Average of the daily mean temperature. The orange bar is the case 1, the yellow bar is the case 2 and the brown bar is the measurements, each one of them with their respective standard deviation.

In figure 4.3 the daily mean temperature, for four days, is presented and compared both simulation cases with the measured. It can be observed that the lower differences between the measurements and the simulations are for the in days that have lower solar radiation . It can also be observed that the difference between the results of case 1 and case 2 are minimum in the days that solar radiation is low, which can reaffirm the assumption that the model is subvaluating the solar radiation absorbed by the building.

Figure 4.4 presents the average of the daily maximum temperature. It can be observed that the maximum difference is between the case 1 simulation and the measurements, $1.5°C$. The difference between the case 2 simulation and the measurements is approximately of $1°C$. The daily maximum temperature in case 2 variates more than in case 1.

In figure 4.5 the average of the daily minimum temperature for both simulation cases and the measurements are presented. It can be observed that the value in both simulation cases is almost the same. It can be observed that the maximum difference between the measurements and the simulations is of $0.5°C$.

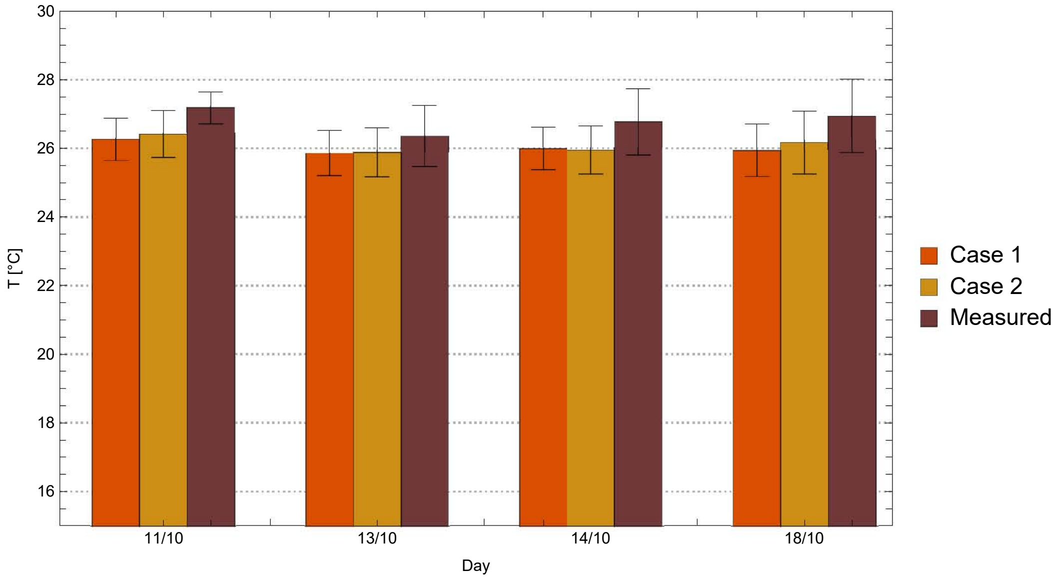


Fig. 4.3 Daily mean temperature. The orange bar is the case 1, the yellow bar is the case 2 and the brown bar is the measurements, each one of them with their respective standard deviation.

In figure 4.6 the decrement factor is presented for five of the ten days simulated. It can be observed that the higher difference between measurements and both simulation cases is the fifteen of October, this day had higher solar radiation than other days. It can also be observed that most of the decrement factors improved in case 2 with respect to the measurement, except in the eleven of October.

Figure 4.7 shows the linear adjustment of the simulated T_i with respect to the T_i measured, for case 1 and case 2. The related metrics are included on table 4.2. It can be observed from figure 4.7 that the simulation is underestimating the temperature. In figure 4.7b can be observed that the linear adjustment of the results obtained by case 2 is closer to the ideal case, where m=1, b=0 and $R^2 = 1$, than case 1.

Table 4.1 presents the results of the lag time from measurements and the simulations, case 1 and case 2. It can be observed that in most of the days the lag time of both simulation cases is the same and are different from the lag time of the measurements. In the days the lag time of the simulations is different, case 2 has closer results to the measurements in comparison to case 1. The days 11 and 13 of October the maximum outdoor air temperature measured was late in the afternoon compared to the other days, this explains the negative values obtained in the lag time of those days.

Table 4.2 presents the results of the calculations for the metrics in each of the simulations. From the value of mbe, ΔT_{imax} and ΔT_{imin}, it can be observed that the temperature in both simulations is underestimated. In case 2 all the values are slightly better than case 1,

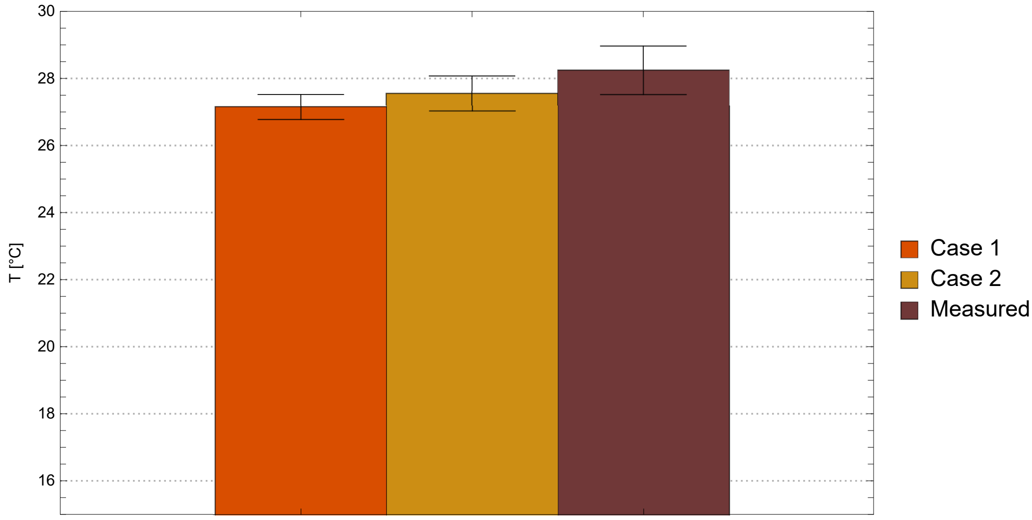


Fig. 4.4 Average of the daily maximum temperature. The orange bar is the case 1, the yellow bar is the case 2 and the brown bar is the measurements, each one of them with their respective standard deviation.

Table 4.1 Lag time results comparison

lag time [min]	10/10	11/10	12/10	13/10	14/10	15/10	16/10	17/10	18/10	19/10
Measurements	56	-50	260	-43	96	23	-	58	12	-
Case 1	150	70	110	40	200	120	130	130	110	210
Case 2	150	70	110	40	100	110	130	100	90	160

indicating that the solar protections that are absorbing solar energy due to their red color could be transferring heat to the building by conduction and by radiation. The results in this thesis obtained for R^2 are greater than the minimum value acceptable.

Table 4.2 Metrics and tolerance ranges given in the literature

	r [-]	drms [°C]	m [-]	b [°C]	R^2 [-]	ΔT_i [°C]	ΔT_{imax} [°C]	ΔT_{imin} [°C]	Δdf [-]	Δlg [min]
Case 1	0.87	1.04	0.62	9.3	0.77	-0.9	-1.1	-0.4	- 0.06	62
Case 2	0.89	0.91	0.76	5.6	0.80	-0.8	-0.7	-0.6	-0.02	45
Andelković et al. (2016)	-	-	-	-	≥ 0.75	-	-	-	-	

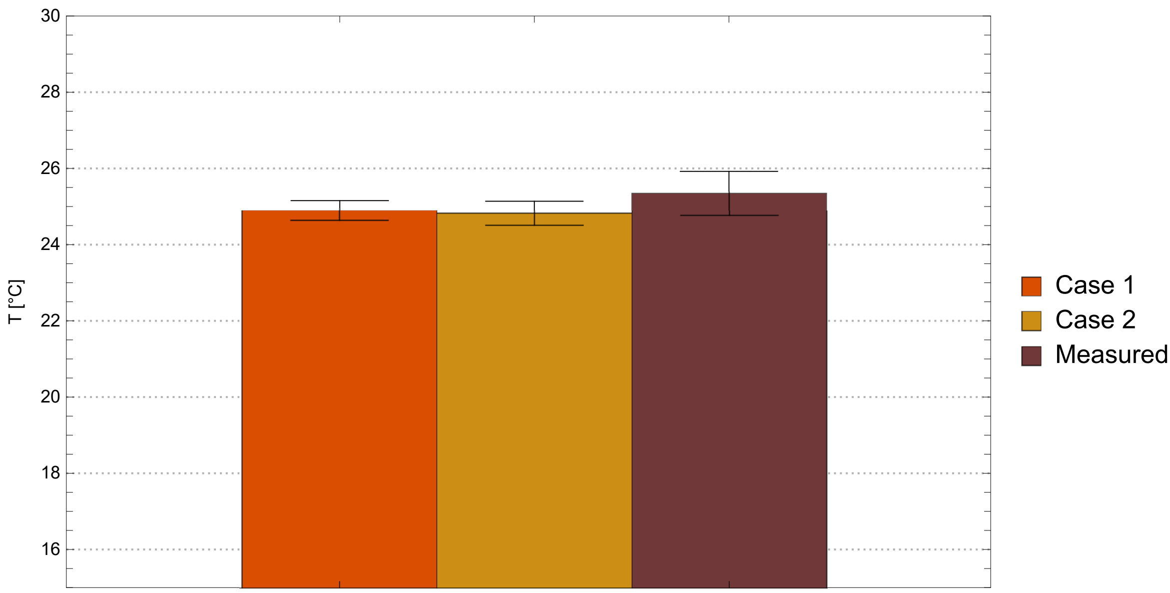


Fig. 4.5 Average of the daily minimum temperature. The orange bar is the case 1, the yellow bar is the case 2 and the brown bar is the measurements, each one of them with their respective standard deviation.

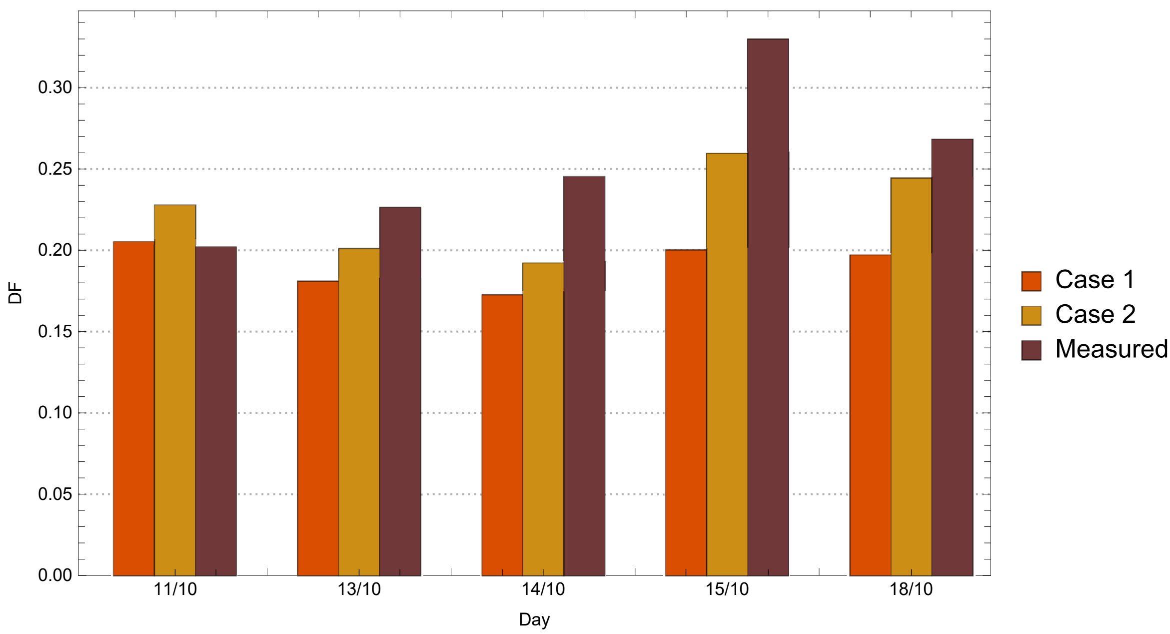


Fig. 4.6 Decrement factor. The orange bar is the case 1, the yellow bar is the case 2 and the brown bar is the measurements, each one of them with their respective standard deviation.

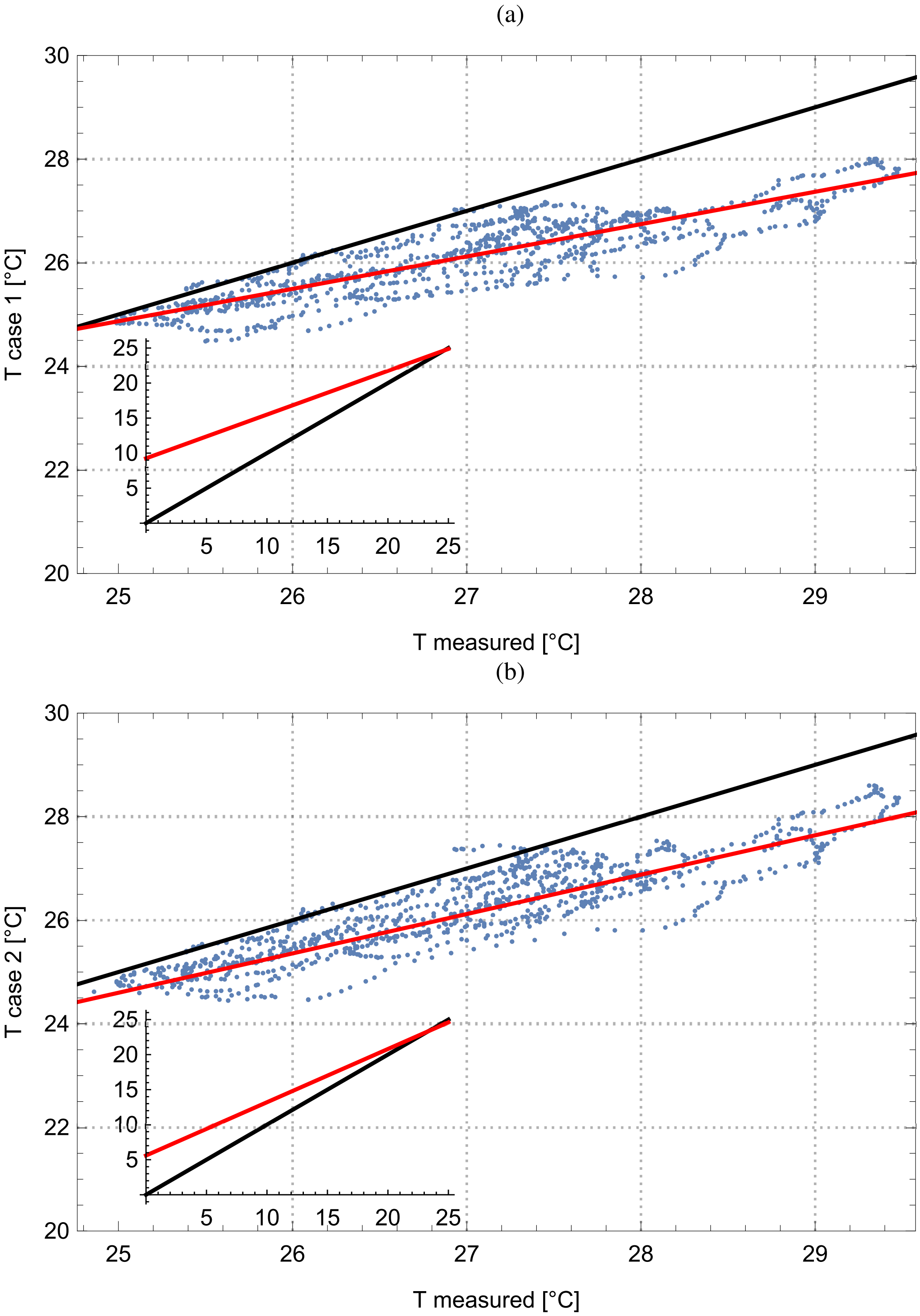


Fig. 4.7 Linear adjustment. (a) The indoor air temperature of the measurement and of case 1 of the simulations. (b) The indoor air temperature of the measurement and of case 2 of the simulations. The red line represents the linear adjustment to the data from each case. The black line represents the linear adjustment for a perfect match between the measured and simulated data.

4.1 Comparison with results of the literature

The values of the metrics obtained in case 2 of this thesis are compared with the ones reported in the literature (table 1.1). The results of Andelković et al. (2016) shows: the value of mbe indicates that the temperature was subestimated in the simulation as is obtained in this thesis; ΔT_{imin} is similar than the one of this thesis and ΔT_{imax} is larger than the value of this thesis. The results of R^2 in Dahanayake and Chow (2017) are better and very near to 1 in comparison to the results obtained in this thesis which are near to 0.8. Barbaresi et al. (2015) obtained a value of r very near to 1 in comparison with the results obtained in this thesis which is near to 0.9. Barbaresi et al. (2015) also obtained an m very close to one and b very close to 0, in this thesis m is 0.76 and b is 6 °C. Huelsz et al. (2017) reported Δdf of less than 0.1, which is higher than the results obtained in this thesis. For Δlg Huelsz et al. (2017) reported a value of 114 min which is larger than the double of the result obtained in this thesis.

Chapter 5

Conclusions

In this thesis a literature review regarding articles that compared simulations in EnergyPlus and experimental data was made. A review of a procedure to simulate buildings proposed in a book found in the literature was done. The description of metrics found in the literature and the tolerance ranges proposed for these metrics were included. The lack of air conditioning systems in the building and the literature review were the main reason why the indoor air temperature was used as the comparison variable. The methodology followed for the simulation is proposed, based in the literature review. This methodology divide the EnergyPlus input data into model inputs and control variables.

A building from the Renewable Energies Institute (IER) was simulated following the methodology proposed, the internal gains from people and the infiltration were used as control variables. The base case of the simulation was built, including only the model inputs. Case 1 was built with the best qualitative results from the variation of the control variables and includes the solar protections in the building as a shading group. The qualitative results of case 1 showed that the simulation underestimated the temperature at hours of solar radiation for which a case 2 was proposed. The main considerations when the solar protections are modeled as shading group are that they do not have materials or constructions and that these elements do not count in the heat transfer. In reality the solar protections are red hollow bricks and transfer heat by radiation and conduction to the building. For this reasons case 2 was proposed and has no solar protections. The other option to simulate the solar protections is to draw them as thermal zones, due to number of solar protections in the building this is not viable.

The qualitative comparison of results was made with plots of the measurements and the two simulated cases. The quantitative comparison was made with the most common metrics described in the literature review. The results of the metrics from case 1 and case 2 are compared with the studies in the literature and the tolerance ranges.

In all the comparisons, case 2 presents better results than case 1, suggesting that the solar protections in the building are absorbing heat due to their red color, and are transmitting heat by conduction and radiation to the building indoor. The temperature in both simulation cases is underestimated in the day, when there is solar radiation. The real solar protections are of red hollow brick and thus are functioning as fins that absorb heat and transmitting it to the entire building. For this building, it is recommended to paint white or light grey the solar protections. In general, and particularly for the new building for the LIER, it is recommended to use solar protections with low thermal mass and solar absorptance, and preferably also with low thermal emissivity and that reflect diffusely.

The results and the tolerance ranges from the literature review provide a reference frame to know if the results obtained in this thesis are acceptable. Both cases have R^2 greater than the acceptable minimum value of 0.75. The results in this thesis showed that the temperature is subestimated in both cases, as in most of the studies in the literature. For both cases Pearson's index are greater than 0.5, meaning that both cases have a significant correlation. For metrics that there not tolerance range in the literature, the values obtained in both cases are similar to the ones reported in the articles reviewed. In case 2 the average difference of the simulated value and measured value of the daily maximum indoor air temperature is -0.7°C. In case 2 the average difference of the simulated value and measured value of the daily minimum indoor air temperature is -0.6°C. Indicating good results.

Due to the values of the metrics obtained in this thesis and the comparison of them with the ones in the literature, the methodology for the simulation process developed in this thesis can be used to simulate the new LIER building. For the simulations of the new LIER building it is indispensable to include the internal gains from people, lights and electrical equipment. It is recommended to make simulations with maximum people capacity of all spaces and with the expected uses of the spaces.

For the new building the best choice as comparison variable is the indoor air temperature, because the objective of the project is to achieve a thermal comfortable building by using bioclimatic design and low energy cooling systems. However, it would be interesting to also use the electrical consumption as comparison variable.

The simplification of the EHLS method could also be causing the discrepancies between the simulated and the measured temperatures when there is solar radiation. A way to prove this problem of the simplified EHLS is to measure the radiation on the walls. The indoor and outdoor surface temperatures can also be included as variables of comparison in both, the simulated building of this thesis and the new building of the LIER, to have more variables to compare the results for the model validation. The instrumentation, with temperature sensors, of the central zone of the simulated building is recommended. A next step that could improve the model for the simulated building would be to have more details of the internal gains by thermal zone. For future work, a simpler building to evaluate the effect of the type of solar protections that have the simulated building and the strategies to simulate them is proposed.

References

AEAEE, NAIMA, and EC (2012). ZEH in Mexico. page 14. Asociación de Empresas para el Ahorro de Energía en la Edificacaión, North America Insulation Manufactrers Association and Environment Canada.

Aguilar Mier, J. M. (2018). Validación de la simplificación del método ehls para la transferencia de calor a través de la envolvente de una edificación. Universidad Politécnica del Estado de Morelos (UPEMOR).

Andelković, A. S., Mujan, I., and Dakić, S. (2016). Experimental validation of a EnergyPlus model: Application of a multi-storey naturally ventilated double skin façade. *Energy and Buildings*.

Barbaresi, A., De Maria, F., Torreggiani, D., Benni, S., and Tassinari, P. (2015). Performance assessment of thermal simulation approaches of wine storage buildings based on experimental calibration. *Energy and Buildings*, 103:307–316.

Barrios, G. (2017). *S-EHLS program*. Renewables Energies Institute- UNAM.

Calixto-Aguirre, I. and Huelsz, G. (2018). Consumo de energía en edificios en México. *Legado*.

Cedeño Valdeviezo, A. (2010). Materiales bioclimáticos. *Teconología, medioambiente y sostenibilidad*, pages 100–110. Asociación de Empresas para el Ahorro de Energía en la Edificacaión, North America Insulation Manufactrers Association and Environment Canada.

Coakley, D., Raftery, P., and Molloy, P. (2012). Calibration of whole building energy simulation models: detailed case study of a naturally ventilated building using hourly measured data. Technical report.

Cortés Portillo, O. (2008). Análisis térmico de los sistemas constructivos comunes utilizados en techos y muros en vivienda versus la normatividad oficial en el tema, en los diversos bioclimas de méxico. Universidad Nacional Autónoma de México (UNAM).

Dahanayake, K. W. C. and Chow, C. L. (2017). Studying the potential of energy saving through vertical greenery systems: Using EnergyPlus simulation program. *Energy and Buildings*.

Gudnason, G. and Scherer, R. (2012). *eWork and eBusiness in Architecture, Engineering and Construction*. CRC Press.

Huelsz, G., Barrios, G., Rojas, J., Tovar, R., and Jalife-Lozano, S. (2017). Implementation of the equivalent-homogeneous-layers-set method in whole-building simulations: Experimental validation. *Journal of Building Physics*.

IER-UNAM (2010). *ESOLMET-IER*. http://esolmet.ier.unam.mx [Accessed: 22/12/2018].

IER-UNAM, UNISON, UAT, and UC (2014). *Ener-Habitat*. http://www.enerhabitat.unam.mx [Accessed: 22/12/2018].

International Energy Agency, I. and International Partnership for Energy Efficiency Cooperation, I. (2015). Building Energy Performance Metrics. *Building Science Digest*, 4(8).

LBNL (2018). Input Output Reference. EnergyPlus. EnergyPlus:2691.

NREL, ANL, LBNL, ORNL, and PNN (2013). *OpenStudio*. https://www.openstudio.net/downloads [Accessed: 22/12/2018].

Pernetti, R., Prada, A., and Baggio, P. (2014). *The Calibration Process of Building Energy Models*. Springer International Publishing Switzerland.

Sang, Y., Zhao, J. R., Sun, J., Chen, B., and Liu, S. (2017). Experimental investigation and EnergyPlus-based model prediction of thermal behavior of building containing phase change material. *Journal of Building Engineering*, 12(June):259–266.

SENER (2017). Balance Nacional de Energía 2016. *Secretaría de Energía*.

Simá, E., Chagolla-Aranda, M. A., Huelsz, G., Tovar, R., and Alvarez, G. (2015). Tree and neighboring buildings shading effects on the thermal performance of a house in a warm sub-humid climate. *Building Simulation*.

ST-IER-UNAM (2005). *Edificio Posgrado*. Secretaría Técnica Instituto de Energías Renovables de la Universidad Nacional Autonóma de México. Planes and information.

Yang, J., Fu, H., and Qin, M. (2015). Evaluation of Different Thermal Models in EnergyPlus for Calculating Moisture Effects on Building Energy Consumption in Different Climate Conditions. In *Procedia Engineering*.

Appendix A

QUESTemp$^{\circ}$ 34

The first step to use the QUESTemp is to turn it on the device, using the button on the back part. The next step is to press the button of Run/Stop and let the device record ten minutes so it can stabilize, after that press again the button Run/Stop to save the data. Press again the Run/stop button to measure the actual period that you want to monitor. When you finish using the device press the button I/O until a countdown appears on the right lower corner of the screen. This action will return the principal menu and then you can turn off the device with the button on the back of the device.

To download the data, a license for the corresponding program should be acquired. The device should be plugged to a computer with the program. Then the device should be registered in the program, after this step is done it should be able to visualize the device with the measurements on a plot on the program. With the right click on the name of the device a report can be made quite easily. Also with the right click on the plot of the results a .csv file can be exported.

Appendix B

The building orientation calculation

The building long façades are oriented almost to the South and North, with a small angle to the West and East, respectively. For the calculation of this angle, the following procedure is used. First a satellite photo is taken from Google Maps and paste in Word. The orange line in B.1 was drawn at 0°, with a right click on the mouse the option shape format is selected. At the right of the B.1 the menu for this option can be seen, the second shape (pentagon) is selected, Z spin is the one that can be useful to know the angle of the building. The Z spin was changed until the orange line was aligned with the building, the angle found was 173.2° which means the building North façad is rotated 6.8° to the East.

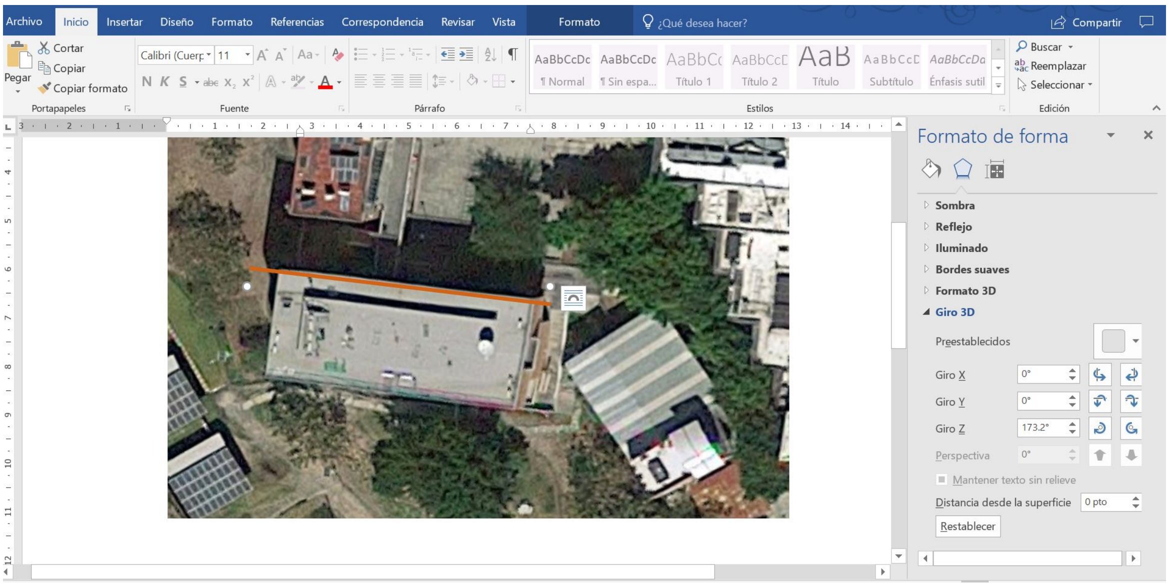


Fig. B.1 Satellite view of the building to determine the orientation

Appendix C

Wind speed profile correction

The correction of the wind speed profile used in the simulation has to be made because the simulated building is just the top two stories of a five story building. EP calculates the wind speed profile with the following equation.

$$U_{\infty} = V_{met}\left(\frac{\delta_{met}}{z_{met}}\right)^{a_{met}}\left(\frac{z}{\delta}\right)^{a} \tag{C.1}$$

Where U_{∞} is the wind speed at z height, z_{met} is the height of the standard meteorological station or wind speed measurement, the layer thickness (δ_{met}) and the exponent (a_{met}) are the coefficients of the terrain where the meteorological station is located. The z is the height at which the wind speed needs to be calculated, the layer thickness (δ) and exponent (a) are of the terrain where the building is located, which in the case of the building studied correspond to urban coefficients.

In figure C.1 the wind profile of the urban zone, which represents the expected wind profile for the building and the one used for the simulated building are presented. To obtain the wind speed profile for the simulation, the values for the layer of thickness (δ) and the exponent (a) were changed for the ones corresponding to a wind speed profile of the ocean. The wind speed of the ocean profile at the height of the simulated building is almost two times larger than the real wind speed profile. Due to the wind speed velocity of the ocean profile, a correction factor had to be applied to the wind speed. This correction factor was calculated using the value of the speed of the real wind speed profile and the ocean wind profile at a height of 25 m measured from the base of the building, the value obtained was of 0.56. The wind speed profile of the ocean profile was multiplied by that correction factor with the purpose of having the same wind speed in both profiles at height of 25 m. Once the speed of both profiles was the same at the top of the simulated building, the values for the layer of thickness (δ) and the exponent (a) were varied until the wind speed profile for the simulation, the yellow line in figure C.1, was as similar as possible to the wind speed profile in reality, the blue line, for the simulated building, corresponding to the top two stories of the real building. To create the weather file for the simulation the wind speed measured by the weather station was multiplied by the correction factor, this modification makes the weather file very specific for this simulation.

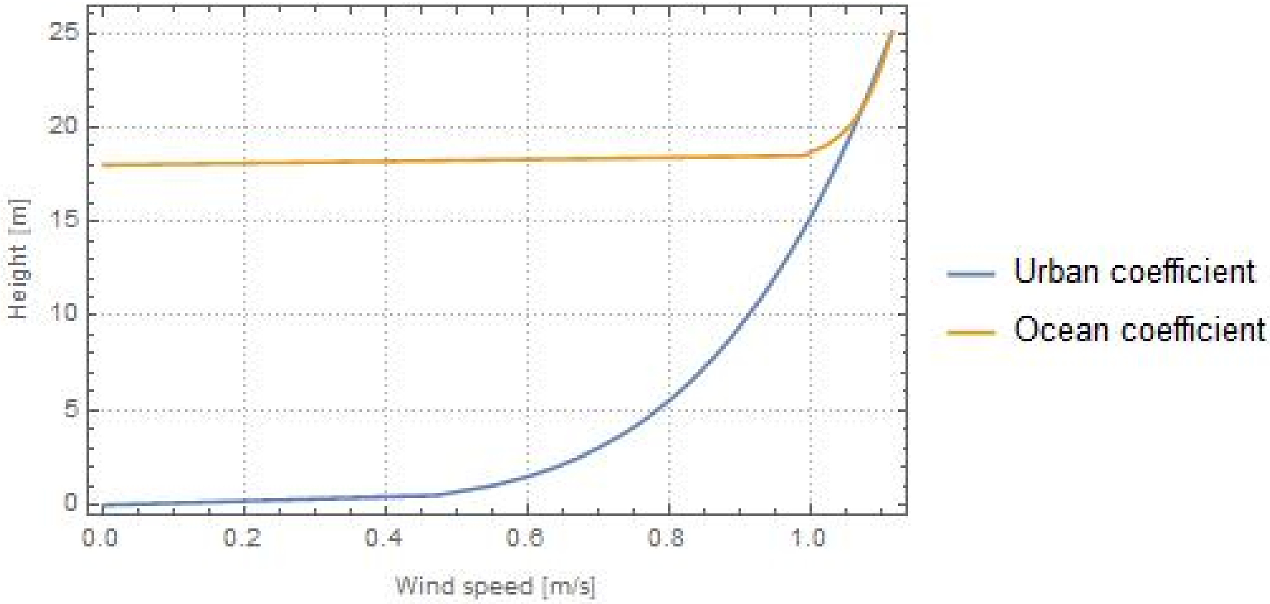


Fig. C.1 Wind speed profile. The wind speed calculation of the five story building can be seen in color blue, the values that represent this wind speed profile are $\delta = 370$ and $a = 0.22$. In color yellow can be seen the wind speed profile of the simulated building, the values to represent it are $\delta = 10$ and $a = 0.045$ and a correction factor of 0.56 to the V_{met} value.

Appendix D

Internal mass calculation

For the internal mass calculation a construction has to be created with the materials of the object that wants to be represented, the thickness of the material is the thickness of the object that wants to be represented. Once the material is created, the area exposed to the zone air has to be specified. In the case of a wall that is dividing two thermal zones the area that counts is the length times the width of this walls. In the case of furniture like a table the area that will be input in EnergyPlus is the area of the table times two because the front and back sides of the table are within the thermal zone.

For the calculations of the internal mass, in this study the area of the desks used in the building was measured and multiplied by two. This procedure was also followed for the shelves. Once the area for desks and shelves was calculated, the area was multiplied by the number of people in each thermal zone, considering there is one desk and a shelf per person.