

Thermal Comfort Metamodel Tool compared to EnergyPlus simulations:

A comparison using an University building

HELDER GATTONI MEDEIROS¹, ANA CAROLINA DE OLIVEIRA VELOSO¹, ROBERTA VIEIRA GONÇALVES DE SOUZA¹

¹Universidade Federal de Minas Gerais, Belo Horizonte, Brazil

ABSTRACT: This paper aims to compare the percentage of occupied hours in thermal comfort (PHOCT) in an under construction naturally ventilated building in the Campus of the Federal University of Minas Gerais (UFMG) obtained by an EnergyPlus simulation and by a metamodel tool developed by Rackes et al. The building has 5 floors with a total area of 2678 m². PHOCT was obtained considering the adaptive comfort model for naturally conditioned environments proposed by ASHRAE 55-2013 in both cases. To use the metamodel it was necessary to adequate the following input parameters: 1) building maximum depth, 2) maximum floor to floor height and 3) maximum room power density of the occupied spaces to fit them within the range of the metamodel. Although such adjustments had to be made so the metamodel could be used to evaluate the thermal comfort it is considered that the proposed tool presented close PHOCT estimations both for INMET and TRY weather files when compared to simulations. Results found in metamodel were of 89% and 71% of occupied hours in comfort while the results obtained by EnergyPlus were of 92% and 77% for each weather file, the tool presenting a huge time saving when compared to simulation.

KEYWORDS: Simulation, Thermal Comfort, EnergyPlus, Natural Ventilation.

1. INTRODUCTION

The important role of buildings in energy consumption opened the eyes of the world for building energy efficiency. This is no different in Brazil which launched in 2009 the Technical Quality Regulation for the Energy Efficiency Levels of Commercial, Service and Public Buildings (RTQ-C) published by Inmetro (National Institute of Metrology, Quality and Technology), the agency responsible for the Brazilian Labelling Program, PBE. This Regulation aims to create conditions to rate the energy efficiency level of buildings [1,2]. This regulation aims to label the level of energy efficiency of office buildings, hospitals, schools, museums and other non-residential buildings.

In this Regulation the air conditioning system has a final weight of approximately 70% in the definition of the rank (approximately 40% directly for the air conditioning system (AC) efficiency classification and 30% indirectly for the building envelope (ENV) classification [1]. The criteria adopted to evaluate the ENV efficiency level focused on the development of a regression equation which provides an electricity consumption indicator [3]. The envelope prescriptions in this Regulation are based on electricity consumption equations developed with 5000 simulations to provide a method to evaluate the envelope efficiency level when two HVAC efficiencies

were used (3.19 W/W and 1.82 W/W for cooling and 2.39 W/W and 1.36 W/W for heating) [3].

AC and ENV evaluation present both 1) a simplified calculation system based on tabulated values and on equations developed by linear regressions and 2) an energy simulation method.

The full implementation of the RTQ-C regulation in Brazil may potentially reduce the buildings energy consumption significantly in the long term [4], and simplified methods should help in this way. Even though computational simulation does not represent the reality in its totality, it is considered to be the most flexible and complete way to evaluate issues related to the energy efficiency of buildings [5]. But to get reliable simulations results, there must be a great investment both in financial and in time consuming terms demanding highly skilled and experienced workforce [5]. In Brazil, less than 18% of the buildings labelled by RTQ-C from July 2009 to February 2020 used the simulation method [6].

As previously seen, RTQ-C is strongly oriented to air-conditioned buildings even though there are many buildings in Brazil that tend to be naturally ventilated in the commercial, service and public sectors. Schools, public universities, public health centres, small street stores are examples of buildings that use natural ventilation as their main means of air conditioning in the country. In this sense the problem regarding naturally ventilated buildings is that in RTQ-

C [1] the efficiency of naturally ventilated buildings must be calculated via a thermal simulation, with no simplified method. The analysis of naturally ventilated spaces is made through the calculation of the Percentage of Occupied hours in Thermal Comfort, PHO_{Ct}. A PHO_{Ct} of 80% would give an A level to the analysed spaces that would substitute the evaluation of the air conditioning system in these spaces [1].

PHO_{Ct} estimation has great importance in the labelling of passive buildings but simulations to obtain internal temperatures values are complex due to the need of controlling the opening and closing of windows according to the external and internal conditions taking a long time to be done and needing specialized consultants to carry out reliable simulations. This fact may discourage the construction industry to test the performance of natural ventilated buildings.

In fact, this tendency could be inferred when the building energy efficiency labels emitted in Brazil are analysed. In the Brazilian system when all systems are evaluated a Global label is emitted but a Partial label can also be emitted provided the building envelope is analysed. Of the buildings simulated until March 2020, 24% did not evaluate the efficiency of the air conditioning system - only the envelope performance was evaluated, probably using an auto-sized air conditioning system, indicating that those buildings may be naturally ventilated. 26% of the buildings evaluated by the prescriptive method did not evaluate this system either indicating that those buildings may be naturally ventilated too. [6].

In order to overcome this and other barriers as appointed by Wong & Kruger [4] the Brazilian Government opened a public consultation by Ordinance No. 248 of July 10, 2018, with the objective of improving the RTQ-C. The proposal renames the regulation to INI-C - Inmetro Normative Instruction - Commercial, Service and Public Buildings [7]. INI-C proposes a new method which uses the building's energy consumption as an evaluation parameter, comparing it with reference conditions. For each of the evaluated items, it is possible to use a simplified method or a simulation method. In the case of naturally ventilated buildings the novelty is the proposal of a simplified method capable of estimating the percentage of occupied hours in thermal comfort (PHO_{Ct}) with the input of simplified climate-related parameters and building characteristics [8].

The simplified method uses a tool proposed by Rackes et al. [8] supposed to promote the validation of natural ventilation strategies. The importance of such a tool relies on the fact that it was verified that in mild temperate climates present in many regions of Brazil, naturally ventilated buildings can

significantly diminish energy use intensity [9,10] and have a better chance to adapt to climate change [11]. In this sense buildings with natural conditioning must be proven to meet the conditions of thermal comfort when not using artificial conditioning systems. It is not enough that they present a lower energy consumption. That is, a building is considered more energy efficient than another when it provides the same environmental comfort conditions to its user, with lower energy consumption [12].

Although the simplified method is considered easier to use than the thermal simulation, studies testing it against real buildings could not be found in the literature. It also presents ranges to some input parameters values which might not correspond to an actual building design. This paper then aims to estimate the PHO_{Ct} of an academic building in the Campus of the Federal University of Minas Gerais (UFMG) using the metamodel proposed by Rackes et al. [8] and to compare the results obtained by the computational simulation method using EnergyPlus software.

2. STUDY CASE

The study case is the under construction building of the School of Fine Arts of UFMG, located in the Campus Pampulha in Belo Horizonte, MG, Brazil.

The building will have 5 floors with a total area of 2678 m². It has 24 professor offices, 4 dancing rooms, a library, 13 administrative rooms, as well as living areas and toilets (see figure 1).

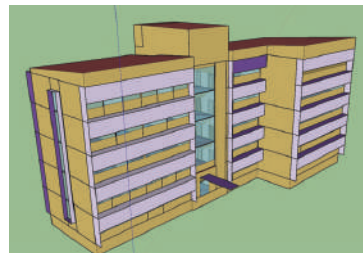


Figure 1: Analysed building

The construction is in reinforced concrete coated structure and presents an internal vertical circulation box with reinforced concrete stairs and 2 elevators. The building has internal divisions and external walls in masonry, wooden doors and lining only in the sanitary areas. The windows are sliding sheets with aluminum frames.

The external walls are to be built in 14x19x29cm ceramic brick and the internal walls in 09x19x29cm ceramic brick. The external painting will be white and yellow, with 89% of the area in white and 11% in yellow with absorptances of 0.2 and 0.3, respectively. The building will have a white sandwich panel roof above a concrete slab. Simple 6mm glass will be used in the openings, and solar shading devices will be

used on all windows. It is intended that the building will operate using natural ventilation and therefore no air conditioning system was envisaged. Figure 2 show a picture of the building.



Figure 2: Analysed building under construction

Brazilian territory is divided into 8 climatic zones [13]. Belo Horizonte is in Bioclimatic Zone 3 that represents the temperate mild climate with hot rainy summers and mild dry winters. This climate is classified as temperate (Cwa), according to Köppen's climatic classification. Average winter temperatures are of 18°C and average summer temperatures are of 27°C. The annual relative normal humidity is 67%, the annual average of total precipitation is 1,602.6 mm. The climate presents, according to the adaptative model of ASHRAE 55-2017 [14], from 61% (TRY weather data) to 66% (INMET weather data) when natural ventilation is used according to the software Climate Consultant 6.0 and considering the operating hours of 8 a.m. to 10 p.m. corresponding to the academic buildings operating hours.

3. METHODOLOGY

The building's PHOCT was evaluated both by computer simulation in EnergyPlus and by the metamodel. For both evaluations, the adaptive comfort model for 80% acceptability proposed by ASHRAE 55-2017 [14] was used to define the acceptable thermal conditions for naturally conditioned environments. This is an empirical model based on users' continuous adaptation to outdoor temperatures which uses equations 1 and 2 to determine the upper and lower limit for the operative temperature to grant 80% acceptability.

$$T_u = 0.31T_{pmao} + 21.3 \quad (1)$$

$$T_L = 0.31T_{pmao} + 14.3 \quad (2)$$

Where T_u – Upper 80% acceptability limit (°C)

T_L – Lower 80% acceptability limit (°C)

T_{pmao} – Prevailing mean outdoor air temperature.

The temperature limits and T_{pmao} both vary with time. The window for T_{pmao} can be from 7 to 30 days. In the simulation and metamodel the window used is of 7 days.

2.1 Simulation Methodology

To evaluate PHOCT through simulation, the building was modeled in SketchUp Make, version 2017, using the Euclide plug-in version 0.9.3 and each room was considered a thermal zone. The simulation was performed in EnergyPlus Software version 8.7.0.

The operating schedules of occupancy, lighting, and equipment use were obtained with the building administrators. The *Ventilation Control Mode* for window and doors opening chosen was the “TEMPERATURE” rule, thus they were set to open only when the rooms are occupied AND the temperature is above 20°C AND the zone internal temperature is higher than the outside temperature.

Two climatic files were used in this study for the city Belo Horizonte: TRY and INMET [15]. Both files were used to the simulation and in the metamodel tool to estimate de PHOCT.

As the output of the simulation software we obtained the operative temperature (T_o) of each zone and the dry bulb external temperature (T_e) were obtained. With these data and considering Equation 1 and 2 (ASHRAE 55-2017) the PHOCT, and the number of exceedance hours (EH), or hours in which the comfort limit was exceeded, divided by the total number of occupied hours were obtained. According to Rackes et al the EH is the standard metric indicated by ASHRAE 55-2017 for evaluating thermal acceptability over time and two indexes were defined by the authors: the “exceedance hour fraction – hot” (EHF_{hot}) and the “exceedance hour fraction – cold” (EHF_{cold}), were calculated, representing the hour fractions that exceeded the upper and lower limits respectively. [8]

2.1 Metamodel Methodology

The creation of the metamodel is expected to facilitate the validation of passive ventilation systems, encouraging the use of this solution. The climates found in Brazil have great potential to use passive solutions which also avoid problems of concentration of pollutants (such as CO₂) in the interior and offer significant savings in energy costs of the building. This tool was designed to be used in warm and hot climates in which comfort performance was quantified by the average annual fraction of occupied hours that exceeded the upper limit of an adaptive comfort zone [8].

According to INI-C, PHOCT may be estimated by simulation or using the metamodel. When using the metamodel the PHOCT is 100% minus the best value for EHF_{hot} estimated by the metamodel. The metamodel consists in a routine developed in Python version 2.7. The user must enter 38 parameters to determine the occupant comfort in naturally ventilated buildings in hot and mild climates [8]. The first nine parameters refer to climate, derived from

weather files. The program provides data for 428 cities in Brazil although if users want to analyze a building in a different place or with a newer climate data the program presents a routine to translate a weather file into those nine parameters. The other 29 parameters are related to building characteristics. Table 1 presents the 9 parameters related to climate data with their units and the values entered for the two weather files TRY and INMET, available for the city of Belo Horizonte.

Table 1: Metamodel input climate data

Parameter	Unit	Climate data	
		TRY	INMET
Tout	°C	22.6	21.8
ToutDailyVar	°C	10.4	9.4
ToutAnnualVar	°C	13.8	13.6
CDD18	°C *days	1764	1483
CDD25	°C *days	304	164
radDirNorm	W/m ²	175	95
radDiffHoriz	W/m ²	108	91
windSpeedMet	m/s	2.1	2.2
elevation	m	785	869

Where:

- Tout – Mean annual outdoor air temperature (To,a)
- ToutDailyVar – Annual mean of To,a daily amplitude
- ToutAnnualVar – Annual mean of To,a daily amplitude
- CDD18 – Cooling degree days base 18 °C
- CDD25 – Cooling degree days base 25°C
- radDirNorm – Mean direct normal solar radiation
- radDiffHoriz – Mean diffuse horizontal solar radiation
- windSpeedMet – Mean wind speed at meteorological station
- elevation – Elevation above sea level

The others 29 parameters entered in the metamodel are shown in Table 2, which also shows the minimum and maximum limits for each parameter allowed by the metamodel.

Table 2: Metamodel input building data

Parameter	Unit	Min	Max	Adopt.
bldgLength	m	13	200	45.56
bldgDepth	m	8	50	12.73
floorHeight	m	2.75	4.25	3.20
Nfloors	-	1	5	5
roomSize	m ²	9	400	33.81
stairFracFPA	-	0	0.28	0.052
WWR	-	0.05	0.70	0.264
shadingAngle	°	0	45	37.41

extWallAbs	-	0.2	0.8	0.211
extWallU	W/m ² *K	0.1	5.0	1.85
extWallCT	kJ/m ² *K	40	500	105
roofAbs	-	0.2	0.8	0.259
roofU	W/m ² *K	0.1	5.0	0.558
roofCT	kJ/m ² *K	10	400	247
SHGC	-	0.2	0.8	0.635
windowU	W/m ² *K	1.0	6.0	5.792
roomELPD	W/m ²	1	25	25
publicELPD	W/m ²	1	15	2.933
occDensity	occ/m ²	0.01	1.00	0.274
dayStart	h	6	10	8
dayEnd	h	14	22	22
windAlpha	-	0.10	0.40	0.22
averageShelter	-	0.3	1	0.9
windowMaxOpenFrac	-	0.2	1.0	0.442
NVW_WWR	-	0	0.17	0.0125
PW_width2height	-	0.1	50	4.513
PW_Cd	-	0.4	0.8	0.6
interiorELAPERLen	-	0.0001	.4	0.21
ceilFanAirSpeedDelta	m/s	0	0.9	0

Where

- bldgLength – Building Length (higher dimension)
- bldgDepth – Building depth (shorter dimension)
- floorHeight – Floor-to-floor height
- Nfloors – Number of floors
- roomSize – Average room size
- stairFracFPA – Fraction of the building footprint area occupied by stairwells
- WWR – Window-to-wall ratio
- shadingAngle – Shading angle from building façade
- extWallAbs – Exterior walls solar absorptance
- extWallU – Exterior walls overall thermal transmittance
- extWallCT – Exterior walls thermal capacity
- roofAbs – Roof Solar Absorptance
- roofU – Roof overall thermal transmittance
- roofCT – Roof thermal capacity
- SHGC – Windows solar heat gain coefficient
- windowU – Windows thermal transmittance
- roomELPD – Occupied room power density
- publicELPD – Public spaces power density
- occDensity – Occupants density
- dayStart – Day starting hour
- dayEnd – Day ending hour
- windAlpha – wind speed correction factor
- averageShelter – Sheltering obstacles correction factor
- windowMaxOpenFrac – Maximum windows fraction opening
- NVW_WWR – night ventilation window-to-wall ratio
- PW_width2height – Typical windows width divided by its height
- PW_Cd – Typical windows discharge coefficient

- interiorELaperLen – Effective leakage area between occupied rooms and public spaces per length of shared wall
- ceilFanAirSpeedDelta – Air speed enhancement provided by fans

As a result, the metamodel estimates the building's E_{HFhot} generating 5 values, the best estimated value by the metamodel, minimum and maximum for a precision of 95% and minimum and maximum for a standard deviation.

Since the metamodel method is simplified, it has limitations. Thus, it was necessary to modify some parameters of the real building to make them fit within the range of the metamodel. Among them we can mention adequacy in the width of the building (bldgDepth) due to its shape. As it can be seen in figure 03, the building is not a rectangular one, so it was necessary to calculate a mean building depth.

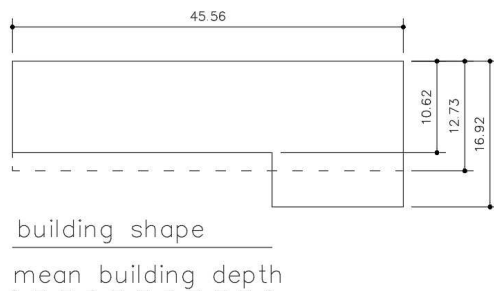


Figure 3: Building shape with an indication of the mean building depth (m).

It was also necessary to adequate the floor-to-floor height (floorHeight) due to the metamodel limit of the building height of 16m. The actual floor-to-floor height is of 3.75 and the total building height is of 18.75. The adjustment implied in a 15% decrease in the floor-to-floor height.

A more extreme limitation was verified in the installed power density in occupied rooms (roomELPD) where the limit imposed by the metamodel tool is of 25 W/m² and the value found for the building is of 39.9 W/m². It is important to reinforce that ELPD is calculated for the occupied rooms associating both lighting and equipment. This high value found in the building is due to a high power density in illumination (50 W/m²) for the dance rooms due to the use of special lights for their practice and also because in teacher offices the equipment power density is high (51.5 W/m²) because the layout estimates that there'll be 3 computers in an area of 10.3 m.

3. RESULTS

Table 3 shows the metamodel estimated exceedance hour fraction E_{HFhot} estimated using TRY and INMET weather files.

Table 3: E_{HFhot} estimated by the two precisions given in the metamodel (%)

	Best Value	95% precision		One Standard deviation (68.2% precision)	
		Min.	Max.	Min.	Max.
TRY	28.5	12.9	51.4	20.8	37.7
INMET	11.3	4.1	25.7	7.6	16.4

Using INMET weather file the PHO_{Ct} obtained was 91.7% for EnergyPlus simulation and 88.7% for the metamodel (3.0% difference). While using TRY weather file the results was a PHO_{Ct} of 76.6% for simulation and 71.5% for the metamodel (5.1% difference). Both results, using TRY or INMET, were considered to be very close for PHO_{Ct}. The metamodel is only capable of evaluating the hot discomfort while with EnergyPlus it is possible to evaluate hot and cold discomfort. Figure 3 compares each result.

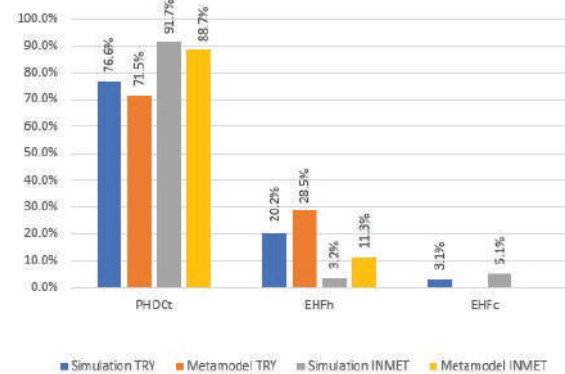


Figure 3: PHO_{Ct}, EHF_h e EHF_c for each method.

As we can see, although PHO_{Ct} values given by the simulation and by the metamodel present values that could be considered similar (a maximum difference of 5,1%), when EHF_{hot} is analyzed higher differences are found. This may be because the exceedance hour fraction for cold is not considered in the metamodel but appears in the simulation process.

4. CONCLUSION

The tool presented close PHO_{Ct} results to those obtained through simulation with a huge time saving.

Some parameters limitations restrict the application of the simplified method. In this study it was necessary to adjust the parameters "bldgDepth", "floorHeight" and "roomELPD". These adjustments may have influenced in the divergence in the values obtained.

The adequacy in the parameters were the reduction of the installed power density of the occupied rooms (roomELPD) from 39.9W/m² to

25.0W/m² to input a value for this parameter inside the metamodel range. A “virtual” width has been inputted to maintain the building area because it does not present a rectangular shape such as required by the metamodel. And the floor-to-floor height (floorHeight) had to be changed from 3.75m to 3.19m because the metamodel only accept buildings with total height under 16m.

In tropical countries like Brazil the increment in floor-to-floor height is a recommended strategy to improve the comfort, especially in high density occupation rooms like classrooms. The edification code of Belo Horizonte city [16] for instance considers 4.00m as the minimum floor-to-floor height for classrooms with 48m² or more, which is almost the upper limit of the tool (4.25 m). Thus, the limit of 16 meters for the building height would allow the evaluation of schools up to 4 floors only. This may not be a problem for schools evaluation, but it should be a problem when naturally ventilated office building towers are evaluated once they present a higher number of floors.

This analysis is of special importance once the metamodel was specially targeted to verify comfort based on office and school buildings such as the one analysed in the present study. INI-C could provide guidelines for acceptable parameter adequacy to fit then in the range to extend the application of the simplified method and to promote natural ventilated buildings.

If a compliance range is sought for the PHOCT, it is important to verify the influence of the weather file selection as results between files varied in approximately 20%.

Studies with more buildings should be performed to ensure that adjustments do not make the results unusable.

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