Thermal performance improvements for university dormitories in a tropical climate

Alternativas para a melhoria do desempenho térmico para moradias universitárias em clima tropical

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ABSTRACT
The building envelope exerts considerable influence on maintaining comfortable indoor conditions. Consequently, it is important to better understand the role that the envelope elements play in building thermal performance. This paper presents an improvement proposal for the thermal behavior of a university dormitory located in Belo Horizonte, Brazil. The assessment was carried out in seven bedrooms located on different floors and orientations. EnergyPlus tool and local weather data were used to simulate annual indoor temperatures considering the original envelope and alternatives based on the Brazilian performance building standards.
code NBR 15.220/2005. The performance analysis covered degree-hours for heating and cooling and comfort indicators considering 80% acceptability limits set by ASHRAE 55/2017. It was found that changes in building envelopes have significant contributions to the indoor thermal conditions. The results showed that the simulation tool evaluated the global heat transfer in building adequately. Greater wall thermal lag combined with a smaller window opening provided better thermal behavior results considering all simulation models. In a broader sense, the present work contributes to demonstrating that numerical simulation plays an important role in emulating indoor thermal conditions and also fosters improvements in building thermal performance.

**Keyword:** Building thermal performance. Indoor thermal conditions. Numerical simulation. University dormitory.

### RESUMO
O envelope do edifício exerce uma influência considerável na manutenção de condições internas confortáveis. Consequentemente, é importante entender melhor o papel que os elementos do envelope desempenham na construção do desempenho térmico. Este artigo apresenta uma proposta de melhoria para o comportamento térmico de um dormitório universitário localizado em Belo Horizonte, Brasil. A avaliação foi realizada em sete quartos, localizados em diferentes pisos e orientações. A ferramenta EnergyPlus e os dados meteorológicos locais foram utilizados para simular a temperatura interna anual, considerando o envelope original e as alternativas baseadas no código de construção de desempenho brasileiro NBR 15.220/2005. A análise de desempenho abrangeu graus-hora para indicadores de aquecimento e refrigeração e conforto, considerando os limites de aceitabilidade de 80% estabelecidos pela ASHRAE 55/2017. Verificou-se que as alterações nos envelopes de construção têm contribuições significativas para as condições térmicas internas. Os resultados mostraram que a ferramenta de simulação avaliou adequadamente a transferência de calor global na construção. Um maior atraso térmico da parede combinado com uma menor abertura da janela proporcionou melhores resultados de comportamento térmico considerando todos os modelos de simulação. Em um sentido mais amplo, o presente trabalho contribui para demonstrar que a simulação numérica desempenha um papel importante na emulação de condições térmicas internas e também promove melhorias no desempenho térmico da construção.

**Palavras-chave:** Construindo desempenho térmico. Condições térmicas internas. Simulação numérica. Dormitório universitário.

### 1 INTRODUCTION
Enhance the thermal performance of buildings envelope allows to prevent overusing of energy consumption for heating and cooling. Likewise, improvements in indoor thermal comfort conditions for occupants can also be noticed [1]. The building envelope is mainly responsible for providing indoor thermal comfort according to outdoor climatic conditions. Since the thermal comfort demands increase, the building envelope has assumed a climate-
regulating function [2]. Thus, it is important to carry out studies that promote design solutions considering the local climate.

In Brazil, 50.8% of the electrical energy supply is used in the building sector. The residential buildings consumed 26.0% of this amount showing to be the most representative sector below only those industrial [3]. Approximately 16.7% of Brazilian households have some type of air conditioner to optimize seasonal comfort conditions [4]. The National Energy Plan (PNE 2030) presents a 10% reduction goal in electricity demand by autonomous and induced progress. Energy efficiency is treated as an investment option to meet domestic consumption demand in return for the energy generated or purchased for this purpose [5].

The understanding of building performance and user’s habits and attitudes under different climatic contexts is significant to plan and evaluate strategies and policies to be adopted. Those results can contribute to provide thermal comfort conditions with the lowest possible power consumption at reduced investment cost. Besides, it can contribute to meet the Government Plan for Energy Efficiency and also to comply with worldwide initiatives such as the Paris agreement focused on the greenhouse gas reduction, the global warming contention initiatives and so on [4].

In several countries, Higher Education Institutions offer student-paid housing as part of their services, such as Australia, Canada, Ireland and the United States [6]. In Brazil, it aims, especially, to accommodate students in unfavorable socioeconomic conditions, coming from cities and states far from the university campus. Most of the time they are free, but in some cases fees are charged considering the student's socioeconomic classification criteria established by the institution [6, 7]. Although the percentage of students living in university dormitories remained 2.5% [8], the number of students displaced from their family context upon entering university that need housing support was 34.8% [7]. The literature shows some benefits for those residents such as increase academic performance, persistence in higher education [8, 9], general and social adaptation [10] and so on. However, university dormitories can provide some difficulties in studying, such as thermal discomfort, sleep disturbance and noisy accommodations that increase the student stress level [11]. University dormitories investigations are still scarce in Brazil [12]. A previous study in João Pessoa, Brazil, indicated a poor student satisfaction due to its thermal discomfort [13]. The understanding of different behaviors and life experiences could be useful for remodeling projects or also as feedback improvements for new planning design, and construction of this sort of building. The building
envelope analysis can also contribute to design a suitable building under different climatic conditions.

The Brazilian building thermal performance code, NBR 15,220/2005 [14], established technical envelope recommendations for social houses according to its bioclimatic zones. This standard presents limits for the thermal properties of walls and roofs as well as for window openings area. Although it specifies criteria for building thermal performance, it does not include any thermal comfort index. However, the building construction guideline is grounded on Givoni Bioclimatic chart [15] and Mahoney's worksheets [16]. It aims to optimize the building thermal performance and to provide users thermal comfort through adaptive strategies. Previous studies [15-16] has been successfully used as a reference for building systems and bioclimatic strategies of social houses. In the absence of other building typology guidelines, the Brazilian building thermal performance code [14] has been also used for several building types as a conceptual design project source.

In Brazil, there is no national thermal comfort index. The first studies were conducted in schools located in Rio de Janeiro [17], and also in São Paulo [18]. The results showed that the comfort temperature does not follow a static pattern, but an adaptive dynamic that changes throughout the seasons [17]. In this context, studies carried out from the 1990s onward were influenced especially by Fanger [19], de Dear, Brager, and Cooper [20]. The thermal comfort of Brazilian occupants was based on international standards such as ASHRAE 55 and ISO 7730. However, studies have shown that the Fanger model used in ISO 7730 [19] is not proper to predict thermal comfort for acclimated Brazilian resulting in a more pronounced sense of thermal discomfort than is perceived by users. On the other hand, de Dear model [20] have shown more effective results for user thermal comfort evaluation in naturally ventilated Brazilian buildings [21]. In most parts of Brazil, these buildings have a great potential to provide comfort conditions naturally. This research field is still scarce, requiring further studies in different locations and variations of building systems and typology. Further, most of the studies were conducted on office spaces, classrooms or residential buildings. Indeed, very little researches had been investigating university dormitory [12].

The standard ASHRAE 55/2017 [22] introduces the adaptive comfort model, that correspond to indoor temperature ranges considered acceptable in comparison to the outdoor temperatures. The adaptive thermal comfort model assumes that after some time, the building occupants will adequate their clothes, behavior and environment to deal with climatic conditions of the space. Therefore, they can accept a wide range of thermal conditions [23].

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There are two ranges for acceptable thermal conditions [22]. One is set for 80% acceptability (used in usual applications) and the other one applies for 90% acceptability (used when a higher thermal comfort standard is required).

The thermal comfort is also related to architectural and constructive characteristics of buildings, such as layout, dimensions, window–wall ratios, shadings, and thermal properties of its envelope. Thus, passive strategies and a suitable envelope can provide thermal comfort and minimize the energy demand [24].

Numerical simulation is a tool that allows building performance evaluation according to environment, occupancy and systems [25]. Furthermore, simulations are widely used in building design optimization [26]; for envelope [27] and energy-efficient alternatives selection [28]; for thermal and energy performance evaluations [29]; and for decision-making process [25]; among others.

There are several tools to develop and validate whole-building energy models. These models solve mass and energy balance equations for all thermal zones of the building, considering the relations between outdoor climatic conditions and indoor heat sources. Whole-building simulation tools have proven to effectively simulate the thermal behavior, heating and cooling loads of buildings. One of these is EnergyPlus, an open-source software developed by the US Department of Energy (DOE) and managed by the National Renewable Energy Laboratory. This tool allows to emulate heat transfer and energy use of a whole building considering its lighting, heating, cooling and ventilation systems as well as other parameters [26]. Besides, EnergyPlus is widely used in building simulation researches across the world [25] and meets the ASHRAE 140 requirements [30]. Furthermore, it was considered the best energy simulation program to calculate the heat transfer through windows [31].

For more reliable results and better represent the case study, a calibration step of the simulation model shows relevant. This process consists in improving the model, by using more precise input parameters and real data measured in the building [32]. Several studies have been conducted on this process [33–35] to obtain data that represent the real building behavior.

Some previous studies investigated the influence of building envelope on its thermal performance and thermal comfort for the occupants. Belazi et al. [36] analyzed the uncertainties regarding user behavior and envelope materials considering the energy performance simulation of an office building under different climates. Random variations of parameters were also performed to evaluate uncertainties concerning its final energy consumption. Their results demonstrated that the energy demand of the building has a great
variety due to uncertainties related to users' behavior and envelope materials properties. Besides, the major variables that influence the energetic demand were users, under hot climates, and envelope material, under cold climates.

Du, Bokel and Dobbelsteen [37] evaluated spatial configuration, building microclimate and thermal comfort relations for a modern house under a hot and humid climate. The geometry, spatial boundary conditions and human activities in the building were analyzed. Then, field measurements were carried out to investigate the house’s indoor climatic conditions. A thermal simulation was performed by using EnergyPlus to predict thermal comfort over the summertime. A comparison between simulated and measured results, and also adaptive thermal comfort was used to evaluate the thermal comfort conditions.

Considering different temperature boundary conditions and geometrical sizes, Zhang and Yang [38] assessed heat flow and heat transfer characteristics of the envelope insulation air layers. The authors concluded, after simulation of a case study in EnergyPlus, that the air layer adoption as insulation can contribute to minimizing the annual heat transfer over the building envelope depending on the climate characteristics.

Rincón et al. [39] analyzed an alternative low-cost earthen construction system combined with passive design to evaluate improvements in its thermal comfort conditions. Building energy simulations were performed by using EnergyPlus. Besides temperature results, the authors also used two indicators of annual comfort: hours of discomfort and discomfort degree days. The ASHRAE Standard 55 Adaptive Comfort model was used to evaluate thermal comfort conditions.

The main objective of this paper is to evaluate the influence of building envelope changes in its thermal comfort conditions. For this purpose a study case was carried out considering the thermal behavior of a university dormitory located in Belo Horizonte, Brazil. The analysis was performed considering the original building envelope and some alternatives based on the Brazilian performance building code NBR 15,220/2005 [14]. Thus, it is intended to contribute to the environmental adequacy of the university dormitory as well as to the decision-making process related to future projects, allowing the dissemination of ways and strategies related to energy efficiency and sustainability applicable to this building and/or similar. The solutions presented may allow a better use of public resources through unnecessary expenses savings. Besides, this purpose shows to be in line with the National electricity reduction, among other goals.
2 MATERIALS AND METHODS

To evaluate the thermal performance of a university dormitory envelope, the following steps were adopted:

1. Thermo-energetic model design: a representative model of the case study was created by using SketchUp and EnergyPlus.

2. Model Calibration: a manual and iterative calibration was performed to improve the accuracy of the case study model. In this process, some model parameters were changed to increase the correspondence between measured and simulated dry bulb temperatures.

3. Numerical Simulations: simulations of a reference case and varied models based on strategies recommended by the Brazilian performance building code NBR 15,220/2005 [14] were performed.

4. Analysis of thermal performance and comfort indicators: degree-hours for heating and cooling and comfort indicators were analyzed to compare results obtained for the real building envelope and its alternative envelope.

2.1 CASE STUDY

The present case study is a university dormitory located in Belo Horizonte (Brazil) classified as a humid tropical climate (Cwa), according to Köppen-Geiger climatic classification [40]. Its wind predominant direction is east. This building is part of the Housing Assistance Program created by a non-profit foundation to assist students with low socioeconomic status. Users co-participate monthly for its maintenance costs according to their socioeconomic classification [41]. The dormitories are distributed in two buildings (Figure 2) built-in structural concrete blocks with 2.60m of floor-to-ceiling height. All bedrooms are naturally ventilated [42].
According to the building's documents [42], during the architectural design, some passive thermal comfort techniques were adopted, such as the facades orientation study and also the brise soleil design suitable for the building. The bedroom’s facades are oriented in northwest and southeast directions. Brise soleils were used to protect the bedrooms of sunstroke from northwest orientation. These elements were constructed through slabs and masonry extension over the facade, reducing direct sunstroke.

The penthouse apartment floor plan is showed in Figure 3.
2.2 BUILDING MODEL

The Block I of the university dormitory, composed of 5 floors, was the analysis subject of this work. Its model geometry was created in SketchUp Pro 2016 interface using Euclid 0.9.3 plugin. Then, the model was exported in idf format to EnergyPlus software.

Seven university dormitory representative rooms (Bedroom 1 to 7) were selected to evaluate their envelope thermal performance. Each one has a different opening orientation and it is located on distinct floors (Figures 4 and 5). Thermal zones were created for those bedrooms and the other rooms adjacent to them. The remaining rooms were input as a single thermal zone.

Figure 4. Northwest façade 3D model with the bedrooms 1 to 4 highlighted. Without scale.

![Figure 4](image1)

Figure 5. Southeast façade 3D model with the bedrooms 5 to 7 highlighted. Without scale.

![Figure 5](image2)

The building material thermal properties such as thermal conductivity, density and specific heat are presented in Table 1. An equivalent thickness was determined to the concrete blocks, according to the method presented by Lamberts et al. [43].
Table 1. Layers of components and materials properties.

| Component | Material       | Thickness (m) | Conductivity (W/m.K) | Density (kg/m³) | Specific Heat (J/(kg.K)) |
|-----------|----------------|---------------|----------------------|-----------------|-------------------------|
| Outer wall| Mortar         | 0.025         | 1.150                | 2100            | 1000                    |
|           | Concrete block | 0.100         | 1.750                | 2400            | 1000                    |
|           | Plaster        | 0.005         | 0.350                | 900             | 870                     |
| Inner wall| Mortar         | 0.025         | 1.150                | 2100            | 1000                    |
|           | Concrete block | 0.100         | 1.750                | 2400            | 1000                    |
|           | Mortar         | 0.025         | 1.150                | 2100            | 1000                    |
| Floor     | Porcelain tile | 0.010         | 1.210                | 2250            | 766                     |
|           | Mortar         | 0.025         | 1.150                | 2100            | 1000                    |
|           | Concrete       | 0.100         | 1.750                | 2400            | 1000                    |
|           | Plaster        | 0.005         | 0.350                | 900             | 870                     |
| Ceiling   | Mortar         | 0.025         | 1.150                | 2100            | 1000                    |
|           | Expanded polystyrene | 0.002 | 0.040       | 18             | 1420                    |
|           | Extruded polystyrene | 0.025 | 0.027       | 38             | 1420                    |
|           | Asphalt membrane | 0.007    | 0.230       | 1000           | 1460                    |
|           | Concrete       | 0.100         | 1.750                | 2400            | 1000                    |
|           | Plaster        | 0.005         | 0.350                | 900             | 870                     |

Adapted from ABNT NBR 15,220/2005 [44].

The solar absorptance of opaque surfaces was obtained using the portable spectrometer Alta II of Vernier. These tests were performed according to the methodology presented by Pereira et al. [45]. Previously studies demonstrated that their results can serve as a current surface solar reflectance indication with an uncertainty of ± 0.10 in absolute values [45].

The model ventilation was input using AirflowNetwork. Besides, data regarding the air exchange and ventilation control was defined. The windows and doors were temperature-controlled to enable airflow when the indoor temperature was higher than the outdoor or at any time that outdoor temperature was greater than 21.07 °C. This setpoint represents the lower limit average of Belo Horizonte monthly neutral temperatures. Further building model pieces of information can be found in Table 2.
Table 2. Input details of the building model.

| Parameters                                | Specifications                                      |
|-------------------------------------------|-----------------------------------------------------|
| Location                                  | Belo Horizonte, Brazil                              |
| Geographical location                     | Latitude: 19°55’14.99"S                             |
|                                          | Longitude: 43°56’16.01"W                            |
| Timestep                                  | 4                                                  |
| Simulation period                         | One year                                           |
| Sky model                                 | Clear sky                                          |
| Calculation option                        | Standard                                           |
| Main orientation                          | SW - NE                                            |
| Plan shape                                | Rectangular                                        |
| Number of floors                          | 5                                                  |
| Simulated floors                          | 1st, 3rd, 5th                                      |
| Floor to floor height                     | 2.6m                                               |
| Floor dimension                           | 2.2m x 3.6m                                        |
| Window area                               | 2.47m²                                             |
| Solar absorptance for exterior surfaces   | 0.21 for external walls (light color)               |
|                                          | 0.71 for the roof (mortar)                         |
| airflow Network Simulation Control        | Multizone Without Distribution                     |

During this study the real building had not been occupied yet. For this reason, the digital building representation used on the model calibration step was considered vacant. However, residents and lighting gains were included as internal heat sources during the thermal performance analysis according to the schedules showed in Figures 6 and 7. Occupancy heat gains (81W/person) were adopted considering the Brazilian Technical Regulation for Energy Efficiency Labelling of Residential Buildings (RTQ-R) [46] as a reference.

The bedroom lighting power density was 3.12W/m² and it was calculated according to the equipment power for 24 hours a day during the whole simulation period. Occupancy and lighting schedules (Figures 6 and 7) were defined according to the routine reported by neighborhood students during an interview.

Figure 6. Bedrooms’ occupancy schedules
The Slab extension calculated the average soil temperature for each month of a year using average temperature values available in the weather data file. The dynamic computer simulations carried out using EnergyPlus, version v8.7. A TMY (Test Meteorological Year) weather data of Belo Horizonte was input in the building model. This file updated in 2018 includes representative months from different years and also is available at no cost [47].

2.3 MODEL CALIBRATION
The calibration of the university dormitory model has consisted of 2 steps:

1) Monitoring a bedroom air temperature;
2) Iterative changes in the EnergyPlus input data to obtain a model that better represents the building thermal behavior.

Dry bulb temperature was monitored in Bedroom 1, located in Block I of the university dormitory, for two weeks. In the first week, from 05/07/18 to 05/14/18, its door and window remained closed and the ventilation occurred only through the cracks. In the second week, from 06/04/18 to 06/11/18, its door and window were input as completely open.

Model changes took place by adjusting some parameters and comparing them to the indoor temperature simulations results with those previously measured. A manual and iterative calibration occurred through a parameter changes for each simulation. When satisfactory, alterations remained unchanged in the following simulations. The input parameters changed during the calibration step were: thermal properties of envelope materials, solar absorptance of external surfaces, air infiltration and discharge coefficient.

The calibration results were detailed in a previous study [48] and their summary was presented in Figures 8 and 9. After the calibration step, measured and simulated data presented a difference between 0.72°C up to 3.34°C. The calibrated model, considered as a reference in
this study, was able to predict the indoor temperature with ± 1.5 ºC of accuracy in 88% of the time.

Figure 8. Dry-bulb temperature variation over time for the initial model (no occupancy and no ventilation)

Figure 9. Dry-bulb temperature variation over time for the calibrated model (No. 18)

2.4 ENVELOPE ALTERNATIVES

The envelope influence in building thermal behavior was analyzed through some modifications, starting from the calibrated model. The geometry and its thermal zones were the same for all simulations. The building changes as well as the envelope thermal transmittance, solar factor and thermal delay calculations were based on the Brazilian performance building code, NBR 15,220/2005 [14, 44]. According to this standard, Belo Horizonte is located in bioclimatic zone 3. The constructive recommendations for this case are medium window openings area (between 15% up to 25% of floor area) shaded by a device that allows winter sun. The outer walls must have light thermal inertia and should be reflective.
On the other hand, the roofs must have light thermal inertia and thermal insulation. The solar heating in the building is recommended in winter as well as an internal seal with high thermal inertia. During the summer the cross ventilation is recommended.

The case study windows have a sliding leaf that allows a 100% opening. The bedrooms have an 8m² area its window opening has about 28% of its floor area which is greater than the NBR 15,220/2005 standard limits [14]. Therefore, 15, 20 and 25% of the floor area, respectively, were used as an option for window opening area simulation input.

The envelope properties summary shown in Table 3 indicated that only the ceiling did not meet a standard limit. Although the compliance of walls, input changes were set in both envelope systems to obtain a solution that would provide improvements in building thermal behavior.

| Envelope          | Thermal transmittance W/(m²·K) | Solar factor (%) | Thermal lag (h) |
|-------------------|--------------------------------|------------------|----------------|
| Walls             | NBR 15,220 limits              | ≤ 3.60           | ≤ 4.00         |
|                   | Case study                     | 2.78             | 2.22           |
| Ceiling           | NBR 15,220 limits              | ≤ 2.00           | ≤ 3.30         |
|                   | Case study                     | 0.83             | 0.99           |

2.5 ANALYSIS OF THERMAL PERFORMANCE

The thermal performance of the university dormitory was evaluated by degrees-hour for cooling (Dcool) and heating (Dheat) sum, as previous researches [26, 49], according to Equations 1 and 2.

\[
D_{\text{cool}} = \sum_{h}[\text{Top}(h) - \text{Tupper}(h)] \\
D_{\text{heat}} = \sum_{h}[\text{Tlower}(h) - \text{Top}(h)]
\]

where Top(h) is the operative temperature in bedroom at the hour h, Tlower and Tupper are the lower and upper admissible temperature. Considering the sum ranges as a whole year, the discomfort hours obtained through the total degree-hours is established by Equation 3:
The adaptive thermal comfort criteria presented by ASHRAE 55/2017 [22] was the long-term comfort indicators. The admissible temperatures $T_{lower}$ and $T_{upper}$ were calculated considering 80% acceptability limits, as shown in Equations 4 and 5.

$$T_{lower} = 0.31 \, T_{pma(out)} + T_{ll},$$

$$T_{upper} = 0.31 \, T_{pma(out)} + T_{ul},$$

where $T_{pma(out)}$ is the prevailing mean outdoor temperature, $T_{ll}$ is the lower limit temperature and the $T_{ul}$ is the upper limit temperature.

The limits were calculated based on the neutral temperature of Belo Horizonte from INMET historical weather data (1981 – 2010) [50]. Unlike other studies, [26, 51] a variable limit temperatures were adopted, in this work, for degree-hour calculations for cooling and heating. According to Wang et al. [52], the neutral temperature varies throughout the year which demonstrates the influence of climatic conditions on the adaptation of individuals. Indeed, it is important to perform an analysis in which neutral temperatures are variable to obtain more accurate results. Thus, the monthly temperature limits of degrees-hour for cooling and heating sum analyzes are shown in Figure 10.

The prevailing mean outdoor temperature was considered equal to the average monthly dry-bulb air temperature. This procedure provides a better estimation, according to Vecchi et
al. [53], considering a study performed under two climates in Brazil. These authors pointed out a marginal difference in the mean averaged method and the weighting of the sequential day's method, both allowed by ASHRAE 55/2017 [22].

3 RESULTS AND DISCUSSION

3.1 BUILDING THERMAL PERFORMANCE

The environmental conditions of the reference model was obtained through the correlation between indoor and outdoor temperatures assessed for seven bedrooms (Table 4). In agreement with studies of Coley and Kershaw [54], the relation between indoor and outdoor temperature changes was linear.

Table 4. R2 for the correlation between indoor and outdoor temperatures for the bedrooms

| Bedroom | Floor | Orientation | R²  |
|---------|-------|-------------|-----|
| 1       | Fifth | Northwest   | 0.8559 |
| 2       | Fifth | Northwest   | 0.8291 |
| 3       | Third | Northwest   | 0.8835 |
| 4       | First | Northwest   | 0.8767 |
| 5       | Fifth | Southeast   | 0.8424 |
| 6       | Third | Southeast   | 0.8210 |
| 7       | First | Southeast   | 0.8600 |

The envelope thermal properties changes were obtained before an initial simulation of the reference model. In this context, only those changes that met the Brazilian standard (Table 5) were simulated. After its initial simulation, other tests were carried out with input parameter changes, considering a one-year interval. Concerning the roof, to meet the thermal lag criteria of NBR 15.220-3/2005 [14], its slab thickness should decrease. Thus, a minimum option of 8cm, according to concrete structures design Brazilian Standard NBR 6,118/2014 [55], should replace the 10cm original slab thickness, in all simulations.
Table 5. Description and thermal properties of simulated opaque envelopes

| Model | Description | Thermo-transmittance W/(m².K) | Solar factor (%) | Thermal lag (h) |
|-------|-------------|--------------------------------|-----------------|----------------|
|       |             | **Walls**                       |                 |                |
| 01    | Reference model:                                    | 2.78             | 2.22            | 3.26           |
|       | Internal plaster (0.05cm)                           |                  |                 |                |
|       | Concrete block (14.0 x 19.0 x 39.0cm)               |                  |                 |                |
|       | External mortar (2.5cm)                             |                  |                 |                |
| 02    | Internal mortar (2.5cm)                             | 2.68             | 2.14            | 3.96           |
|       | Concrete block (14.0 x 19.0 x 39.0cm)               |                  |                 |                |
|       | External mortar (2.5cm)                             |                  |                 |                |
| 03    | Internal plaster (2.0cm)                             | 2.43             | 1.94            | 3.73           |
|       | Concrete block (14.0 x 19.0 x 39.0cm)               |                  |                 |                |
|       | External mortar (2.5cm)                             |                  |                 |                |
| 04    | Internal mortar (2.5cm)                             | 2.01             | 1.61            | 4.8            |
|       | Concrete block (14.0 x 19.0 x 39.0cm)               |                  |                 |                |
|       | External mortar (2.5cm)                             |                  |                 |                |
| 05    | Internal plaster (2.0cm)                             | 1.84             | 1.46            | 4.48           |
|       | Ceramic block (14.0 x 19.0 x 39.0cm)                |                  |                 |                |
|       | External mortar (2.5cm)                             |                  |                 |                |
| 06    | Original envelope                                    | 0.83             | 0.99            | 11.04          |
|       |                                                       |                  |                 |                |
|       | Ceiling                                               | **07**           |                  |                |
|       |                                                       | External mortar (2.5cm) | 1.94 | 2.32 | 6.48 |
|       |                                                       | Extruded polystyrene (0.6cm) |            |               |        |
|       |                                                       | Asphalt membrane (0.7cm) |            |               |        |
|       |                                                       | Concrete slab (8.0cm) |            |               |        |
|       |                                                       | Internal plaster (0.3cm) |            |               |        |
| 08    |                                                       | Ceramic tile (1cm) |            | 1.96 | 3.14 | 6.26 |
|       |                                                       | Air chamber (>5.0 cm) |            |               |        |
|       |                                                       | Concrete slab (8.0cm) |            |               |        |
|       |                                                       | Internal plaster (0.3cm) |            |               |        |
|       |                                                       | **09**           |                  |                |
|       |                                                       | Fiber-cement tile (0.8cm) | 1.98 | 3.17 | 6.22 |
|       |                                                       | Air chamber (>5.0 cm) |            |               |        |
|       |                                                       | Concrete slab (10.0cm) |            |               |        |
|       |                                                       | Internal plaster (0.3cm) |            |               |        |
|       |                                                       | **10**           |                  |                |
|       |                                                       | Original envelope + Openings: 15% of the floor area | 2.78 | 2.22 | 3.26 |
|       |                                                       | **11**           |                  |                |
|       |                                                       | Original envelope + Openings: 20% of the floor area | 2.78 | 2.22 | 3.26 |
|       |                                                       | **12**           |                  |                |
|       |                                                       | Original envelope + Openings: 25% of the floor area | 2.78 | 2.22 | 3.26 |

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A summary of the simulation results was shown in Figures 11 and 12. The slab option that led to better results for heating and cooling degrees-hours was nº. 09. On the other hand, regarding wall changes, the solution that presented the better result was nº. 04. This result can be explained by its envelope thermal lag. A greater thermal lag indicates a superior masonry thermal inertia due to its high capacity to store heat. Thus, the indoor temperature peak presents a greater lag than those outdoor. Concerning the openings, the case that presented better results for degree-hours for heating and cooling was model nº. 10, referring to 15% of the floor area.

Finally, after testing each envelope elements, separately, a model covering the best solutions was simulated (nº. 13). This option refers to the combination of models nº. 04, 09 and 10. Indeed, this alternative envelope presented better results for heating and cooling degrees-hours when compared with all other simulation models.

Figure 11. Calculated degree-hours for cooling

Figure 12. Calculated degree-hours for heating
Through the results, the influence of opening orientation and bedroom position on building thermal performance can be noticed. Regarding to room position, the degree-hours for cooling indicate that bedroom 7 presented the best thermal performance since it is located on the first floor and its opening is southeast-oriented. On the other hand, the worst thermal behavior was noticed in bedroom 1, which has a roof slab, 3 external walls and a northwest oriented opening. Considering the isolated changes strategies, the building simulation n. 10 provided the lowest degree-hours for cooling for all bedrooms. A smaller window opening, for this case, was a better choice to improve the building thermal performance than walls or ceiling minor adjustments. The building simulation n.13, which considered all best changes together, provided even lower values than the n.10, except for the penthouse bedrooms’ number 2 (northwest façade) and 5 (southeast façade). For this two bedrooms, bigger wall thermal lag in conjunction with a smaller ceiling thermal lag made those environmental conditions worse. Besides, bedroom 1 presented another two façades that show to compensate for this negative effect in its indoor conditions.

The degree-hours for heating indicate a low demand for all bedrooms in contrast to its cooling results. As expected, this location does not present very low temperatures at night or in winter. Therefore, in practice, this finding may not result in discomfort or heating consumption as users tend to adapt more easily to minor variations below the lower limit of comfort temperature. In this case, increased isolation of clothing may contribute to alleviate this condition. Considering the isolated changes strategies, the building simulation n. 4 provided the lowest degree-hours for heating for all bedrooms. A bigger wall thermal lag was a better choice to improve the building thermal performance. On the other hand, the building simulation n.13, which considered all best changes together, provided even lower values than the n.4, except for bedroom number 1, 2 (penthouse apartment located in the building corner and northwest façade, respectively) and 6 (in-between apartment in southeast façade). In those cases, the best changes that improve the cooling degree-hours provide the opposite effect considering its results for heating. However, the bedroom 7, also in the southeast façade but with ground contact, does not present the worst indoor conditions. Further analyses in future research could provide more data for this situation.

Despite the bedroom 1 of the reference model presented the worst thermal behavior, considering the degree-hours for cooling, Figure 13 shows its ability to provide a comfortable thermal conditions. Thus, its users can experience operative temperatures inside the ASHRAE 55/2017 adaptive comfort zone, without mechanical cooling, most of the time, especially
between the middle of April and the beginning of September. In agreement with Du, Bokel and Dobbelsteine [19], the hour's distribution of bedroom 1 includes a period in which the operative temperature is below the lower limit. However, when this situation takes place, the occupant’s cold could be solved. As predicted by the adaptive thermal comfort model [22], the occupants could, for example, wear more clothes. If the discomfort hours by cold were not considered, the percentage of comfort hours would increase noticeably.

Several factors can influence the indoor thermal response of the university dormitory. Thus, a more detailed parametric analysis to examine other potential governing factors are need.

### 3.2 COMFORT INDICATORS

Annual building simulation was made through EnergyPlus for 13 model variations. The operative temperature hourly results for the 7 bedrooms selected for the case study were analyzed by statistical bias over 365 days. Since the data samples obtained were larger than 5000 elements the central limit theorem was applied. According to this theorem, there is no need to perform the Normality Test due to the natural tendency to normality of this type of sample. Thus, an analysis of variance (ANOVA) was performed to verify the significance of each factor such as a month, building simulation number (sim) that includes minor building envelope changes, bedroom type (room) and bedrooms’ operative temperature variation (temp). The results were summarized in Table 6. It should be noted that month, sim and room
variables were equally significant for operative temperature variation although the residue is expressive. Besides, a complementary study could be developed subsequently to identify which other factors possibly influenced this result.

Table 6. ANOVA analysis results for monthly bedroom’s thermal conditions

| Factor          | Df  | Sum Sq | Mean Sq | F value  | Pr(>F) |
|-----------------|-----|--------|---------|----------|--------|
| month           | 11  | 1502938| 136631  | 35741.745| <2e-16 *** |
| sim             | 1   | 5363   | 5363    | 1403.039 | <2e-16 *** |
| room            | 1   | 52829  | 52829   | 13819.733| <2e-16 *** |
| month:sim       | 11  | 219    | 20      | 5.197    | 3.10E-08 *** |
| month:room      | 11  | 4770   | 434     | 113.44   | <2e-16 *** |
| sim:room        | 1   | 83     | 83      | 21.737   | 3.13E-06 *** |
| month:sim:room  | 11  | 286    | 26      | 6.791    | 1.55E-11 *** |
| Residuals       | 735792 | 2812727 | 4       |          |        |

Thereafter, a Tukey test was made to deeper the significance analysis for each of those factors in isolated form (Table 7). It should be noted that the bedroom 1 (penthouse apartment located in the building corner) presented the highest average operative temperature (AOT) due to its three façades. This result corresponds to the result found in the previous analysis presented. Likewise, the bedroom 2 (penthouse apartment located in northwest façade) also presented a high AOT. Thus, it can be stated that the average temperature of the penthouse apartments is the highest. On the other hand, the bedroom 7, in southeast façade, presented a low AOT due to its ground floor position. This result also confirms the comfort analysis result.

Table 7. Tukey Test analysis results for the bedrooms

| Rooms | Temperature mean | Rooms | Temperature mean | Rooms | Temperature mean |
|-------|------------------|-------|------------------|-------|------------------|
| 1     | 24.21365         | 1     | 24.21365         | 1     | 24.21365         |
| 2     | 24.02332         | 2     | 24.02332         | 2     | 24.02332         |
| 5     | 23.88672         | 5     | 23.88672         | 5     | 23.88672         |
| 3     | 23.81034         | 3     | 23.81034         | 3     | 23.81034         |
| 4     | 23.72922         | 4     | 23.72922         | 4     | 23.72922         |
| 7     | 23.45445         | 7     | 23.45445         | 7     | 23.45445         |
| 6     | 23.24831         | 6     | 23.24831         | 6     | 23.24831         |

Considering the month variable, the Tukey test indicated March, February, and January as those that presented the highest AOT in that order (Table 8). On the other hand, the lowest AOT were observed in July and August. It is possible to notice that the months with the higher AOT were observed in July and August.
cold discomfort and heat discomfort are also the ones with the lowest and highest AOT, respectively.

| Month      | Temperature mean |
|------------|------------------|
| March      | 25.67703         |
| February   | 25.60278         |
| January    | 24.98256         |
| December   | 24.69176         |
| April      | 24.52642         |
| October    | 24.3463          |
| November   | 24.28252         |
| September  | 23.51175         |
| May        | 22.34708         |
| August     | 22.17756         |
| July       | 21.60572         |
| June       | 21.58772         |

Concerning the building simulation model variation, it should be noted in Table 9 that the simulation n. 8 (ceiling variation), 5 and 3 (wall variation), as well as n. 7 (ceiling variation) presented the highest AOT followed by that with n. 1 (reference model). On the other hand, the building simulation n. 4 and 2 (wall variation) as well as the n. 12 (opening size variation) presented AOT alike followed by n. 9 (ceiling variation), n. 11 (opening size variation) and n. 13 (best strategies together). The lowest AOT was observed in Building simulation n. 10 (opening size variation).

| Simulation | Temperature mean |
|------------|------------------|
| 8          | 23.94227         |
| 5          | 23.91349         |
| 3          | 23.91331         |
| 7          | 23.91076         |
| 1          | 23.85181         |
| 4          | 23.77035         |
| 2          | 23.76245         |
| 12         | 23.74532         |
| 9          | 23.67674         |
| 11         | 23.62921         |
| 13         | 23.57147         |
| 10         | 23.51167         |
Figure 14 shows a boxplot of all bedroom temperatures (AOT) along the months, throughout the year. As presented in Table 9, March and February have the highest AOT, followed by January. On the other hand, June, July and August have the lowest AOT, throughout the year.

It is important to note that the results found in the statistical analyzes were consistent with the results found in the comfort analyzes. In summary, this study analyzed the potential demand for university dormitories acclimatization (cooling and heating degree-hours) and also its thermal comfort conditions, considering the adaptive model for 80% acceptability limits set by ASHRAE 55/2017 [22] to guarantee a baseline for comparison between minor differences of building envelope under a Brazilian humid tropical climate (Köppen-Geiger climate classification Cwa). Thus, in this climatic conditions, a relevant decrease in acclimatization demand, by minor changes in the window opening, wall, and ceiling composition, can be noticed thought the year despite airflow be considered when the indoor temperature was higher than the outdoor temperature, regardless its maximum values or at any time the outdoor temperature was higher than 21.07 °C. Since Brazilian university dormitories present a short governmental budget, an architectural project and its building system validation could assist stakeholders to build more economically for similar cases. Small changes without major cost impacts can also provide minimal environmental conditions for its residents by a natural ventilation system. This strategy can either foster the National Energy Efficiency Plan and the global greenhouse gas reduction initiatives.
In general, after minor changes in the original building envelope, it was possible to verify comfortable conditions, most of the time throughout the year, without any Heating, Ventilating and Air Conditioning (HVAC) system. Besides, previous studies have indicated that the university dormitory's environmental suitability contributes to enhance academic performance and persistence in higher education [8-11].

It should be noted that university dormitories differ a lot of aspects of a residential building. In this context, some particularities of these results meaning should be pointed out. The occupancy through the day can vary according to the course schedule which can be morning or evening. However, in both cases, the residents could experience a more pronounced heat discomfort in the late afternoon despite outdoor temperature shown, most of the time, to be below the upper adaptive comfort limit presented by ASHRAE 55/2017. The longer thermal delay may not be as beneficial as predicted for this building thermal behavior, as an alternative envelope solution. It should be noted that the standard which presents constructive guidelines for the Brazilian climate [14] is based on studies [15, 16] under a hot and humid climate in other countries. Thermal delay variations could be further investigated in the Brazilian context.

Likewise, the occupancy through the year can also vary according to university holidays and vacations that used to start from the begging of December until the end of February and half of July, in Brazil. In this period the residents can visit his family in other cities or also work on vacation internships. Over the same period could be noticed a significant heat discomfort, except in July that a cold discomfort can be noticed. Thus, this discomfort may not be perceived in practice due to the possibility of variation in building occupancy. In this context, the influence of singularities related to university dormitories and its occupation should contribute to validate building envelope options.

Residents in university dormitories are also a variable that presents significant importance and should be further investigated. Airspeed increase could enlarge the operative temperature limit acceptability up to 2.2°C [22] and, consequently, reduce heat discomfort hours. However, user’s behaviors and preferences are diverse in the university dormitory and could vary by age, gender, race, psychological adaptation factors and so on. Thus, this behavioral condition can influence, in practical application, the consumption of electricity for HVAC, despite the building envelope provides climate suitability by a natural ventilation system. Besides, a thermal sensation, develop as a future study, can assist to shape user preferences and verify the need for a mixed-mode building system under this climate
condition. This survey results can also support the available rooms selection according to their preferences considering the different thermal behaviors of the university dormitories in different orientations and floors. This custom room selection can also contribute to building energy savings potential.

4 CONCLUSION

The thermal performance in bedrooms of a university dormitory located in Belo Horizonte, Brazil (humid tropical climate – Köppen-Geiger climate classification Cwa), was assessed through numerical simulation. Measurements were applied to provide the indoor conditions data for the model calibration step.

The northwest bedroom, situated on the top floor, presented a slightly worst thermal behavior amongst the evaluated bedrooms. The results of heating and cooling degree-hours were analyzed. The alternative that presented the best thermal behavior was made up of masonry in structural ceramic blocks with 14cm of width, internal and external mortar, roof composed of fiber cement roofs tiles, solid slab in concrete and smooth plaster for internal coating as well as a small window openings area.

The construction material's thermal properties influence in the building’s thermal performance was noticed, which justifies the study of envelope systems. The main conclusion drawn from this research is that the thermal performance of the evaluated university dormitory would be improved by walls presenting a greater thermal lag and by windows design with small openings area. This fact corroborates the importance of simulations to evaluate the thermal performance in buildings since the simulations allow us to consider a global heat balance of the built environment.

As a limitation, the results of this paper are valid for this specific sort of residential building, along with the natural ventilation and other settings of the presented methodology. Thus, we further acknowledge that the above model is liable to modification with further researches in the region encompassing a wider sort of buildings, different types of built environments, buildings systems, among others. HVAC was not considered during the discomfort periods.

The method enabled searching for an adequate building envelope among some alternatives. The purpose of this paper was not to define an optimized envelope but rather a “proper choice” under a specific climate condition. Thus, an optimization approach would contribute to improve the building thermal performance and thermal comfort for its users.
For professionals, these results can point out alternatives to be considered in university dormitories design. For researchers, this method can be reproduced for other buildings and sort of climates as a tool to find the most suitable performance alternative in different contexts.

Taking this paper as a starting point, a further parametric and a long-term field study should be done to generalize the findings for improving the envelope of university dormitories and the thermal comfort conditions provided. Further field studies thought occupants survey or by environmental measurement could evaluate thermal comfort conditions in natural ventilated or mixed-mode buildings. Unlike residential buildings, in university dormitories the occupants are always coming from different cities and frequently vary by age, gender, race, psychological adaptation factors, and so on. In this context, a long term field studies focus on occupants' comfort perception could also improve the preferences understanding and the energy savings potential.

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