Thermal Performance of Dwellings: Comparative Study Between Simulation Methods with NBR 15,575 (2013) and NBR 15,575 (2021)

M. M. Barbosa, P. E. Silva de Oliveira, A. J. Costa e Silva, J. M. P. Q. Delgado, and A. C. Azevedo

Abstract Depending on the constructive, geographical, and geometric characteristics, the thermal performance of buildings is parameterized by regulatory technical standards that aim to promote appropriate thermal comfort conditions for users. The knowledge of the ways to mitigate radiation, the biggest source of thermal gains in buildings, is essential to enable better thermal energetic levels and, above all, reduce the consumed thermal load. This work aims to carry out a comparative analysis between the computational simulation methods recommended by NBR 15,575 (2013) and NBR 15,575 (2021). For this purpose, two buildings were selected: one housing of social interest and another with q high-end standard level. From this, computational models for thermoenergetic simulation were carried out using the Energy-Plus software. The results obtained in the social interest housing simulations indicated compliance with the minimum level, but there was no compliance with the criteria of the intermediate and superior levels given the two normative methods analyzed. In the simulations carried out in the high-end building, compliance with the minimum level was achieved only with the use of shading devices in the frames, and, like social housing, it did not meet the intermediate and higher levels. When observing the simulations, in spite of being different, the service profile between the two methods was maintained. The house of social interest, whose construction systems are similar to the normative reference model, predisposes to meeting the minimum level, whereas buildings with large areas of transparent elements tend to have greater difficulties in meeting the thermal performance requirement. This work also shows the normative advances given by NBR 15,575 (2021) through the insertion

M. M. Barbosa · P. E. S. de Oliveira · A. J. C. Silva
Departamento de Engenharia Civil, Universidade Católica de Pernambuco, Recife, Brazil
e-mail: angelo.silva@unicap.br

J. M. P. Q. Delgado (✉) · A. C. Azevedo
Departamento de Engenharia Civil, CONSTRUCT-LFC, Universidade Do Porto, Rua Dr. Roberto Frias, s/n, 4200-465 Porto, Portugal
e-mail: jdelgado@fe.up.pt

A. C. Azevedo
e-mail: antonio.costaazevedo@fe.up.pt

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of parameters that incorporate energy efficiency and the concept of annual analysis of buildings.

Keywords Thermal performance · NBR 15,575 (2013, 2021) · Numerical simulation · Energy-plus

1 Introduction

Thermal performance could be defined as thermal parameters established by regulatory standards that a building must meet. The adequate thermal performance implies better conditions of comfort in the use of the building, as well as the reduction of the housing energy consumption. It is valid to state that thermal performance is not equal to thermal comfort, since thermal comfort refers to the physical and mental state that represents the satisfaction of the individual with the thermal environment in which it is inserted (ASHRAE, 2017a; Lamberts et al., 2014; Sorgato et al., 2013).

The thermal performance of a building depends on numerous variables from which they undergo the site of housing (topography and climatic conditions) and characteristics of the building (number of floors, dimensions of the environments, as well as the building height, the orientation of the facades, among others). In terms of thermal performance, Brazil, with continental dimensions and a great climatic variability, is a challenging country for designers and consultants to ensure good conditions of comfort in buildings. Thus, knowledge in the materials used and configuration of the building in the climate in which it is inserted is fundamental to ensure better thermal energetic conditions (Ioannou & Itard, 2015; Novais et al., 2014; Silva & Ghisi, 2014).

In 2020, Brazil presented an energy consumption of 474.22 Twh, of which the residential sector represented a share corresponding to 31% related to total consumption (see Fig. 1).

According to Jardim (2011), the housing adequacy, during use, to thermal comfort represents about 84% of energy consumption and highlights the importance of rationalizing the building envelope in order to promote better levels of thermos-energetic efficiency. The studies presented by Almeida (2014), Fajkus (2013) and Yoshino et al (2017) confirmed the influence of the thermos-energetic properties of the envelope

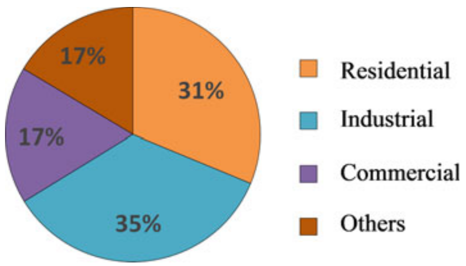


Fig. 1 Distribution of electricity consumption by sector, in 2020 (EPE, 2020)

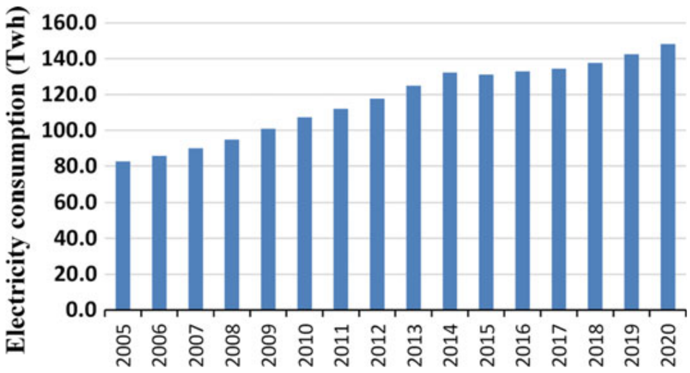


Fig. 2 Electricity consumption of the residential sector (2005–2020), EPE (2020)

on the energy balance of the system and the impact on the energy consumption of buildings.

According to EPE statistics, the growth of energy consumption in the Brazilian residential sector between 2005 and 2020 presented an increase of 79.4% compared to the initial value (see Fig. 2). Based on the technical note 030/2018, EPE states that the acquisition of air conditioners, with a growth of 9% per year, in residential buildings was crucial in the increase of 61% of Brazilian electricity in the residential sector between 2005 and 2017. These data demonstrate the relevance of air conditioning systems in the need of Brazilians to obtain comfort and reinforce their impact on the Brazilian electrical system, which, in turn, implies greater generation and distribution needs to meet energy demands, especially at peak times.

According to Dornelles (2008), the largest source of thermal gains in buildings comes from the incidence of solar radiation and states that the most sustainable means to mitigate heat gains in buildings is given by controlling the effects of solar radiation that reaches constructive envelope. Therefore, the investment in efficient techniques that mitigate thermal exchanges in a building can therefore enable better comfort conditions with reduced energy consumption. In terms of energy, Lamberts et al (2014) states that one building is more efficient than another when it provides the same environmental conditions with lower energy consumption.

In resume, the main research, of this work, is a comparative analysis of the computational simulation methods used in the thermal performance requirement by NBR 15,575 (2013) and the new methods proposed in Amendment 1 of NBR 15,575 (2013), new standard NBR 15,575 (2021). More in detail:

- Study the heat transmission processes of the building envelope;
- Perform computational simulations to obtain internal temperatures in each long-stay enclosure analyzed;
- Perform computational simulations to obtain annual energy consumption of buildings, due to the needs of cooling the bedrooms;
- Analyze the temperature and energy consumption numerical results obtained.

2 Literature Review

External vertical sealing systems, floor systems, roofing systems and windows constitute the building envelope. These systems and elements have the function of isolating the internal environment from external climatic conditions, acting as a barrier to air passage (infiltration and ventilation), heat (thermal energy) and relative humidity. Therefore, being aware of the physical processes that are part of the building envelope becomes essential to investigate the behavior of the building as a function of meteorological changes, the location, besides having competence to define the necessary parameters of the materials that will compose the project since its conception and, consequently, more efficient decision-making.

There are several types of energies such as kinetic, electrical, magnetic, mechanical, nuclear, potential, chemical and thermal energy, whose sum represents the total energy of a system. Among the existing forms of energy, those that relate to the molecular structure of a system and the degree of molecular activity are named microscopic energy. The sum of all microscopic energies results in the internal energy of the system (Çengel and Ghajar, 2012).

Regarding internal energy, which is configured in two ways: kinetic internal energy and potential internal energy, this work is limited to the study of internal energy associated with the kinetic energy of molecules, called sensitive energy or sensitive heat, that is, when thermal energetic transfers do not involve alteration in the physical state of matter. In this context, heat, or thermal energy, is conceptually understood as energy associated with the random movement of atoms and molecules whose average velocity and degree of activity are proportional to the temperature increase.

The general concept for defining specific heat is the energy needed to increase the temperature by a degree of a given unit of mass of the substance. There are two specific heat types: heat specific to constant pressure and specific heat to constant volume; the values for the two specific types of heat are equivalent when it comes to incompressible substances, when the density does not change due to temperature or pressure variation. The specific heat of incompressible substances depends only on a variable, temperature, and therefore the mathematical expression that measures the physical concept of variation of internal energy (sensitive heat) of solids or liquids, is represented by Eq. (1),

$$Q = m\,c\,\Delta T \tag{1}$$

where Q is the heat flow (J), m is the mass (kg); c is the specific heat (kg/J · K) and ΔT is the temperature gradient (K).

Understanding heat transfer mechanisms is crucial to achieving better conditions of comfort and thermal performance, as well as energy efficiency. Specht et al. (2010) state that "*The design of energy-efficient buildings requires knowledge about the transfer of heat from the external environment to the interior of the buildings, in order to create solutions that associate different materials and layer dimensions with the desired conditions of thermal comfort. The production of this knowledge through* *the construction of prototypes, besides being costly, presents difficulties with regard to the variation of the materials and dimensions of the layers*".

It is also worth mentioning that, in NBR 15,575 (2013), it is contemplated the analysis of the thermal properties of the building envelope systems in the simplified method of evaluating the thermal performance of buildings, the calculation procedure is expressed in NBR 15,220 (2005) and is based on the determination of thermal transmittance and thermal capacity (seen Sect. 2.1.1 Conduction).

2.1 Heat Transfer Mechanisms

Heat transfer could be defined as thermal energy in transit by the action of a temperature gradient in space. In general, when there is a temperature gradient in a medium or between media, i.e. solid(s) or fluid(s), there will be heat transmission. There are three forms of heat transmission: we call it conduction, the heat transfer that occurs through a stationary medium; convection as the transfer of heat between a surface and a moving fluid and, finally, the thermal radiation that is the energy emitted by matter, which is at a non-zero temperature, through electromagnetic waves (Incropera and Dewitt, 2008).

2.1.1 Conduction

The heat conduction process (see Fig. 3) respects the second law of thermodynamics, which states that the meaning of heat transfer should be in the direction of lower temperature. The heat conduction rate (q') by one medium is proportional to geometry and temperature difference, and inversely proportional to thickness. The governing equation of the heat conduction rate, the Fourier law of thermal conduction, under steady-state conditions, is defined by:

$$\mathbf{q} = -\boldsymbol{\lambda} \cdot \mathbf{A} \cdot \frac{\Delta \mathbf{T}}{\mathbf{L}} \quad (2)$$

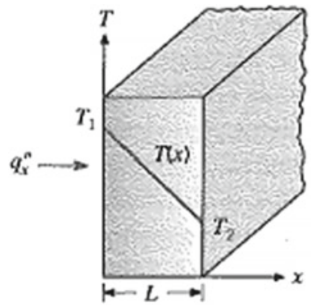


Fig. 3 Heat conduction sketch (Incropera and Dewitt, 2008)

where q is the heat conduction rate (W); λ is the thermal conductivity (W/m · K); A is the area perpendicular to the direction of heat transfer (m^2); ΔT is the temperature difference, obtained by subtracting the cold temperature from the hot temperature and L is the thickness, parallel to the heat transfer direction (m).

Note: The negative sign of the equation ensures that the heat transfer in the positive direction of L is a positive value.

From Eq. (2), the heat flux density (q”) is given by the ratio of the rate of heat conduction by the area, thus:

$$\mathbf{q}'' = \frac{\mathbf{q}}{\mathbf{A}} \therefore \mathbf{q}'' = \boldsymbol{\lambda} \cdot \frac{\Delta \mathbf{T}}{\mathbf{L}} \tag{3}$$

Thermal Resistance of Conduction

In general, thermal resistance is a property associated with the difficulty of passing heat through a medium, taking into account the difference in temperature, thermal energy, cross-sectional area to the transfer direction and thickness. There is a range of ways to treat thermal resistance in engineering, the three most used are:

- **Absolute thermal resistance (R_t)**

This parameter defines the strength of a system whose geometric characteristics of area and thickness are known. For the absolute thermal resistance, only one temperature difference between surfaces is enough to determine the heat transferred from a system. The expression representing by R_t is derived from Eq. (2),

$$\mathbf{q} = \frac{\Delta \mathbf{T}}{\mathbf{R_t}} \tag{4}$$

with the absolute thermal resistance (R_t) given by,

$$\mathbf{R_t} = \frac{\mathbf{L}}{\boldsymbol{\lambda} \cdot \mathbf{A}} \tag{5}$$

where R_t is the absolute thermal resistance (K/W).

- **Thermal resistance as R-value (R)**

This parameter is a constant of the material and indicates the difficulty of changing the temperature of the material, every linear meter, by inserting a unit of energy. Material thickness and a temperature difference are necessary to establish the transferred heat. The units representing the specific thermal resistance are mK/W.

- **Thermal resistance as R-value (R)**

The R value is known as the thermal insulation factor, it is directly proportional to the insulation, that is, the higher the R-value, the better the resistance of the material against the passage of heat in its environment. Expresses the thermal resistance of the unit area of a system. The unit representing this type of thermal resistance is $m^2 \cdot K/W$. For the determination of transferred heat, an area and temperature difference is required. The physical model that defines R is:

$$\mathbf{R} = \frac{\mathbf{L}}{\boldsymbol{\lambda}} \tag{6}$$

Therefore, the heat flux density is expressed as:

$$\mathbf{q}'' = \frac{\Delta \mathbf{T}}{\mathbf{R}} \tag{7}$$

In composite systems, it is common to use an analogy to Newton's law of cooling as a way of treating the system's heat transfer. In this mode, a U coefficient is adopted which means *global heat transfer coefficient*, or thermal transmittance, and expresses the rate of heat flux that crosses the unit area of a component when there is a thermal gradient of 1 K between its faces. Thermal transmittance obeys the following expression:

$$\mathbf{U} = \frac{\mathbf{q}''}{\Delta \mathbf{T}} \tag{8}$$

where U is the thermal transmittance coefficient ($W/m^2 \cdot K$). Correlating Eq. (7) with Eq. (8), the thermal transmittance of a component can be understood as the inverse of the sum of the thermal resistances of each element that integrates the component, demonstrated by,

$$\mathbf{U} = \frac{1}{\sum \mathbf{R}} \tag{9}$$

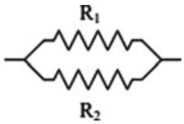
Electrical Analogy

There is an important analogy made from the heat conduction rate equation with the electric current flow equation.

$$\mathbf{I} = \frac{\Delta \mathbf{V}}{\mathbf{R_e}} \tag{10}$$

$$\mathbf{q} = \frac{\Delta \mathbf{T}}{\mathbf{R_t}} \tag{11}$$

Just as electrical resistance is associated with conducting electricity, thermal resistance is associated with conducting heat. This relationship is very favorable when you have different materials that make up a medium, as you can use the rule of summing the resistance of electrical circuits for thermal circuits and determine an equivalent resistance of the thermal circuit, being associated in series and/or parallel.



$$\mathbf{R_{eq}} = \sum_{i=1}^{n} \mathbf{R_i} \tag{12}$$

$$\frac{1}{\mathbf{R_{eq}}} = \sum_{i=1}^{n} \frac{1}{\mathbf{R_i}} \tag{13}$$

Thermal Diffusivity

In transient heat conduction analyses, a property that measures the speed of heat propagation in a medium is called thermal diffusivity and it is linked to the thermal conductivity and thermal capacity of the material. This, in turn, concerns the heat storage capacity of a material, as well as specific heat, but it differs from specific heat in that it refers to the heat storage capacity per volume unit, whereas specific heat refers to up to the heat storage capacity per unit of mass.

The diffusivity of a given material is the result of the fraction between its thermal conductivity and its thermal capacity. Thermal capacity is the result of the product between density and specific heat of a material,

$$\kappa = \frac{\boldsymbol{\lambda}}{\boldsymbol{\rho c}} \tag{14}$$

where κ is the thermal diffusivity (m^2/s); λ is the thermal conductivity ($W/m \cdot K$); ρc is the thermal capacity ($J/m^3 \cdot K$); ρ is the density (Kg/m^3) and c is the specific heat ($kg/J \cdot K$). Should be noted that it is common to find in some literatures and standards, especially when it comes to constructive systems, the thermal capacity as a result of the product between the density, thickness and specific heat of the corresponding material. In this particularity, the thermal capacity expresses the heat storage efficiency of a material per unit area, which must be perpendicular to the heat transfer direction, in $J/m^2 \cdot K$.

Brazilian Convention for the Calculation of Thermal Capacity and Thermal Resistance

In Brazilian civil construction, the calculation of thermal capacity and thermal resistance of building component and element systems are recommended by the NBR 15,220 (2005) standard.

2.1.2 Convection

The convection heat transfer mode involves the transfer of heat between a moving fluid, gas or liquid and a surface of which there is a temperature gradient. Convection takes place through two mechanisms: energy transfer by random molecular motion and by global, or macroscopic, fluid motion (advection). It is noteworthy that in the absence of mass movement of a fluid, heat transfer between the solid surface and the adjacent fluid takes place through a conduction process.

A model for understanding the conduction process is to consider a hot surface which must be cooled by cold air on its face. The consequence of the interaction between the heated surface of the surface and the fluid is the emergence of a region whose velocity varies from zero (in contact with the upper surface.higher, $y = 0$) to a finite value (v_∞); there will also be a region where the surface temperature will vary from Ts, at $y = 0$, to T_∞, fluid temperature. In this way, we say that surface heat is cooled by convection, caused by the combined effect of conduction within the air caused by random movement of air molecules and by mass movement or macroscopic movement of the air that replaces the heated surface air with a cooler air. It is important to note that when the fluid velocity reaches the finite value (v_∞), this region is known as the hydrodynamic or velocity boundary layer and it is at this same level that we will also have the thermal boundary layer, with the fluid reaching temperature T_∞).

The classification of conduction heat transfer varies according to the nature of the fluid flow and can be forced, mixed or natural. We claim that convection is said to be forced when fluid is forced to flow over the surface by external means such as a fan, pump, or atmospheric winds. In the case of natural convection, fluid flow is caused by fluctuating forces induced by density differences, due to fluid temperature variation. In mixed convection, both forced and natural convection processes occur simultaneously.

Regardless of the nature of the fluid flow, the rate of heat transfer by convection respects Newton's law of cooling, expressed as

$$\mathbf{q} = \mathbf{h} \cdot \mathbf{A_s} \cdot (\mathbf{T_s} - \mathbf{T_\infty}) \quad (15)$$

where h is the convection heat coefficient $W/m^2 \cdot K$); A_s is the area of the surface on which convection heat transfer is taking place (m^2); T_S is the surface temperature (ºC or K) and T_∞ is the fluid temperature far enough from the surface. (ºC or K).

Should be noted that the value of the convection heat coefficient h is experimentally determined and depends on all boundary layer variables that influence convection, such as surface geometry, nature of fluid movement, fluid properties and mass velocity of the fluid.

There are some important considerations to note about Newton's law of cooling. First, when the surface temperature is greater than the fluid temperature, it follows that heat is being transmitted from the surface to the fluid. Second, when the fluid temperature is greater than the surface temperature, it follows that heat is being transmitted from the fluid to the surface. From these two considerations, one can arrange the convection heat transfer rate equation according to the two scenarios mentioned so that the transfer rate results in a positive value.

Finally, the expression that represents the thermal convection resistance is obtained from a reorganization of Newton's law of cooling, given by

$$\mathbf{q} = \frac{(\mathbf{T_s} - \mathbf{T_\infty})}{\mathbf{R_{conv}}}, \tag{16}$$

$$\text{with } \mathbf{R_{conv}} = \frac{1}{\mathbf{hA}} \tag{17}$$

where $\mathbf{R_{conv}}$ is the thermal resistance of the convection surface against heat or the thermal resistance of convection (K/W). It is worth noting that, regardless of the surface geometry, when the convective coefficient is very hight, resistance $h \to \infty$ of convection is equal to zero, this means that the surface does not offer any resistance to convection, therefore, it does not hinder the passage of heat. This case is commonly observed on surfaces that boil and condense.

2.1.3 Radiation

Unlike transfer by conduction and convection, transfers that occur by radiation do not require the presence of a material medium. Radiation is the energy emitted by the matter through electromagnetic waves due to changing electron configurations of atoms or molecules.

For the study of heat transfer, what matters to us is thermal radiation, which differs from other forms of radiation that are unrelated to temperature such as electromagnetic radiation, gamma rays, x-rays, microwaves, radio and television waves. Thermal radiation is the energy emitted by matter at a non-zero temperature.

As the main energy source in the solar system, solar radiation, when crossing the Earth's atmosphere, can be absorbed, reflected or dispersed depending on the presence of particles and gases present in it. In the process of transmitting solar radiation, opaque materials absorb or reflect part of the received energy and transparent materials allow direct or diffuse transmission of the incident energy portion.

Solar Absorbance

According to Dornelles (2008), solar absorptance corresponds to the amount of radiant energy absorbed by a surface as a result of the total energy incident on it. This characteristic depends on variables such as absorptivity, surface color, roughness, geometric shape of the body, among others.

Also according to Dornelles (2008), solar absorptance has a direct effect on the temperatures reached by surfaces exposed to solar radiation, which influence the intensity of the thermal flux that permeates constructive systems. Thus, it is interesting to be aware of the characteristic whose objective is to mitigate heat gains in buildings and promote better thermoenergetic performance.

Relationship Between Absorbance, Reflectance and Transmittance

The relationship that defines the amount of radiant energy incident on the surface of a material transfigured by means of absorption, reflection and transmission could be expressed from the first law of thermodynamics (ASHRAE, 2017b):

$$\boldsymbol{\alpha} + \boldsymbol{\rho} + \boldsymbol{\tau} = 1 \tag{18}$$

where α is the absorbance, absorbed portion from incident radiation (-); ρ is the reflectance, reflected portion from incident radiation (-); τ is the transmittance, transmitted portion from the incident radiation (-).

In opaque materials, the total radiant energy incident on surfaces is determined through the absorptance and reflectance portions. The transmittance, in this case, is null. In view of this, it is possible to determine any one of the properties based on the other (Dornelles, 2008).

$$\boldsymbol{\alpha} = 1 - \boldsymbol{\rho} \tag{19}$$

2.2 Energy Balance

The energy balance in the building envelope is based on the first law of thermodynamics, the law of energy conservation. This law establishes that the amount of thermal energy (heat) that enters a control volume—in this case the envelope (Ea), plus the amount of heat generated inside the volume (Eg), minus the amount of energy that leaves the volume (Es) must equal the increase in the amount of stored energy (Ear) in the control volume.

$$\mathbf{E_e} - \mathbf{E_s} + \mathbf{E_g} = \mathbf{E_{ar}} \tag{20}$$

2.3 Thermal Bridges

According to EN ISO 10211, thermal bridges could be defined as portions of the building envelope in which the thermal resistance changes significantly, due different thermal conductivities of the materials used, thickness and layers variations, differences in external and internal areas of the building, etc.

Some works such as presented by Freitas et al (2016) and Gioelli et al. (2015) reported the importance of including this mechanism in thermoenergy simulations, justified by the growing impact of energy consumption in buildings at different bioclimatic zones.

2.4 Building Performance

Social interest housing are buildings provided by actions of the federal government in partnership with states, municipalities, private companies and non-profit entities whose purpose is to guarantee subsidies to the low-income population that does not have access to formal housing or conditions for such. This federal program continues to expand and improve as technology advances and there are regulatory norms establishing limits to be respected for each necessary housing requirement. In accordance with this, it is common knowledge the precariousness in the quality in which these buildings were built. As a result of this, the NBR 15,575 (2013) standard emerged, aiming to recommend construction parameters for new housing buildings, with an emphasis on housing of social interest, and establish the responsibility between the agents involved in the civil construction field: builders, suppliers, designers and users. In this way, it is possible to guarantee urban development and reduce the housing deficit while maintaining decently acceptable housing conditions.

ISO 6241, which was developed in 1984, was a milestone in terms of the concept of performance, due the definition of fourteen basic requirements that should be met by construction products, including stability, fire safety, air purity and quality, acoustic comfort, visual comfort, safety in use, tactile comfort, among others.

Through the definition of qualitative requirements and quantitative premises or criteria, it could be established that performance is studied worldwide, through methods that allow understandable assessments of meeting the requirements made by the user, when the built unit is inhabited (NBR 15,575, 2013).

The standard makes it clear that for all the requirements and criteria that are available in it, there is a minimum level of performance that must be considered and, consequently, meted, considering basic health and safety needs, as well as the economic factor. In addition to it, the standard mentions intermediate and superior performance, the latter being optional (NBR15575-1, 2021). It is of great importance to emphasize how the thermal performance in buildings must be appreciable, especially in low-income buildings.

In accordance with this the thermal performance of a building depends on several factors that must be observed both in the building itself, such as the temperature, relative humidity, materials used, dimensions, the number of floors, etc. (CBIC, 2013).

For Siqueira (2005): "A building designed for the climate in which it is located becomes comfortable, in addition to saving energy". What is quite satisfactory for the user, considering that in addition to providing comfort, the economic factor will be very beneficial.

In the computational simulation procedure, the normative method, established by NBR 15,575 (2013) is based on comparisons between the air temperature outside the building with the internal air temperature inside environments, criterized by the bioclimatic zone belonging to the building. These temperature values are referenced in typical summer and winter days that represent, respectively, the maximum and minimum annual temperature; the typical days should be determined according to the climatic data in which the building is located. In the thermal performance evaluation, it is defined that only prolonged stay environments, such as bedrooms and living rooms, must be evaluated, although the entire housing unit must be included in the simulation. The standard indicates the choice of the most critical pavement, thermally, in computer simulation, which tends to be the roof floor, as it has a larger area of exposure to radiation effects, and prescribes the choice of the most critical housing unit to represent the level of performance of the building. The service condition adopted in the simulation is based on the use of different room ventilation rates. These values should be equal to 1 air renewal per hour (1 rph); for cases, in summer situations, which did not meet the criteria of the typical day, NBR 15,575 (2013) recommends that a new computer simulation be carried out with the following changes: increase in ventilation to 5 air changes per hour (5 rph), consideration of shading on glazed surfaces (which can be configured as sun protection devices, external or internal, capable of mitigating, at least 50% of the incident direct solar radiation) with a ventilation rate of 1 rph and, finally, the combination of the two previous strategies.

On the other hand, the simulation model proposed by NBR 15,575 (2013) introduces a new simulation concept. In such a case, the housing unit is simulated based on comparisons between the real and reference models and allows the assessment of the units at the minimum, intermediate and higher levels.

This computer simulation procedure evaluates the annual thermal performance of the building envelope in relation to the reference model, which represents the building evaluated with changes (see Table 1) based on normative preconceptions that are both geometric and constructive, such as, for example, reconfiguration of the transparent elements of environments of prolonged stay and modifications in the constructive elements. For the computer simulation program, it is required to be in accordance with ASHARAE 140, able to model the effects of thermal inertia, consider heat exchanges between soil and building, calculate latent and sensitive thermal loads, capable of simulating shading effects, elements outside the thermal zones and cross ventilation in one or more rooms.

Table 1 Characteristics of the reference model

Thermal properties of the building elements for the reference model

Element	Thermal conductivity W/mK	Specific heatJ/kgK	Solar radiation absorbance	Long wave emissivity	Density kg/m^3
Outer walls	1.75	1000	0.58	0.9	2200
Internal walls	1.75	1000	real model value	real model value	2200
floors	1.75	1000	real model value	real model value	2200
Tile (6 mm thick)	0.65	840	0.65	0.9	1700
Slab (100 mm thick)	1.75	1000	real model value	real model value	2200

Thermal properties of the roof insulation material for the reference model in the bioclimatic zone 8

Element	Thermal resistance (m^{2}K)/W	Absorbance to solar radiation	Long wave emissivity
Thermal insulation	1.75	0.7	0.9

Characteristics of the transparent elements in the frames for the reference model

Element	Solar factor	Thermal transmittance W/m^{2}K	Transparent elements %
Transparent elements	0.87	5.7	17

Percentage of opening for ventilation in the frames for the reference model

Element	**Percentage of opening for ventilation** (%)
Ventilation opening	7.65

(continued)

Table 1 (continued)

Thermal properties of the building elements for the reference model			
Characteristics of frame profiles for the reference model			
Element	Absorbance to solar radiation	Long wave emissivity	Thermal conductance W/m^2K
Frame profiles	0.58	0.9	56

Initially, an analysis of the climate file must be carried out to determine the parameters and normative criteria from the average of the external dry bulb temperatures. Therefore, it is possible to identify the operating temperature values used in the parameter percentage of hours occupied within an operating temperature range (PHFT). The parameters used to meet the minimum level of performance are the PFHT indicator and annual maximum or minimum operating temperatures during the occupation of extended stay environments, the analysis to determine the minimum level of thermal performance comprises computational models operating with natural ventilation.

In the numerical analyses whose purpose is to verify the service of the housing unit at the intermediate or higher level, the criteria used to determine the minimum level are replicated, with a difference in the PHFT parameter, which makes a difference between the values obtained in the real and reference model and compared with the normative minimum values. As the last parameter used in the evaluation of the intermediate or higher level, calculations are carried out for the reduction of the total thermal load (cooling and heating) between the real and reference models to compare with the minimum defined due to meeting each level of thermal performance. The calculations of total thermal load reduction (cooling and heating) are performed between the real and reference models to compare with the minimums defined in terms of meeting each level of thermal performance. The calculations of total thermal load reduction (cooling and heating) are performed between the real and reference models to compare with the minimums defined in terms of meeting each level of thermal performance.

3 Methodology

The methodology used to carry out this research was based on four main steps:

- Choice of two buildings: one house of social interest (HIS) and another framed in the high standard profile,
- Modeling the buildings through sketchup and computational numerical simulation using the EnergyPlus software,
- Numerical analysis of the results obtained from the numerical simulations.

3.1 Buildings Analysed

The buildings considered in this work were simulated, located in the city of Recife, capital of the state of Pernambuco, and are part of the bioclimatic zone 08, according to NBR 15,220–3 (2005). For the purposes of this research, housing units facing northwest were chosen as the object of study of the work, representing the critical condition for buildings located in hot climates.

The architectural project on the ground floor of the social housing and the high-end building with the environments considered in this analysis are represented in Figs. 4, 5, 6, 7. The HIS-type building has four floors that each have eight apartments; the high-end building is configured in a 20-story tower, having a total of 40 housing units (two per floor).

Tables 2 and 3 indicate the constructive composition of the opaque and translucent materials used in the analyzed buildings. The calculations performed to obtain the values of thermal transmittance and thermal capacity of opaque materials followed the recommendation of the NBR 15,220–2 (2005) standard.

Fig. 4 Sketch of the ground floor plan, from HIS, with representation of the evaluated environments

Fig. 5 Floor plan of the type and roof pavement, from HIS, with representation of the evaluated environments

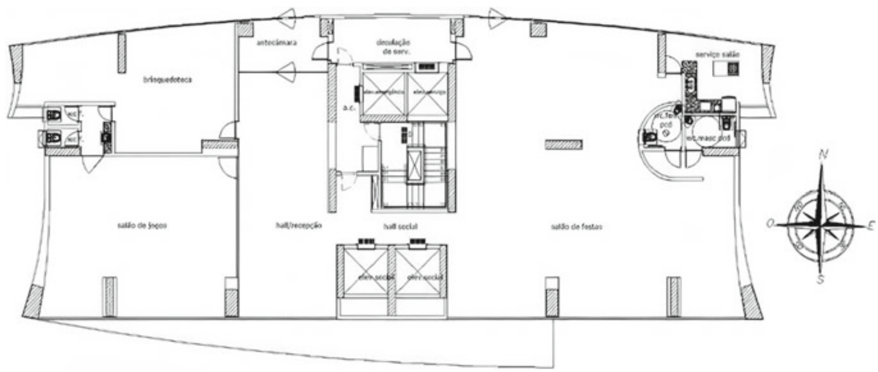


Fig. 6 Ground floor plan of the high-end building

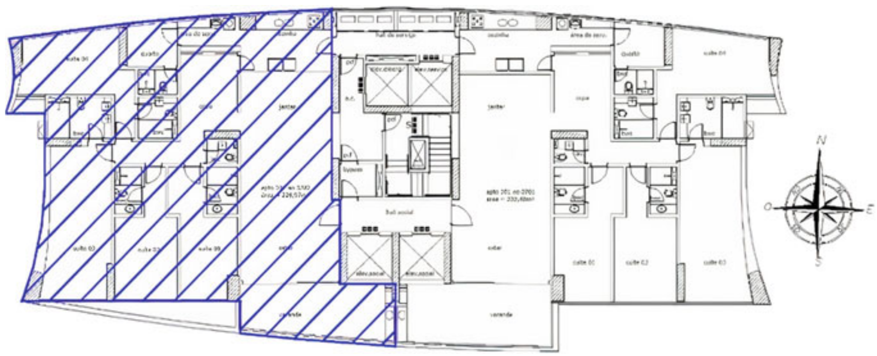


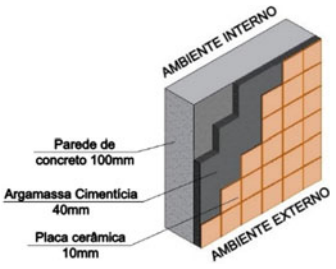
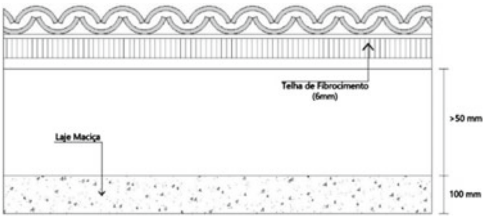
Fig. 7 Floor plan of the type and roof pavement of the high-end building, with representation of the evaluated environments

3.2 Computer Modeling and Simulation

As described in the previous sections, the three-dimensional modeling was performed in Sketchup software (see Figs. 8, 9), using the OpenStudio plugin that intercepts the modeling data for calculation in EnergyPlus.

EnergyPlus is a thermo-energetic simulation program, created from the BLAST and DOE-2 programs, the origin of which refers to concerns arising from the energy crisis that affected the United States in the 70 s, and had as target audience the designers who they wanted to dimension HVAC equipment (Heating, ventilation and air conditioning), to optimize the thermo-energetic performance of buildings, etc. EnergyPlus was developed by the Building Technologies Office (BTO), an agency linked to the DOE (United States Department of Energy), in partnership with the National Renewable Energy Laboratory (NREL), private sector companies and academic institutions (DOE, 2020 and NREL, 2020).

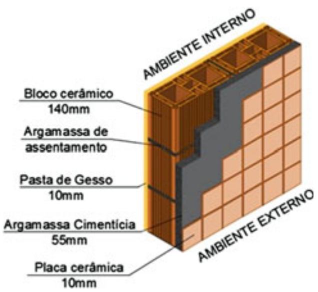
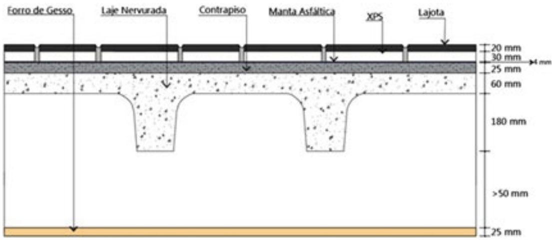
Table 2 Physical characteristics of the materials used in the housing envelope of the HIS type

Physical properties of opaque materials	
External vertical sealing system	Thermal characteristics
	Thermal transmittance (U) 3.66 W/m^{2}K
	Thermal capacity (CT) 338.4 kJ/m^{2}K
	Solar absorbance of the external coating (α) 0.3
Cover system	Thermal characteristics
	Thermal transmittance (U) 2.07 W/m^{2}K
	Solar absorbance of the external coating (α) 0.3
Thermoenergetic and luminous properties of translucent materials	
Thickness (mm)	4.00
Transmission to solar radiation (%)	83.0
Reflectance to solar radiation—external (%)	8.00
Solar radiation reflectance—internal (%)	8.00
Visible transmittance (%)	89.0
Visible radiation reflectance—external (%)	8.00
Visible radiation reflectance—internal (%)	8.00
Emissivity (%)	0.89
Thermal Conductivity (W/mK)	1.00

Widely used in Brazilian research (Santos, 2018). The EnergyPlus computational tool is certified “ASHRAE Standard 140” for the calculation of envelopes, as well as meeting the requirements of standards and regulations such as, for example, NBR 15,575 (2021), ASHRAE Standard 90.1 (2016), among others. Written in Fortran 90 language, EnergyPlus communicates easily with other programs as it presents a well-defined modular structure (LBNL, 2010).

EnergyPlus allows you to carry out simulations involving the interaction of the building in the environment of which it is inserted, soil-building interaction, consideration of internal loads such as people and their respective energy values of metabolic rates, energy consumption of lighting and equipment, cross ventilation

Table 3 Physical characteristics of the materials used in the envelope of the high-end housing

<table>
<tr><td colspan="2">Physical properties of opaque materials</td></tr>
<tr><td>External vertical sealing system</td><td>Thermal characteristics</td></tr>
<tr><td rowspan="3">
</td><td>Thermal transmittance (U)
2.53 W/m^{2}K</td></tr>
<tr><td>Thermal capacity
(CT)
264 kJ/m^{2}K</td></tr>
<tr><td>Solar absorbance of the external coating (α)
0.3</td></tr>
<tr><td>Cover system</td><td>Thermal characteristics</td></tr>
<tr><td rowspan="2">
</td><td>Thermal transmittance (U)
0.76 W/m^{2}K</td></tr>
<tr><td>Solar absorbance of the external coating (α)
0.6</td></tr>
<tr><td colspan="2">Thermoenergetic and luminous properties of translucent materials</td></tr>
<tr><td colspan="2">Glasses used in frames exempt from safety requirements</td></tr>
<tr><td>Thickness (mm)</td><td>4.00</td></tr>
<tr><td>Transmission to solar radiation (%)</td><td>44.0</td></tr>
<tr><td>Reflectance to solar radiation—external (%)</td><td>5.00</td></tr>
<tr><td>Solar radiation reflectance—internal (%)</td><td>5.00</td></tr>
<tr><td>Visible transmittance (%)</td><td>72.0</td></tr>
<tr><td>Visible radiation reflectance—external (%)</td><td>7.00</td></tr>
<tr><td>Visible radiation reflectance—internal (%)</td><td>7.00</td></tr>
<tr><td>Emissivity (%)</td><td>0.89</td></tr>
<tr><td>Thermal Conductivity (W/mK)</td><td>1.00</td></tr>
<tr><td colspan="2">Glass used in frames that meet safety requirements</td></tr>
<tr><td>Thickness (mm)</td><td>8.40</td></tr>
<tr><td>Transmission to solar radiation (%)</td><td>26.0</td></tr>
<tr><td>Reflectance to solar radiation—external (%)</td><td>5.00</td></tr>
<tr><td>Solar radiation reflectance—internal (%)</td><td>5.00</td></tr>
<tr><td>Visible transmittance (%)</td><td>57.0</td></tr>
<tr><td>Visible radiation reflectance—external (%)</td><td>6.00</td></tr>
<tr><td>Visible radiation reflectance—internal (%)</td><td>6.00</td></tr>
<tr><td>Emissivity (%)</td><td>0.89</td></tr>
<tr><td>Thermal Conductivity (W/mK)</td><td>1.00</td></tr>
</table>

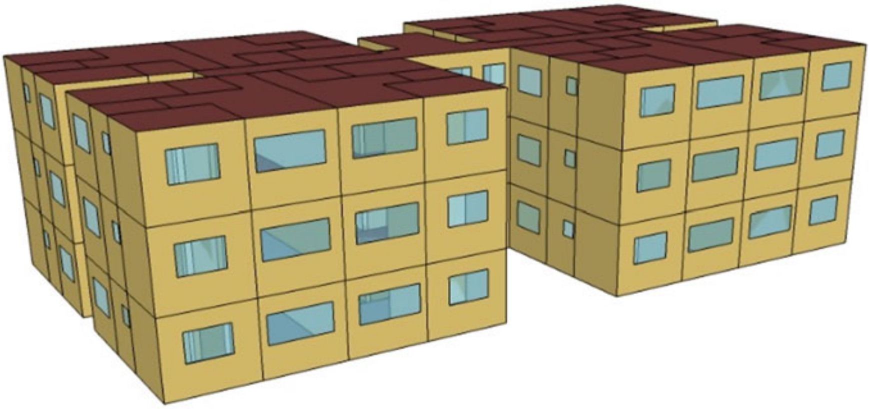


Fig. 8 HIS modeling, used in the analysis

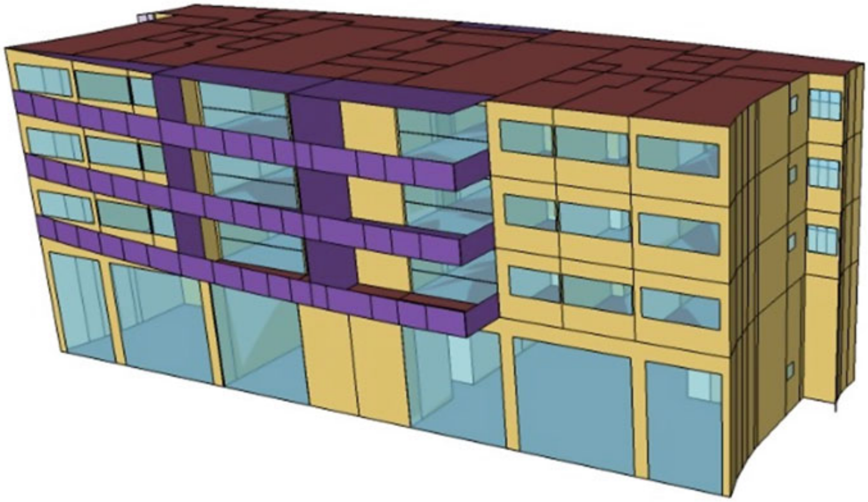


Fig. 9 High standard building modeling used in the analysis

effects, shading, insertion of HVAC systems in environments, photovoltaic systems etc. The software's calculation model is based on the fundamental principles of mass and energy balance, making it possible to determine the thermoenergetic behavior of a building, in the inserted climate, and its transient systems in an integrated and simultaneous manner, as well as to reproduce the inertia effects thermal. The program makes available data of great value, with regard to the investigation of energy efficiency and thermal performance of a building, for example, annual energy consumption by cooling or heating, internal temperature in simulated environments, surface temperature, etc. To provide this output data, EnergyPlus works with three modules:

simulation manager module (responsible for controlling the simulation process), heat and mass balance simulation module and building systems simulation module (DOE, 2020).

In this study, the buildings were modeled according to their architectural design and corresponding geographic north. The type of climate file adopted was the INMET file for the city of Recife/PE. The SLAB pre-processor method was used in order to calculate the thermal exchanges between the ground floor of the building and the ground, thus continuing the simulations and evaluating the buildings thermoenergetically.

4 Results and Discussion

4.1 Results According to NBR 15,575 (2013)

The numerical results represents the analyzes carried out in accordance with the parameters established by NBR 15,575 (2013). The criteria for buildings in bioclimatic zone 08 refers only the evaluation of the building for a typical summer day. So, the internal air temperature inside the rooms is less than or equal to the outside air temperature and is characterized as the requirement to meet the minimum level of thermal performance. It should be noted that the typical summer day considered for evaluation was February 22.

To meet the intermediate and higher levels, it is necessary that the internal temperatures of the environments have a decrease in the total value equivalent to that established by standard, in accordance with the corresponding bioclimatic zoning of the building. Thus, the established decrease, referring to bioclimatic zone 08, to service the intermediate and higher level is -1 °C and -2 °C, respectively.

4.1.1 Building of Social Interest

Figure 10 shows results obtained for the maximum annual operating temperature are expressed for the typical summer day considered. Three lines are also represented that define the maximum criteria required for each level of performance investigated.

It is observed, from the Fig. 10, that the HIS-type building met the thermal performance requirement for all the environments evaluated, adopting a ventilation rate of 1 air change per hour, called the standard condition. The Room 02 environment served at an intermediate level of thermal performance, however, as the Living and Room 01 environments only respected the minimum level of service, the indicative profile that expresses the building's level of service is consistent with the minimum level of performance thermal.

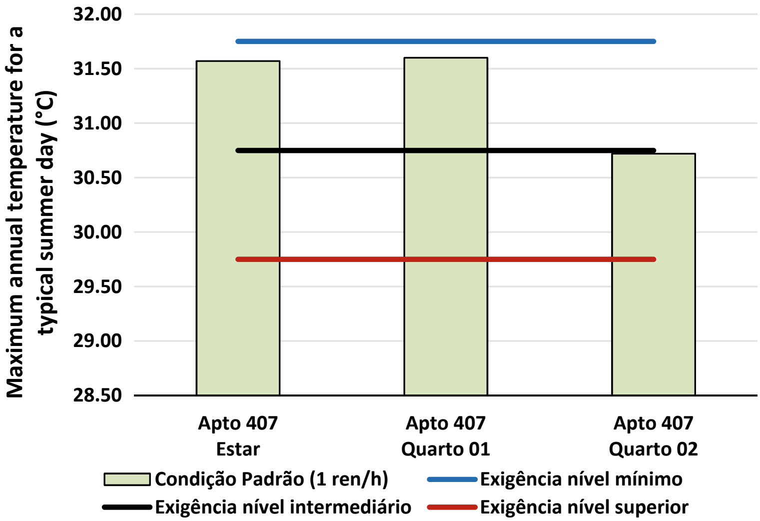


Fig. 10 Numerical results for the HIS-type building

4.1.2 High Standard Building

Figure 11 indicates the representation of the values obtained in the simulation of the high standard building for evaluating the compliance with the thermal performance requirement, as well as the ranges of requirements corresponding to each level of service.

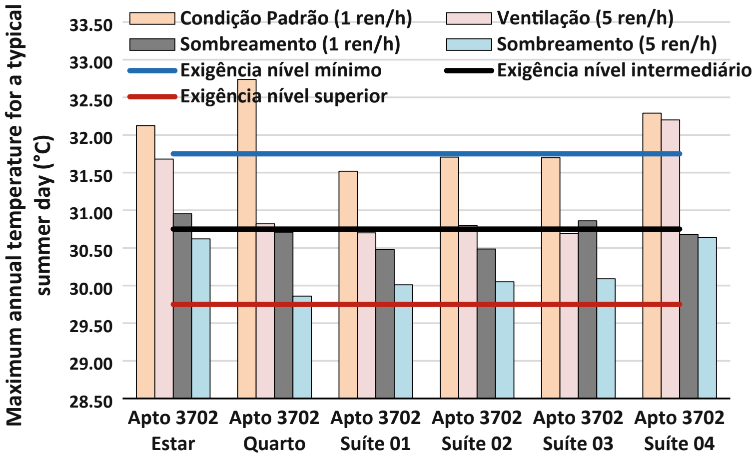


Fig. 11 Numerical results for the.high standard building

According to Fig. 11, it is possible to observe that the nemerical simulations with ventilation rates of 1 air change per hour (1 rph) and 5 air changes per hour (5 rph) did not met the minimum level of thermal performance. There are environments as the living room, bedroom (all with 1 rph) and Suite 4 (1 rph and 5 rph), which exceeded the recommended limits to meet the requirement. However, when the simulation was carried out with the adoption of shading in the frames, the minimum level of thermal performance was met for the simulated condition considering a ventilation rate of 1 rph, at an intermediate level, when the ventilation rate of 5 rph.

4.2 Numerical Results According to NBR 15,575 (2021)

Below are the products of the simulations for thermal performance evaluation in accordance with NBR 15,575 (2021). The evaluation is divided into two parts: the first refers to the analysis for evaluating the project at the minimum level of thermal performance, which is the normative requirement, and the last one relates to the analysis for evaluating the intermediate and higher level.

Before carrying out the simulations, normative amendment 1 recommends the verification of the climate file as the average value of the external dry bulb temperature (TBSm) to determine the operating temperature values to be considered in the calculation of the parameter of the percentage of hours occupied within a comfort temperature range (PHFT). According to the simulations carried out, the TBSm value obtained for the climate file INMET Recife was 25.19 °C and, therefore, operating temperatures below 28 °C (interval 2) were the criterion adopted for calculating the PHFT. Figure 12 expresses the behavior of external temperatures of dry bulb in the city of Recife during the year.

Fulfilling the objective of generating comparative effects, only the simulations carried out in the high-end building will have shading adoptions in the frames. That said, the simulations in the HIS-type building will be carried out without the use of shading generator devices.

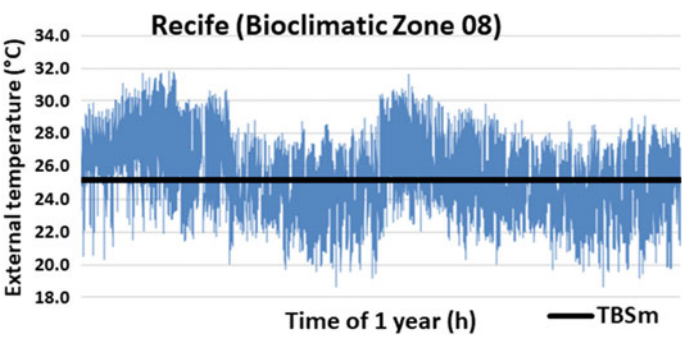


Fig. 12 Annual behavior of the external dry bulb temperature for the city of Recife/PE

4.2.1 Building of Social Interest

The following sections present the thermal performance evaluations for the minimum to the superior level of performance, based on the numerical results obtained from different simulations.

Assessment at the Minimum Level of Thermal Performance

In Fig. 13, the normative parameters used to verify the minimum level of thermal performance are illustrated, which are the percentage of hours occupied in the operating temperature range (PHFT) and the maximum annual operating temperature.

In view of the results obtained, it is observed that the HIS-type building provided an excellent distance margin, compared to the values obtained in the reference model. The criterion for minimum level was met in all floors, as the PHFT of the real model was greater than 90% of the PHFT belonging to the reference model. The criterion

Fig. 13 Numerical results for evaluating the minimum level of performance of the social building

Fig. 14 Numerical results for evaluating the intermediate and superior level of performance of the social building

of maximum annual operating temperatures was also met, taking into account that, on both floors, the maximum annual operating temperatures of the real model were lower than those obtained in the reference model with the respective increments.

Assessment at Intermediate and Upper Level of Thermal Performance

Data for investigating compliance with the attenuated regulatory conditions at the intermediate and higher levels are presented in Fig. 14. The established criteria are defined based on an analysis of the percentage increase of hours occupied in the operating temperature range (PHFT), maximum annual operating temperature, similarly to what is required in meeting the minimum level, and reduction of the total thermal load (RedCgTT).

In view of the results presented in the figure above, it is possible to verify that the intermediate level of the PHFT increment criterion was met, since the three floors analyzed had values greater than the minimum required. The minimum values for the increment of the PHFT are determined when the calculation of the PHFT of the reference model is inferior to 70%. On the other hand, to meet the intermediate level of the total thermal load reduction criterion, the condition of compliance is given when the real model has lower energy consumption compared to the reference model; in the case in question, the intermediate floor does not meet the RedCgTT criterion and therefore implies that the HIS building does not meet the intermediate level of thermal performance.

In the analysis of the service of the building at the higher level, the criteria used in the maximum annual operating temperature and minimum increment of the PHFT are maintained, however, minimum values of thermal load reduction of the real model compared to the reference model are determined. Given the ratio of the total thermal load of the reference model to the sum of the areas of the long-stay environments, the minimum required reduction is 40, 50 and 40% for the ground, 3th and top floors, respectively.

4.2.2 High Standard Building

In this section, thermoenergetic simulations are presented to evaluate the thermal performance of the high-end building. These simulations are divided into two parts: without adopting shading in the frames and with admission of shading in the frames. A priori, the results obtained are verified regarding the attendance at the minimum level and later the evaluation of the attendance at the intermediate and higher level.

Simulation Without Shading in the Frames

Assessment at the Minimum Level of Thermal Performance

Figure 15 shows the results obtained in the simulation of the high standard building without the use of shading in the frames through graphics that will be used in the evaluation of the thermal performance at the minimum level.

In light of the above, it is noted that a high-end building met the PHFT criterion on the ground and intermediate floor, however the roof floor obtained lower values corresponding to the PHFT parameter of the real model when compared with a 10% reduction in the calculated PHFT in the reference model and provokes the disapproval of the high standard building at the minimum level of performance. However, the established criterion for evaluating the maximum annual operating temperatures was respected in all analyzed pavements.

Assessment at Intermediate and Superior Level of Thermal Performance

Taking the assessment of the minimum level of thermal performance as an example, it is to be expected that the building under analysis does not meet the intermediate or higher level. In this way, from the Fig. 16 it can be seen that the analyzed building does

Fig. 15 Numerical results for evaluating the minimum level of performance of the high standard building

not meet the intermediate or superior level of thermal performance, as the roof floor obtained negative values in the difference in PHFT between the real and reference model and thermal load reduction; and the real model of the ground floor also proved to be less efficient than the real model in terms of thermal load reduction. As a result of these data, both the intermediate level and the upper level cannot be reached.

Simulation with Shading in the Frames

Assessment at the Minimum Level of Thermal Performance

As the last simulation condition, the high-end building was simulated with additions of devices that cause shading in the frames, capable of reducing, at least, 50% of the direct solar radiation. Figure 17 shows the numerical results obtained from the building in question to assess compliance with the minimum level of thermal performance.

Fig. 16 Numerical results for evaluating the intermediate and superior level of performance of the high standard building

According to the results expressed in Fig. 17, it is possible to notice the gain achieved in the real model in the PHFT indicator with shading admission in such a way that the strategy allowed the reaching of the high standard building to the minimum level of performance. Despite having met in the simulation situation without the use of shading devices, a decrease in annual maximum operating temperature values was also verified and the parameter remained met.

Assessment at Intermediate and Superior Level of Thermal Performance

Finally, the project was simulated with the admission of shading in the frames to assess the service at the intermediate or higher level. The results obtained in the numerical simulations are presented in Fig. 18, that represents the building's efficiency in terms of the PHFT indicator and thermal load reduction compared to the reference model.

According to the efficiency level of the parameters, represented by Fig. 18, the successful advance in thermal performance indicators is evidenced by the real model

Fig. 17 Numerical results for evaluating the minimum level of performance of the high-end building

of the high-end building when comparing it with the reference model. Investigating the data to check the service at the intermediate level, the PHFT values of the real model were sufficient to meet the normative criteria required for both conditions imposed on the PHFT value of the reference model. According to the total thermal load reduction table (RedCgTT), the ground and intermediate floors met the established minimum, 0 and 25%, respectively, but the roof floor did not have a satisfactory percentage of RedCgTT to meet the minimum required which should be greater than 20%

The parameters required to service the higher level are the same as those for the intermediate level, with the exception of the criteria used in the minimum values for RedCgTT, which are more rigorous. Similarly, because the building does not meet the RedCgTT criteria required for the intermediate level, the studied building does not meet the higher level. To achieve this service, the percentage of RedCgTT should be greater than 40% for the ground floor, 50% reduction for the intermediate floor and 40% for the roof floor.

Fig. 18 Numerical results for evaluating the intermediate and superior level of performance of the high-end building

5 Conclusions

Based on the simulations performed, some considerations could be presented about this work:

- The characteristic profile of the level of performance between the buildings studied was maintained, despite the different procedures between the two normative methods;
- The building framed in the HIS class met the minimum level of performance with some clearance. Because of having construction systems and glazed areas similar to the reference model, buildings of type HIS with solar upper-bodies smaller than the reference model follow a strong tendency to meet the minimum level of performance in hot climate regions.
- To achieve the minimum level of thermal performance, buildings with large glazed areas, as was the case with the high standard building, can follow a trend with higher requirements of the thermal properties of the materials that compose them;

- The analysis, promoted by the new method, represents a progress in the elaboration of the computational methodology of thermal performance, taking into account the annual simulation of the building and withdrawal of the analysis criteria considered of typical summer and winter days. Thus, it is possible to optimize strategies to obtain better thermos-energetic indices of a building;
- The PHFT indicator allows for more significant analyses, especially with regard to the thermal behavior of housing units during the year;
- The thermal load analysis, required to meet the intermediate and higher levels, affects the normative advance in the study of energy efficiency in buildings.

Finally, some future recommendations:

- Comparison between models with high and low values of thermal inertia, for different values of external solar absorbance;
- Feasibility study encompassing energy efficiency between alternative scenarios with more efficient construction systems thermos-energetically than those presented in the real model;
- Comparative simulation between projects contemplated in regions with different bioclimatic zoning.

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References

ALMEIDA, L. S. S. (2014). Influência de parâmetros físicos e geométricos no desempenho termoenergético de habitações unifamiliares. Dissertação (Mestrado em Engenharia Civil)—UFSC.

AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS—ASHRAE. (2016). ANSI/ASHRAE/IESNA Standard 90.1—2016: “Energy Standard for Buildings Except Low-Rise Residential Buildings”. Atlanta.

AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS—ASHRAE. ASHRAE Handbook—Fundamentals (SI). (2017a). Mark S. Owen (Ed.), American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Atlanta, Georgia, USA.

AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS—ASHRAE. (2017b). ANSI/ASHRAE Standard 55–2017: Thermal environmental conditions for human occupancy. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, EUA.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS (ABNT). (2005a). NBR 15.220–1: Desempenho térmico de edificações: parte 1: Definições, símbolos e unidades. Rio de Janeiro.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS (ABNT). (2005b). NBR 15.220–2: Desempenho térmico de edificações: parte 2: Métodos de cálculo da transmitância térmica, da capacidade térmica, do atraso térmico e do fator solar de elementos e componentes de edificações. Rio de Janeiro.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS (ABNT). (2005c). NBR 15.220–3: Desempenho térmico de edificações: parte 3: Zoneamento bioclimático brasileiro e diretrizes construtivas para habitações unifamiliares de interesse social. Rio de Janeiro.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS (ABNT). (2013). NBR 15.575: Edificações habitacionais—Desempenho. Rio de Janeiro.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS (ABNT). (2013). NBR 15.575: Edificações habitacionais—Desempenho: parte 1: Requisitos gerais. Rio de Janeiro

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS (ABNT). (2021). NBR 15.575: Edificações habitacionais—Desempenho: parte 1: Requisitos gerais. Em. 1. Rio de Janeiro.

ÇENGEL, Yunus A., & GHAJAR, Afshin J. (2012). Transferência de Calor e Massa: Uma Abordagem Prática. 4. ed. Porto Alegre: Editora McGrawHill.

DOE—UNITED STATES DEPARTMENT OF ENERGY. (2021). EnergyPlus: Version 8.1.0. Disponível em: https://energyplus.net/. Acesso em: 05 mai.

DOE—UNITED STATES DEPARTMENT OF ENERGY. (2020). Getting Started—EnergyPlus™ Version 9.4.0 Documentation.

DORNELLES, Kelen Almeida. (2008). Absortância solar se superfícies opacas: método de determinação e base de dados para tinta látex acrílica e PVA. Tese (Doutorado em Engenharia Civil) —Programa de Pós-graduação da Faculdade de Engenharia Civil, Arquitetura e Urbanismo, Universidade Estadual de Campinas. Campinas.

EMPRESA DE PESQUISA ENERGÉTICA (EPE). (2021). Consumo de energia elétrica: consumo mensal de energia elétrica por classe (regiões e subsistemas)—1995–2018. Rio de Janeiro: EPE, 2021. Disponível em: https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/Consumo-mensal-de-energia-eletrica-por-classe-regioes-e-subsistemas. Acesso em: 18 abr.

EMPRESA DE PESQUISA ENERGÉTICA (EPE). (2021). Uso de Ar Condicionado no Setor Residencial Brasileiro: Perspectivas e contribuições para o avanço em eficiência energética. Rio de Janeiro: EPE, 2018. Disponível em: http://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/nota-tecnica-epe-030-2018. Acesso em: 18 abr.

FAJKUS, M. Superficial Skins? Super Skins? Shading Structures and Thermal Impact Analysis. Advanced building skins—energy forum, Bressanone, 2013.

FREITAS, J. M. R., LEITZKE, R. K., GIOIELLI, B. I., & CUNHA, E. G. (2016, Dez). Análise da influência das pontes térmicas na simulação de eficiência energética nas paredes de edificações residenciais. Revista de Arquitetura IMED, Passo Fundo, vol. 5, no. 2, pp. 24–41. ISSN 2318–1109.

GIOIELLI, B., ALMEIDA, A., CUNHA, E., & FERRUGEM, A. (2015). Estudo do Efeito de Pontes Térmicas em Estruturas de Concreto Armado no Desempenho Energético de Edifício Hoteleiro Para 4 Zonas Bioclimaticas Brasileiras. XV Encontro Nacional de Tecnologia do Ambiente Construído. Anais do evento. Alagoas.

INCROPERA, F. P., & DEWITT, D. P. (2008). Fundamentos da Transferência de Calor e de Massa. 6. ed. Rio de Janeiro: LTC.

INTERNACIONAL ORGANIZATION FOR STANDARDIZATION. (1984). ISO 6241: 1984 Performance standards in bulding: Principles for their preparation and factors to be considered. USA.

Ioannou, A., & Itard, L. C. M. (2015). Energy performance and comfort in residential buildings: Sensitivity for building parameters and occupancy. *Energy and Buildings, 92*, 216–233.

ISO 10211. (2017b). Thermal bridges in building construction—Heat flows and surface temperatures—Detailed calculations. International Organization for standardization.

JARDIM, Patrícia R. S. A. (2011). Desempenho térmico de coberturas: um estudo comparativo entre as telhas de material reciclado, de fibra e betume, fibrocimento e cerâmica. 2011. 124p. Dissertação (Mestrado)—Universidade Federal do Rio Grande do Norte, Natal.

LAMBERTS, R., DUTRA, L., & PEREIRA, F. O. R. (2014). Eficiência Energética na Arquitetura. 3. ed. São Paulo.

LBNL. (2010). Getting started With EnergyPlus. US Department of Energy, Version 5.0, USA.

NOVAIS, J. W. Z., OLIVEIRA, E. V., JOAQUIM, T. D., LEAL, L. A., NOGUEIRA, M. C. J. A., & SANCHES, L. (2014, November). Comparação do Desempenho Térmico de Painéis em EPS como Alternativa aos Tijolos Cerâmicos no Conforto Térmico de Residências em Cuiabá-MT. UNOPAR Cientifica Exatas Tecnologica, Londrina, vol. 13, no. 1, pp. 39–43.

NREL. (2021). National Renewable Energy Laboratory. Disponível em: https://www.nrel.gov/. Acesso em: 08 mai.

SANTOS, A. C., LIMA, J. V. S., J. R. G., M. S. G. C. (2018). Uso do EnergyPlus em pesquisas brasileiras. XVII ENCONTRO NACIONAL DE TECNOLOGIA DO AMBIENTE CONSTRUÍDO—ENTAC 2018. Foz do Iguaçu.

Silva, A. S., & Ghisi, E. (2014). Análise comparativa dos resultados do desempenho térmico da envoltória de uma edificação residencial pelos métodos de simulação do RTQ-R e da NBR 15575–1. *Ambiente Construído, 14*, 213–230.

SIQUEIRA, Tulio C. P. A, et al. (2005) Dados Climáticos para avaliação de desempenho térmico de edificações. Esc. Minas, Ouro Preto, MG.

SORGATO, M., MELO, A., & LAMBERTS, R. (2013). Análise do método de simulação de desempenho térmico da norma NBR 15575. ENCAC 2013.

SPECHT L. P., BORGES P. A. P., RUPP, R. F., & VARNIER, R. (2010). Análise da transferência de calor em paredes compostas por diferentes materiais. Revista Ambiente construído, porto alegre.

TRIMBLE INC. SketchUp: Versão 8.0.15158. 2012.

YOSHINO, H., HONG, T., & NORD, N. (2017, March). IEA EBC Annex 53: total energy use in buildings, analysis and evaluation methods. *Energy and Buildings, 152,* 124–136.