

IMPACTS OF CLIMATE CHANGE ON THE THERMAL AND ENERGY PERFORMANCE OF BRAZILIAN RESIDENTIAL BUILDINGS

IMPACTOS DAS MUDANÇAS CLIMÁTICAS NO DESEMPENHO TERMOENERGÉTICO DE EDIFICAÇÕES RESIDENCIAIS BRASILEIRAS

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Abstract

Climate change points to a future scenario of heterogeneous projections of terrestrial warming. In this context, buildings are responsible for a significant portion of the global energy consumption, aimed at maintaining the thermal comfort of the occupants, especially when it cannot be obtained through passive conditioning strategies. The objective of the research was to compare the impact of climate change on comfort, thermal performance and energy consumption of a naturally ventilated multifamily building proposing to adapt the windows and vertical envelope system to the local climate. Manaus, Vitória, Brasília and Porto Alegre were selected to carry out simulations of a Real Model - representative of existing buildings - and an Optimized Model - which incorporates recommendations from NBR 15575 and passive conditioning strategies. The climatic scenarios considered were the present (based on the historical period 1961-1990) and future (2020s, 2050s and 2080s). The results showed that, in future scenarios, there is an increase in the number of hours of thermal discomfort due to heat, both in the Real Model and in the Optimized Model. In general, the Optimized Model minimized thermal discomfort, mainly in the current period and in the 2020 time slices, but it showed, from the 2050s, a reduction in the ability to provide comfort, considering the adoption of passive conditioning strategies. It is ratified that NBR 15575 could include parameters for future climate projections, adapting buildings to the climate and containing anthropic climate changes.

Keywords: climate changes, thermal and energy performance, thermal comfort, energy efficiency, building envelope.

Resumo

As mudanças climáticas apontam para um cenário futuro de projeções heterogêneas de aquecimento terrestre. Nesse contexto, os edifícios são responsáveis por uma parcela significativa do consumo energético global destinado à manutenção do conforto térmico dos ocupantes, especialmente quando não pode ser obtido por meio de estratégias passivas de condicionamento. O objetivo da pesquisa foi comparar o impacto das mudanças climáticas no conforto, no desempenho térmico e no consumo energético de uma edificação multifamiliar naturalmente ventilada à sua proposta de adaptação das esquadrias e dos sistemas de vedação vertical ao contexto climático local. Foram selecionadas Manaus, Vitória, Brasília e Porto Alegre para a realização de simulações de um Modelo Real (MReal) - representativo de edificações existentes - e de um Modelo Otimizado (MOt) - que incorpora recomendações da NBR 15575 e estratégias de condicionamento passivo. Os cenários climáticos considerados foram o período atual (com base na série histórica 1961-1990) e futuros (2020s, 2050s e 2080s). Os resultados demonstraram que, em cenários futuros, há aumento no número de horas de desconforto térmico por calor, tanto no MReal quanto no MOt. Em geral, o MOt minimizou o desconforto térmico por calor, principalmente no período atual e na parcela de tempo de 2020s, mas apresentou, a partir de 2050s, redução na capacidade de proporcionar conforto, considerando a adoção de estratégias passivas de condicionamento. Ratifica-se que a NBR 15575 poderia incluir parâmetros de projeções climáticas futuras para adequação das edificações ao clima e contenção das alterações climáticas antrópicas.

Palavras-chave: mudanças climáticas, desempenho termoenergético, conforto térmico, eficiência energética, envoltória.

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Introduction

The impacts and risks of climate change have been discussed since the 1960s (MANABE; WETHERALD, 1967), however studies on the topic were investigated further only from the 1980s (ALVAREZ; BRAGANÇA, 2018). In 2018, the temperature was 0.83°C higher than the average from 1951 to 1980, and the last five years have been, overall, the warmest on modern record (NASA, 2019). The increase in greenhouse gas (GHG) emissions in the atmosphere, from human activities, is considered mainly responsible for climate change.

According to the Brazilian Panel on Climate Change (PBMC, 2016), projected changes to the climate could accentuate the vulnerabilities of cities, reducing their resilience capacities and the occurrence, on a larger scale, of phenomena such as heat islands, air pollution and floods. Thus, the environmental performance of urban structures, including the building scale, influences the quality and length of stay in the environments, thus ensuring the comfort conditions are known in these spaces analyzing studies on the microclimate and human responses to these conditions.

Among the effects of the low environmental performance of buildings against climate change are the physiological limits of heat tolerance. Considering environmental conditions that do not allow adequate evapotranspiration, there is an imbalance of physiological thermoregulation, which is limited by air humidity, which may lead to greater difficulties in evaporating sweat, increasing the sensation of thermal discomfort due to heat (RIVAS; ALLIE; SALVADOR, 2019; LAMBERTS; DUTRA; PEREIRA, 2014). This imbalance poses risks, especially to the most vulnerable populations, such as children and the elderly, consolidating scenarios that are less favorable to human life, especially in places that project greater heating, demanding an increase in energy consumption to maintain thermal comfort (ALVAREZ; BRAGANÇA, 2018; KOČÍ *et al.*, 2019).

Mora *et al.* (2017) highlight that about 30% of the world population is currently exposed to climatic conditions that exceed the body's regulatory limit for at least 20 days per year. Projections indicate that by 2100 this percentage could reach 74% in a scenario of increasing emissions, so that the threat to human life due to excess heat will be aggravated with the non-reduction of GHGs.

Inefficient buildings, not suited to local climatic conditions, can cooperate by increasing energy consumption predicted for the future (OLONSCHECK; HOLSTEN; KROPP, 2011). In Brazil, in 2019, they already accounted for about 45.8% of all electricity consumed (EPE, 2020).

As for the future climate, the Intergovernmental Panel on Climate Change (PACHAURI; MEYER, 2014), in its AR5 report, projects four GHG emission scenarios, called RCPs - Representative Concentration Pathways. Scenario RCP2.6 is considered to be of low emissions, scenarios RCP4.5 and RCP6 are intermediate, while RCP8.5 is considered the most critical, with high GHG emissions. If current GHG emission standards are maintained, without new mitigating measures, it is estimated that the average air temperature will be 4.8 °C higher in 2100 than in the pre-industrial period (PACHAURI; MEYER, 2014).

Faced with such projections of climate change and high energy consumption in the built environment, adaptation strategies and solutions for buildings need to be considered to future climate scenarios (FARAH *et al.*, 2019; NUNES; GIGLIO, 2020), such as those proposed by Guarda, Durante and Callejas (2020); Huang and Hwang (2016); Flores-Larsen, Filippín and Barea (2019); and Alves, Duarte and Gonçalves (2016), so that they can become more resilient and efficient.

Thus, this research aimed to compare the impact of climate change on thermal performance, comfort and energy consumption of a naturally ventilated multifamily building to its proposal for adapting openings and vertical sealing systems to the local climate context.

Methodological procedures

The methodological procedures were organized into three stages: 1) Selection and climatic characterization of the sample cut and “morphing” of the climate files; 2) Case study – model characterization; 3) Thermal performance analysis, simulation and thermal comfort analysis and energy consumption of the models.

Selection and climatic characterization of the sample cut

For the selection of the sample, capital cities located at different latitudes and Bioclimatic Zones (BZ) were chosen, which presented different future climatic conditions, according to the projections of the HadCM3 model, for the A2 emissions scenario, and which had files in EnergyPlus Weather (EPW) format to run the simulations. Thus, Manaus and Vitória (ZB8), Brasília (ZB4) and Porto Alegre (ZB3) were defined, according to territorial climatic differences, whose characteristics are presented in Table 1. Although Manaus and Vitória are located in ZB8, the proposal to review the Brazilian bioclimatic zoning distinguishes its climatic characteristics (RORIZ, 2014).

Table 1 – Climate characterization of cities

City	Population	Latitude/Longitude	Altitude (m)	Class. Köppen	Monthly average temperature		Rainfall (mm/year)	Average TBU	
					Mín.	Máx.		Mín.	Max.
Manaus	2,219,580	03° 6' S/ 60°W	92.0	Equatorial	21.5 °C	27,5 °C	2307.4	25.02 °C (Jun)	25.08 °C (Oct)
Vitória	365,855	20° 32' S/40° 32'W	9.0	Coastal tropical	21.8 °C	28,9 °C	1318.6	18.25 °C (Jun)	23.57 °C (Jan)
Brasília	3,055,149	15° 46' S/ 47°55'W	1171.0	Tropical with dry season	18 °C	22,0 °C	1540.6	13.28 °C (Jul)	19.59 °C (Jan)
Porto Alegre	1,488,252	30° 5' S/ 51° 14'W	3.0	Humid subtropical with hot summer	14.75 °C	24,9 °C	1320.4	12.22 °C (Jul)	21.73 °C (Jan)

Source: IBGE (2021); INMET (2018); LAMBERTS; DUTRA; PEREIRA (2014).

To convert current weather files into future files, the CCWorldWeatherGen tool (version 1.9) was used, developed according to the methodology proposed by Jentsch *et al.* (2013), which allows calculations based on the “morphing” method, proposed by Belcher, Hacker and Powell (2005). The “morphing” process consists of three steps: i) deviation in the current hourly climate file and addition of the projected monthly average variation for the future climate, ii) extension of the current hourly climate file by ordering the projected monthly average variation and iii) combining the previous steps (BELCHER; HACKER; POWELL, 2005; GUARDA; DURANTE; CALLEJAS. 2020).

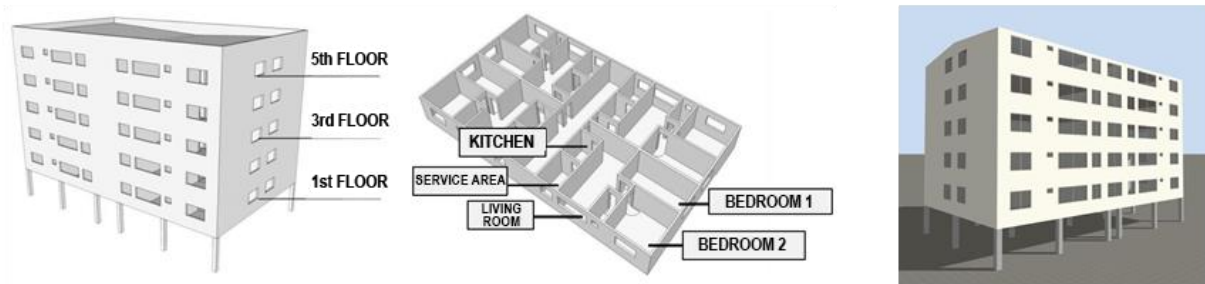
For Brasília, Vitória and Porto Alegre, climate files equivalent to the historical period from 1961 to 1990 were used, with an EnergyPlus Weather (EPW) extension, based on the TRY format, compiled in 2005, using data from INFRAERO – Empresa Brasileira de Infraestrutura Aeroportuária. (LABEEE, 2005), according to the instructions of the conversion tool used. For Manaus, which does not have a file available in the TRY format, the EPW climate file was used, produced from data from the National Institute of Meteorology – INMET, 2016 (LABEEE, 2021).

Case study - characterization of models

In this study, the 'Real Model' (MReal) was adopted as the representative model of the residential building standard of the Technical Quality Regulation for the Energy Efficiency Level of Residential Buildings - RTQ-R (INMETRO, 2012), as it presents common characteristics to the buildings built in Brazil.

MReal has a ground floor (pilotis) and five floors with four housing units each, containing a living room, two bedrooms, a kitchen, service area and bathroom, totaling approximately 70 m² (Figure 1).

Figure 1 –Real Model (MReal)



Source: authors, adapted from INMETRO (2012) and Machado (2019).

For the MReal analysis, the third floor was selected, as it characterizes the influence of the External Vertical Sealing System (EVSS) and openings better, justified by the percentage of samples of intermediate floors in relation to ground floors and roofs in the verticalization process of the buildings.

Bedroom 2, a Long Permanence Room (LPR), was evaluated, located at the corner of the tower. It had greater exposure of opaque surfaces to solar radiation through two facades, and, to allow an evaluation of the EVSS and openings, it was made a variation of the positioning of the openings in each sample of the evaluated room, prioritizing the analysis of the performance of the building considering the change in the position of the window in the main cardinal directions (Figure 2).

Figure 2 - Floor plan with the positioning of the simulated environment in relation to the openings



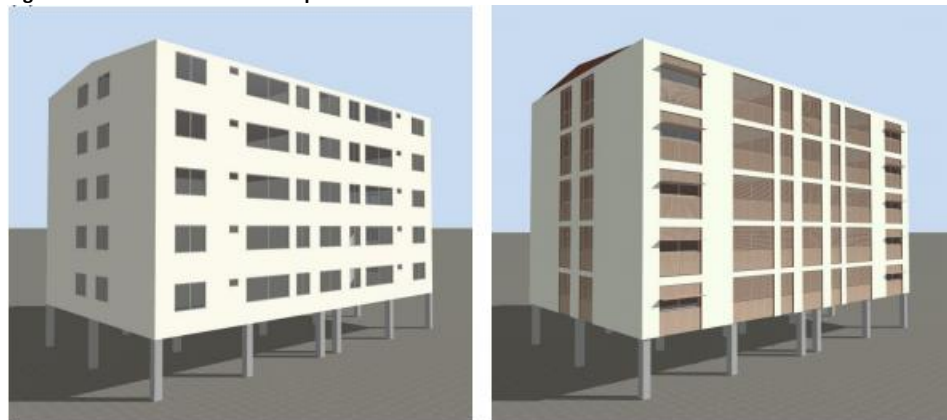
Source: Machado (2019).

For the MReal openings, the minimum proportions established by the building codes of each municipality were used, considering a standard aluminum and glass frame. For the

EVSS, a ceramic block was used, replicating a recurring system throughout the national territory. Although concrete blocks are also a widely used system in Brazilian civil construction, previous analyses have shown that under these conditions, the ceramic block presented worse thermal performance (MACHADO, 2019). Thus, it was decided to adopt the ceramic block, aiming to evaluate the worst thermal performance scenario among the most used sealing materials in the country.

Based on Mreal, the 'Optimized Model' (MOt) was proposed, inserting a ventilated facade, the resizing of the openings and the proposal of a dynamic frame model, in order to reassess its thermal performance, comfort and energy efficiency, considering its adaptation to climate change using passive strategies, recommended by Brazilian standards (Figure 3).

Figure 3 - Reference Model and Optimized Model



Source: Machado (2019).

Thermal performance analysis, simulation and analysis of thermal comfort and energy consumption of the models

The MReal was analyzed by the simplified procedure of NBR 15575, thus assessing whether it would obtain the minimum thermal performance, which is mandatory (ABNT, 2021). To analyze the thermal performance, the thermal characteristics presented in Tables 2 and 3 and the operational properties in Table 4 were used.

Table 2 - Thermal properties of the envelope elements for the third floor of the MReal (continued)

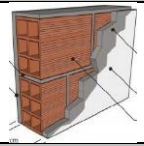
Thermal properties of materials used in ceramic block masonry ²							
Masonry in ceramic block (9x14x24cm), with 6 square holes and 2.5cm plaster on the external and internal faces (14cm)							
Wall thermal transmittance (U)		2.46 W/ (m ² .K)					
Emissivity (E) of walls and floor		0.9					
Absorbance (α) of walls and floor		0.3					
							
Details of wall layers with material properties ²							
EVSS = 14cm	Layers	Materials	Thickness (m)	Thermal conductivity(W/m .K)	Density (kg/m ³)	Specific heat (J/kg.K)	Thermal resistance (m ² .K/w)
	1st	Plaster	0.025	1.15	2000	1000	-
	2nd	Ceramic block	0.01	0.9	1600	920	-
	3rd	Air	0.03	-	-	-	0.16
	4th	Ceramic block	0.01	0.9	1600	920	-
	5th	Air	0.03	-	-	-	0.16
	6th	Ceramic block	0.01	0.9	1600	920	-
	7th	Plaster	0.025	1.15	2000	1000	-

Table 2 - Thermal properties of the envelope elements for the third floor of the MReal (conclusion)

Thermal properties of slabs and roofs ²							
Solid 10.0cm thick concrete slab between floors – 2 times							
Cover thermal transmittance (U)		3.73 W/(m ² .K)					
Thermal Capacity (Ct)		220 kJ/m ² .K					
Roofing system with solid concrete slab 10.0cm thick, air layer and fiber cement tile – 1 time							
Cover thermal transmittance (U)		2.06 W/(m ² .K)					
Thermal Capacity (Ct)		233 kJ/m ² .K					
Details of cover layers with material properties ²							
	Layers	Materials	Thickness (m)	Thermal conductivity(W/m .K)	Density (kg/m ³)	Specific heat (J/kg.K)	Thermal resistance (m ² .K/W)
Slab (10cm)	1st	Ceramic floor	0.01	0.9	1600	920	-
	2nd	Subfloor	0.025	1.15	2000	1000	-
	3rd	Concrete slab	0.1	1.75	2200	1000	-
	4th	Plaster	0.025	1.15	2000	1000	-
Roof. ⁷	1st	Fiber cement tile	0.008	0.95	1800	840	-
	2nd	Air	0.2	-	-	-	0.16
	3rd	Concrete slab	0.1	1.75	2200	1000	-

NOTE: ¹ Considered coverage and two floor slabs of the upper floors; ² Based on ABNT (2005) and INMETRO (2012), ⁷ Coverage. Source: the authors.

Table 3 - Minimum thermal performance criteria by the simplified procedure of NBR 15575 (2021)

City	NBR 15575 parameters					
	Upar	CTpar	PvAPP	PtAPP	AtAPP	Ucob
Manaus	≤ 3.7 W/(m ² .K)	-	≥ 12%	≤ 20%	≤ 4.0 m ²	≤ 1.5. FT
Vitória		-	≥ 8%			
Brasília		≥ 130	≥ 7%			≤ 1.5
Porto Alegre						

Source: authors, based on ABNT (2021).

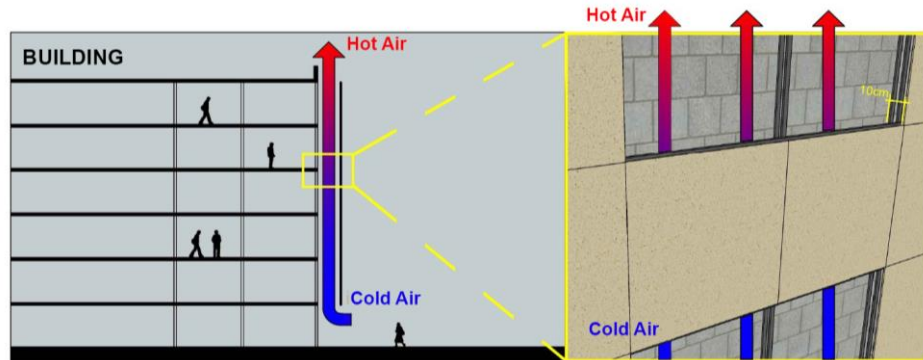
Table 4 – Mreal operational properties

Openings, operation and thermal properties of frame materials	
Characteristics	Dimensions
Bedroom (permanently occupied area)	15 m ²
Windows for Manaus	2.40 x 1.30 x 1.10 m (height x width x sill)
	Total area: 3.12 m ²
	Useful ventilation area: 1.56 m ²
Windows for Brasília and Vitória	1.80 x 1.30 x 1.10 m (height x width x sill)
	Total area: 2.34 m ²
	Useful ventilation area: 1.17 m ²
Windows for Porto Alegre	2.00 x 1.30 x 1.10 m (height x width x sill)
	Total area: 2.60 m ²
	Useful ventilation area: 1.30 m ²
Window model	Opening control ²
Two aluminum sliding sheets with glass pane	8 am– 9 pm = 100% of open window = 50% useful ventilation area
	9 pm – 8 am = 100% of closed window = no useful ventilation area
Thermal properties of frames	
Thermal transmittance (U) of aluminum frame	5.88 W/(m ² .K)
Thermal transmittance (U) of clear glass 6mm	5.77 W/(m ² .K)
Occupancy parameters, characteristics and thermal gains of the equipment	
Occupation	Use
User³	8 am – 1 pm: 0% occupied
	1 pm – 10 pm: 50% occupied
	10 pm– 8 am: 100% occupied
Human parameters⁴	Clothing: Summer = 0.5 Clo / Winter = 1.0 Clo
	Metabolism: 90 W/person
	Standard occupation: 2 people
Thermal gains of equipment	Artificial lighting ⁵ (6 pm – 10 pm) = 5 W/m ²
	Computer ³ (1 pm– 10 pm) = 3.9 W/m ²

NOTE: ² The sliding system allows a maximum ventilation area of 50% of the total window area; ³ Based on the work of Nico-Rodrigues *et al.* (2015); ⁴ Based on Lamberts, Dutra and Pereira (2014); ⁵ Based on INMETRO (2012); ⁶ Based on ABNT (2005) and INMETRO (2012). Source: the authors.

The same thermal characteristics of the MRef were used as a reference in the simulation and analysis of the thermal comfort of the MOt, adding the properties and physical characteristics of the ventilated facade (Figure 4), characterized by the fitting of porcelain tiles 10 cm away from the sealing, as well as the increase in openings and dynamic frames.

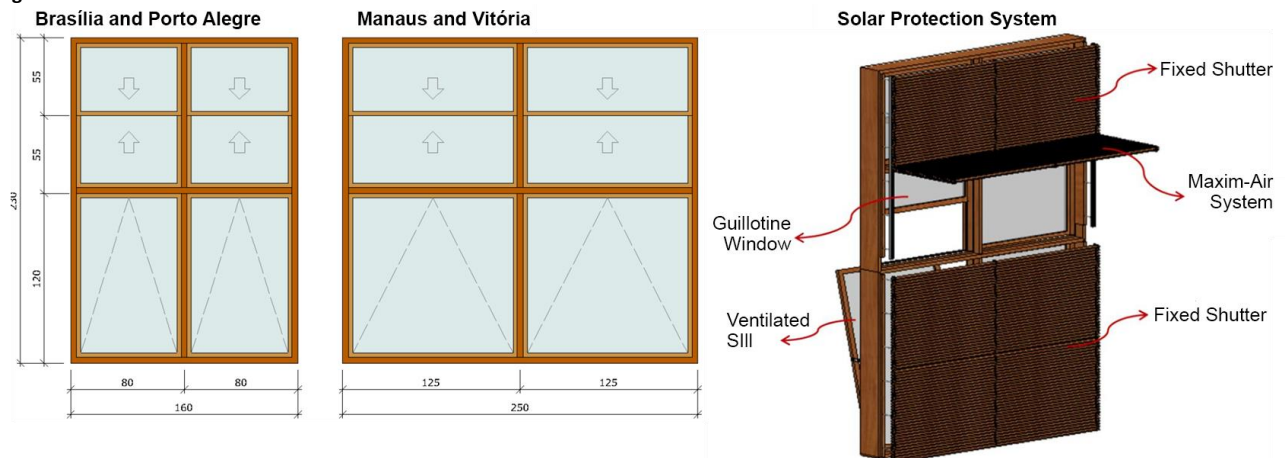
Figure 4 - Multifamily building model and ventilated facade



Source: authors, adapted from Elianetec (2021).

The proposed window model allows control by the building occupants, configuring an adaptive comfort strategy (ABNT, 2005; ASHRAE, 2004). The MOt windows have larger dimensions and allow selective ventilation, indicated for ZB8 and ZB4, as well as dynamic shading, also allowing the entry of solar radiation in winter, recommended for ZB3. It was divided into two parts: ventilated sill in the lower portion and guillotine in the upper portion. The windows are also shaded by wooden shutters: fixed on the ventilated sill and on the upper portion of the guillotine; and furniture, in the maxim-air system, in the central portion of the window, allowing permeability and constant ventilation, contributing to the thermal comfort inside the environment (Figure 5).

Figure 5 –MOt frame model



Source: authors, adapted from Machado (2019).

To evaluate the thermal performance, the MReal simulation was initially performed using the DesignBuilder software, version 3.4.0.041 (DESIGN BUILDER SOFTWARE, 2014). The MReal was simulated implementing windows oriented to North, South, East and West and for a period of one year, considering the 'current period' as the historical period of 1961-1990/2001-2010 - basis for preparing the climate files, and in the time slices 2020s (average from 2011 to 2040), 2050s (average from 2041 to 2070) and 2080s (average from 2071 to 2100) (PACHAURI; MEYER, 2014).

For Brasília, Porto Alegre and Vitória, formatted climate files based on the historical series from 1961-1990, compiled in 2005 from data from INFRAERO – Empresa Brasileira de Infraestrutura Aeroportuária, (LABEEE, 2005) were used, as recommended of the conversion tool (JENTSCH *et al.*, 2013). However, for Manaus, the file in EPW format was used, referring to INMET 2016 data, prepared based on measurements from meteorological stations from 2001 to 2010, as the city did not have records of the previous historical series, suitable for the conversion tool. Although not ideal, it is a practical resource, closer to reality and acceptable for studies in buildings (JENTSCH *et al.*, 2013).

The model simulation was carried out for scenario A2, of the fourth IPCC report, which can be compared to the RCP 8.5 emissions scenario of the IPCC-AR5 (PACHAURI; MEYER, 2014), and was selected because it characterizes a context of maintaining high emissions of GHG, indicating the most critical conditions to which buildings may be subjected in the future climate.

From the MReal simulations for each city and time period, the comfort temperatures were defined, determined from the relationship between the External Monthly Average Temperatures (T_e) and the internal hourly Operative Temperatures (T_o). The limit range for comfort temperatures was obtained from Equation 1, where the Neutral Temperature (T_n) is the result of multiplying T_e by the factor 0.31, whose value is added to 17.8 (ASHRAE 55, 2010).

Equation 1: Calculation of Neutral Temperature (T_n)

$$T_n = 0,31 (T_e) + 17,8$$

Source: ASHRAE 55 (2010).

The thermal discomfort linked to the MReal was evaluated through the Cooling Degree Hours (CDH) index, that is, the number of hours required for cooling, already disseminated by authors such as Oliveira, Sakiyama and Miranda (2017), among others. To define the maximum acceptable limit for the comfort temperature, it is necessary to add 2.5 °C to the value of T_n , resulting in Equation (2), considering the adaptive thermal comfort model of ASHRAE 55, for 90% acceptability, according to authors and international standards, which define it as predictive for naturally ventilated buildings (ASHRAE, 2004; EUROPEAN COMMITTEE FOR STANDARDIZATION, 2007; NICOLS; HUMPHREYS, 2002).

Equation 2: Calculation of Cooling Degree Hours (CDH)

$$CDH = \sum([T_o - [T_n + 2,5^\circ C])$$

Source: Adapted from ASHRAE 55 (2010).

Next, the MOt was simulated for the same cities of the sample, maintaining the same standards of MReal input data (Tables 2 and 4), in addition to the same analysis procedures, in order to compare the possibilities of adaptation of multifamily buildings existing naturally ventilated spaces, to climate change scenarios. The MOt was simulated with the windows facing the orientation that, in the MReal, presented the most critical conditions of thermal comfort in each city.

The analysis of the energy consumption of the two models (MReal and MOt, in each city) was simultaneous to that of thermal comfort and was based on the number of hours in which there was a need for cooling caused by thermal discomfort ($\sum GHR$), allowing to infer the frequency use of household appliances to minimize discomfort through mechanical cooling of indoor environments. A table ventilator and a split air

conditioner was considered, which have the lowest average monthly consumption (kWh) among the equipment in the 'Table of estimation of average monthly consumption of household appliances according to a hypothetical use'. (PROCEL INFO, 2006; ELETROBRÁS, 2015), presented in Table 5.

To define the thermal load (kWh) needed to reduce thermal discomfort, the annual Σ GHR was considered. Although the objective of the work is not to evaluate the contribution of air conditioning equipment and ventilators in the thermal comfort conditions of the occupants, the analysis of energy efficiency was based on the probable average annual consumption (kWh/year), estimating that these appliances could be used to reduce thermal discomfort in the recording hours of the GHR, contributing to the increase in energy consumption in homes. The tariff and tax values for each city were collected and calculated according to each electricity distributor (Table 5). The energy bill resulted from the tariff values already added to the taxes and in Reais (R\$), presented in Equation 3, multiplied by the consumption (kWh) of each model.

Table 5: PIS/PASEP and COFINS rates for 2020⁴

Application fees ¹ - Residential Subgroup							
City	Distributor	Conventional tariff ² (R\$/kWh)	ICMS ³ (%)	Average hourly consumption of a table ventilator ⁵	Average hourly consumption of an air conditioner ⁵		
Vitória	EDP	0.57	-	0.0720	0.5929		
Manaus	AmE	0.693					
Brasília	CEB	0.515					
Porto Alegre	CEEE	0.549					
Period	PIS / PASEP (%)	COFINS (%)	Total (%)	Period	PIS / PASEP (%)	COFINS (%)	Total (%)
December/2020	0.6969	3.1968	3.8937	June/2020	0.4046	2.2196	2.6242
November/2020	0.8830	4.0375	4.9205	May/2020	0.8760	4.0348	4.9108
October/2020	0.9681	4.31409	5.2821	April/2020	1.2860	5.9235	7.2095
September/2020	0.5293	2.6489	3.1782	March/2020	0.8312	3.8283	4.6595
August/2020	0.5986	2.7448	3.3434	February/2020	1.0532	4.8509	5.9041
July/2020	0.4631	2.1337	2.5967	January/2020	1.0201	4.6899	5.710

NOTE: ¹TUSD +TE (R\$/kWh); ²Considering green tariff flag; ³Exempt from the ICMS agreement for Subclass Residential B consumers, with a consumption range from 0 to 50 kW/h; ⁴ Last year of full publication of tariffs; and ⁵ According to Procel Info (ELETROBRÁS, 2015). Source: authors.

Equation 3: Energy tariffs with taxes - calculations based on 12/11/2019

$$Rate\ with\ taxes = \frac{Tariff\ ANEEL}{1 - \frac{Taxes\ \%}{100}}$$

Note: ANEEL tariff = TUSD + TE (R\$); and Taxes = PIS/PASEP + COFINS + ICMS (%). Source: authors, based on ANEEL (2019a); ANEEL (2019b).

Results

Thermal performance analysis for acceptable comfort condition in the analyzed models

The simplified procedure of Amendment 1 of NBR 15575 (ABNT, 2021) showed that the MReal does not obtain the minimum level of performance in Manaus, Vitória and Brasília as the percentage of opening for ventilation of the long-term environment (PvAPP) does not meet the specifications of the standard (Table 6), highlighted in red, and that the interventions presented in the MOt would meet the minimum performance requirements of NBR 15575/2021.

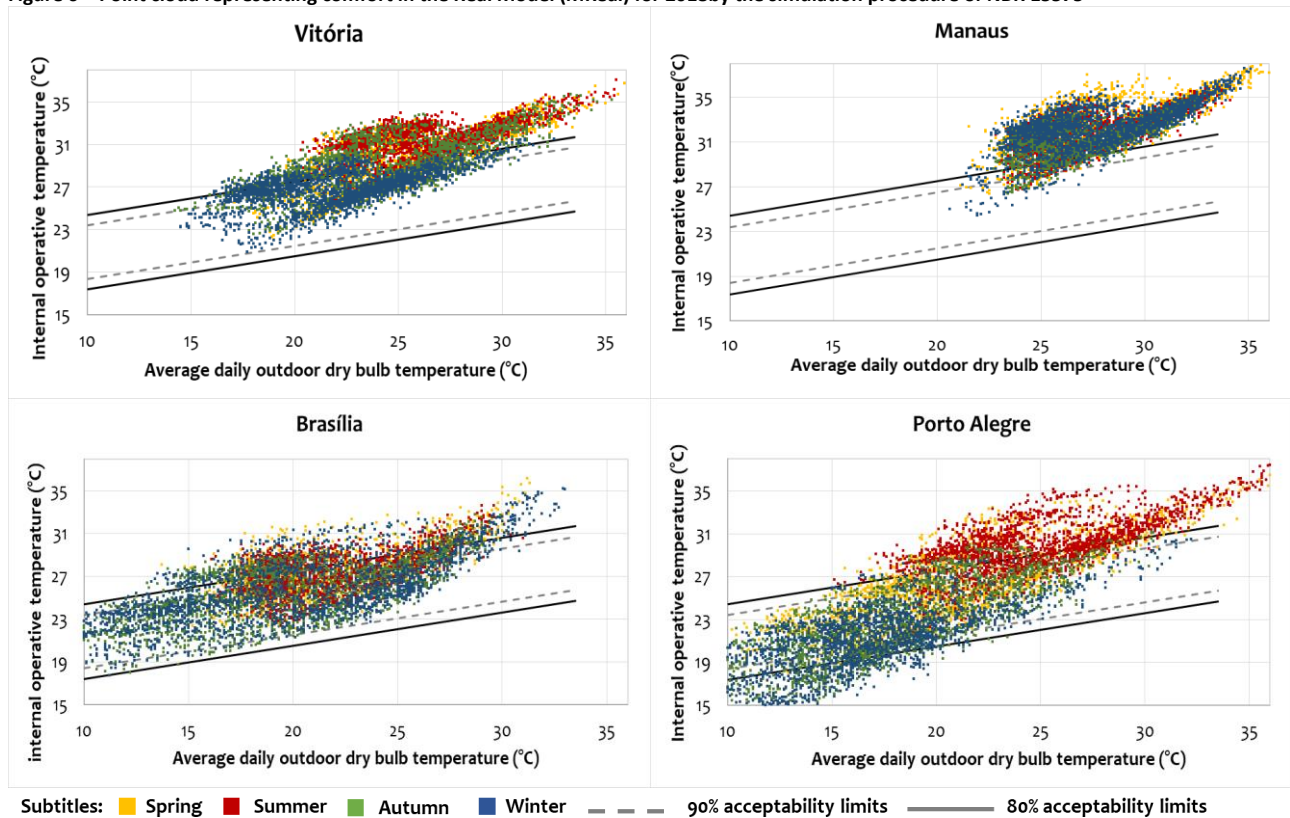
Table 6 - Thermal Performance of the Real Model (Mreal) by the simplified procedure of NBR 15575 (2021)

City	Mreal results					U _{cob}
	U _{par}	CT _{par}	PV _{APP}	Pt _{APP}	At _{APP}	
Manaus	2.46 W/(m ² .K)	-	10%	20%	3.12 m ²	2.06 W/(m ² .K)
Vitória			6.26%	12.52%	1.88 m ²	
Brasília		150 kJ/ m ² .K	8.33%	16.66%	2.50 m ²	
Porto Alegre						

Source: authors, based on ABNT (2021) and local building codes

As shown in Figure 6, the MReal simulation confirmed that, despite meeting the other regulatory requirements, the model already linked, in the current period, a high level of thermal discomfort due to heat, that is, outside the acceptability limits for 90% and 80% comfort (ASHRAE, 2004), for most of the year, in selected cities.

Figure 6 – Point cloud representing comfort in the Real Model (MReal) for 2018 by the simulation procedure of NBR 15575

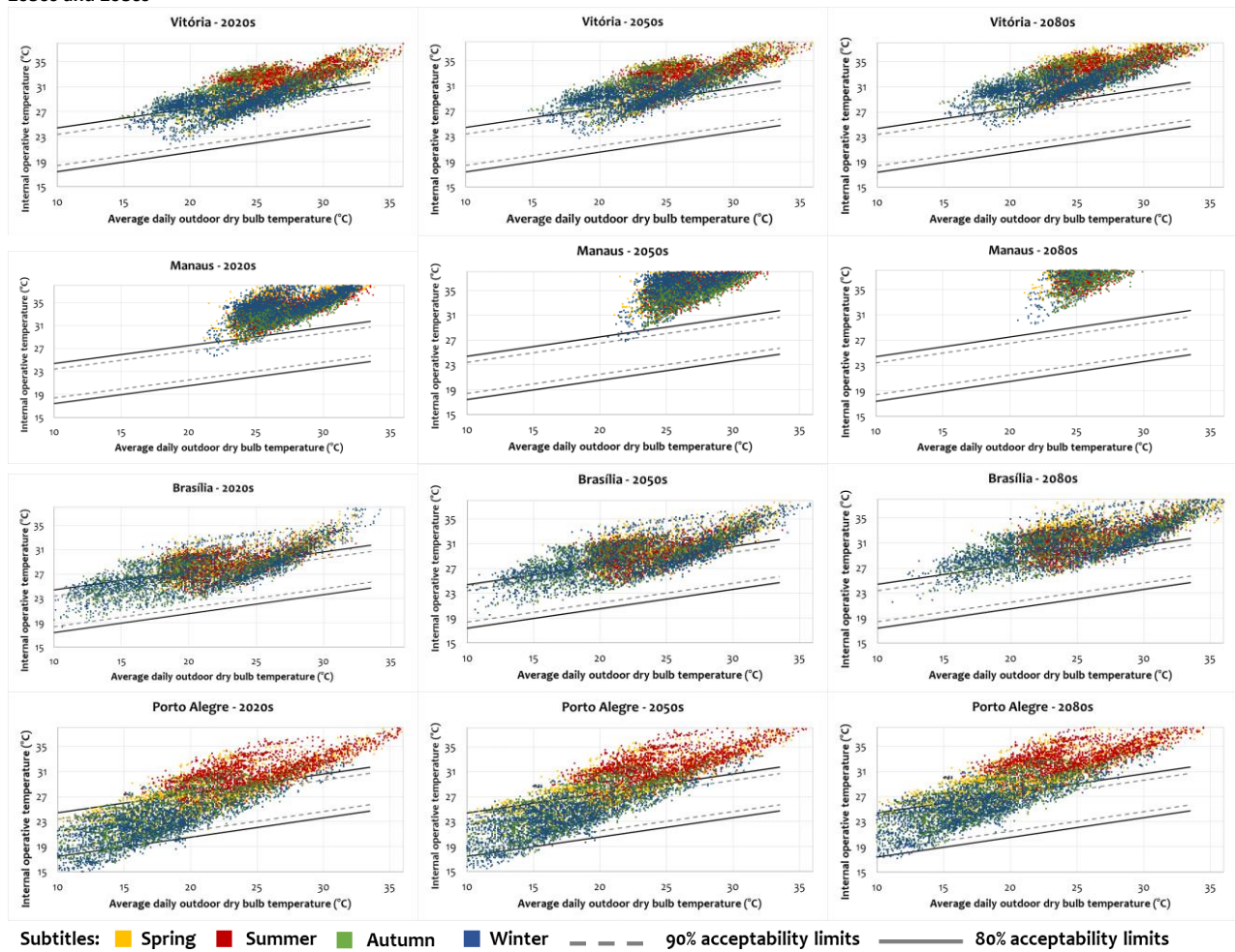


Source: authors.

In the analysis of the time intervals of 2020s, 2050s and 2080s, according to the A2 emissions scenario (PACHAURI; MEYER, 2014), the general assessment of the Real Models showed that the contemporary construction standards used in the building, link a significant slope to the increase in thermal discomfort due to heat considering climatic projections. Considering the average lifespan of 50 years of a building, added to climate changes and their impacts on the imbalance of the climate system, the MReal proved to be inadequate for the future climate for thermal comfort (Figure 7).

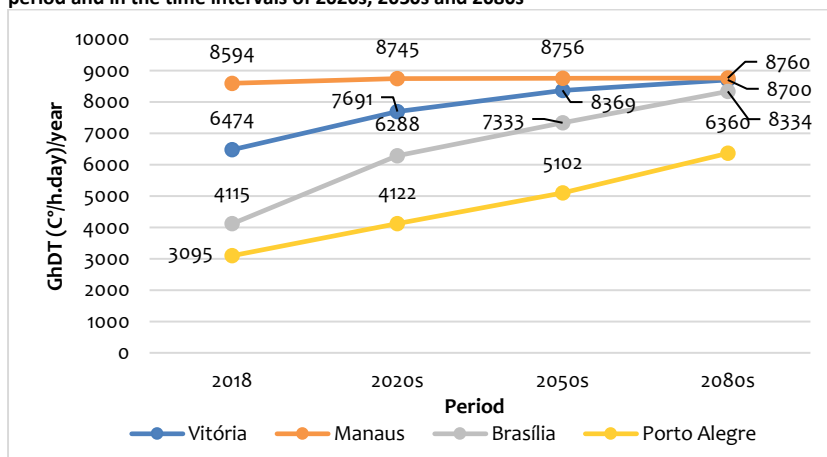
In all scenarios, there was a displacement of the point cloud, extrapolating the comfort limits of 90% and 80% of acceptability. The trend line for the increase in heat discomfort throughout the 21st century (Figure 8) shows a preponderance of thermal discomfort, especially in the 2080s, pointing out the need to expand the use of active conditioning strategies - for example, through ventilators and air conditioners – for at least half the hours of the year, in all cities analyzed.

Figure 7 – Point cloud representing comfort in the Real Model (MReal) by the simulation procedure of NBR 15575 in the time intervals of 2020s, 2050s and 2080s



Source: authors.

Figure 8 - Trend of progression of thermal discomfort by heat in the Real Model (MReal) in Vitória, Manaus, Brasília and Porto Alegre, in the current period and in the time intervals of 2020s, 2050s and 2080s



Source: authors.

Porto Alegre has the lowest annual thermal discomfort index, from 2020s to 2080s. Moreover, the city already links, in the current period, more than 128 full days of heat discomfort during the year, and can count on up to 265 days of discomfort in 2080s. In the A2 scenario, Brasília projects an increase in the average temperature near the

surface of 2 °C and 3 °C, in 2050s and 2080s, respectively, which is greater than Vitória, which can reach 1.5 °C in 2050s and 2 °C in 2080s (WORLD METEOROLOGICAL ORGANIZATION, 2021).

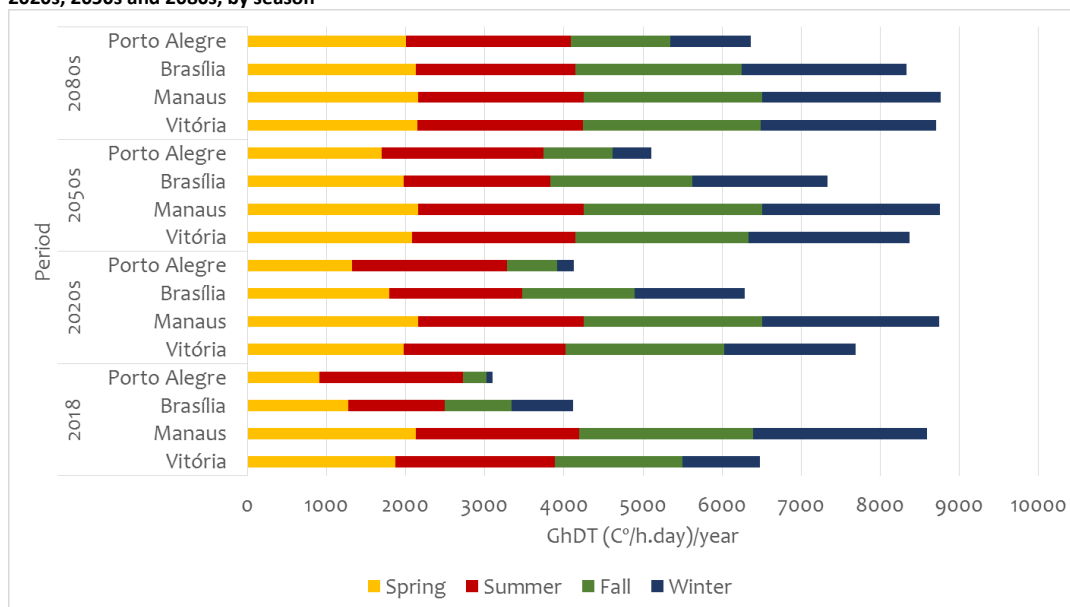
Although the annual discomfort is greater in Vitória, which already has the highest CDH as the current period, a more significant percentage increase is noted in Brasília. The impact of climate change could increase heat discomfort in the 2020s by more than 52% in the city, demonstrating greater intensity in the first decades of the 21st century compared to the 2050 and 2080 periods, with increases greater than 16% and 13%, respectively. However, in absolute values, the ascending trend line in the increase in discomfort shows that the MReal may present, in Brasília, more than 305 days of discomfort in the period 2050s and almost 348 days in the average of 2080s.

Vitória and Manaus, stood out in terms of the increase in thermal discomfort caused by heat considering climate change. In Vitória, more than 320 full days will be thermally uncomfortable in the MReal occupation. The discomfort may rise, in the 2050s and 2080s, more than 348 days and 362 whole days.

In Manaus, the MReal no longer provided even 7 full days of comfort in the current period. In 2020s, the model will only provide a single full day (24 h) of comfort to users. This discomfort will be aggravated in the 2050 and 2080 periods, and will reach, in the second interval, not having any hour of thermal comfort inside the APP, throughout the year, characterizing a permanently uncomfortable model without artificial conditioning.

The greatest rigors correspond to spring and summer, with occurrences in fall and sporadic records in winter. However, in view of climate change and projected warming, all stations begin to present greater uniformity in the increase in thermal discomfort, indicating a decharacterization of the stations as they are currently known (Figure 9).

Figure 9 - Analysis of thermal discomfort by heat in the Real Model (MReal) in Vitória, Manaus, Brasília and Porto Alegre, in the current period, 2020s, 2050s and 2080s, by season



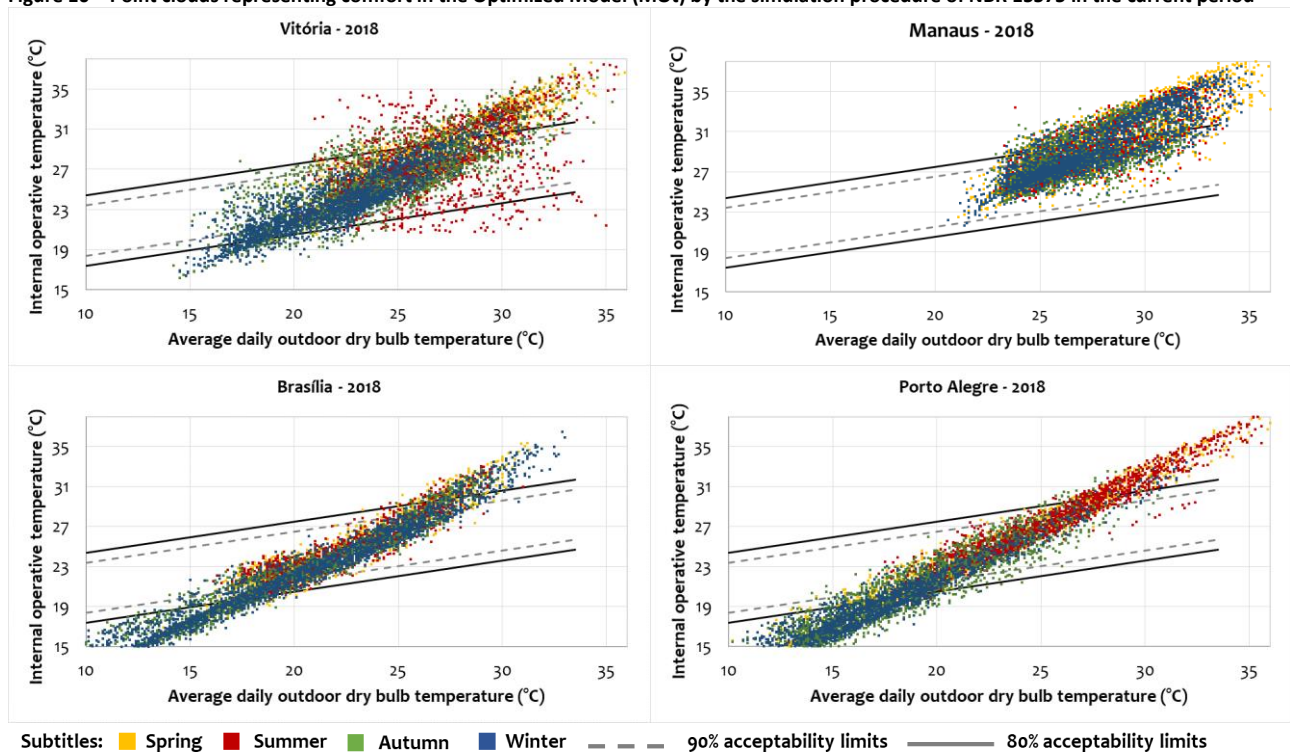
Source: authors.

The new simulations with the MOt propositions demonstrated the model's ability to reduce discomfort since the current period. The contribution of the adequacy of the windows and the ventilated facade system to the feasibility of the occupation of the dwellings in better comfort condition for a longer period of time in the coming decades

is highlighted as the other components of the envelope used in the MReal were not altered.

Although the MReal hourly records show greater uniformity in all cities, even with the greater floating points, especially in the summer and spring seasons, the interventions in the MOt provided a decrease in the hours of discomfort due to heat, presenting greater cloud framing of points in the acceptability limits for thermal comfort (Figure 10). If compared to the MReal, the MOt also significantly helps in adapting the model to future climatic conditions, with records of thermal comfort during a greater annual hourly portion, featuring advantageous solutions for changing the openings and the EVSS (Figure 11).

Figure 10 – Point clouds representing comfort in the Optimized Model (MOt) by the simulation procedure of NBR 15575 in the current period



Source: authors.

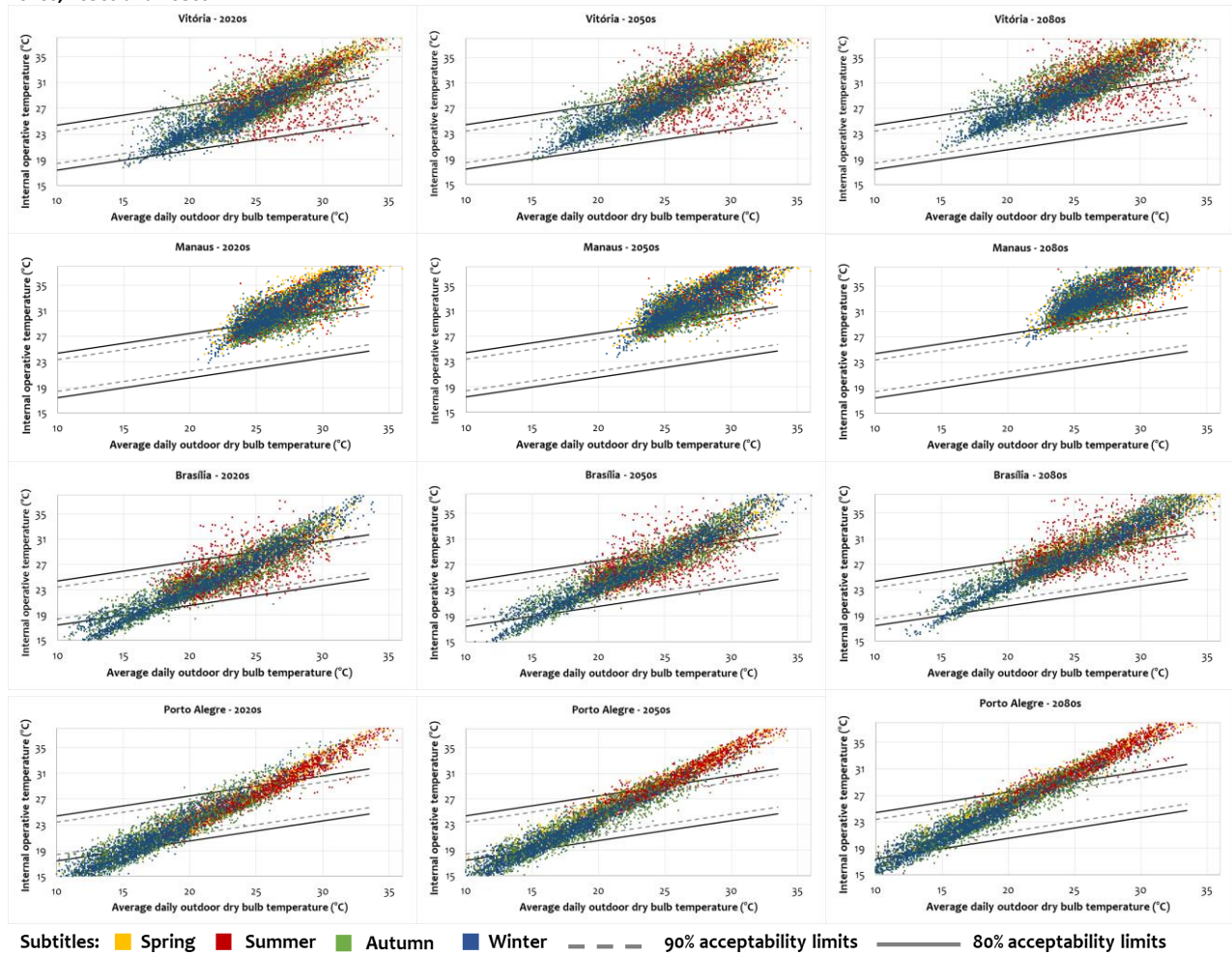
The behavioral profile of comfort is different for cities with a warmer and more humid climate, such as Vitória and Manaus. In Porto Alegre and Brasília, the comfort trajectory indicates greater uniformity in climatic conditions during the analysis period, concentrating the points in a more linear stretch of the graph area. Thus, there is greater constancy in the discomfort panorama, guided by the growing tendency to increase in temperature.

However, in Vitória and Manaus, the more dispersed points indicate greater floating between the hourly records of external air-dry bulb temperature and the operating temperature. As the radiant temperature and the relative humidity of the air directly influence the operating temperature, this factor can be understood by the higher relative humidity of the air in these cities. Thus, a building with the same characteristics presents distinctions in the thermal behavior in cities with higher humidity levels.

Consequently, the high humidity in the current period, added to the increase in local temperature and the increase in water vapors in the atmosphere, in the time intervals of 2020s, 2050s and 2080s, considering the A2 scenario, can intensify the degree of user

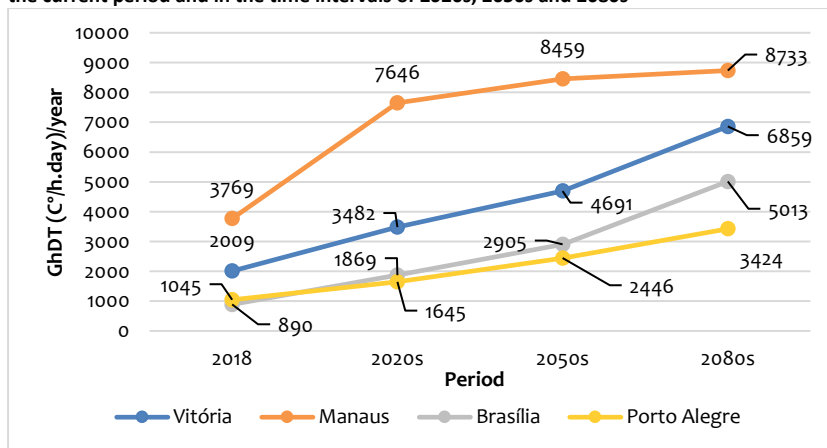
discomfort due to heat in these cities. Numerical values of minimization of the tendency to progression of discomfort, through MOT, are shown in Figure 12.

Figure 11 – Point clouds representing comfort in the Optimized Model (MOT) by the simulation procedure of NBR 15575 in the time intervals of 2020s, 2050s and 2080s



Source: authors.

Figure 12 - Minimization in the trend of thermal discomfort by heat in the Optimized Model (MOT) in Vitória, Manaus, Brasília and Porto Alegre, in the current period and in the time intervals of 2020s, 2050s and 2080s



Source: authors.

In Porto Alegre, which already had the lowest overall discomfort rate for the MReal, the adaptation of the openings and the EVSS provides, in the current period, a reduction of

more than 85 full days of discomfort due to heat during the year. For the time intervals of 2020s, 2050s and 2080s, the decrease in discomfort would reach more than 103, 110 and 122 days, respectively.

If the MOt had already been implemented in the current period, the residents of the city of Brasília would experience, in this year, almost 135 fewer days of discomfort due to heat, reaching, both in the 2020s and in the 2050s, a reduction of almost 185 days. For 2080s, the alleviation of thermal discomfort in the country's capital would exceed 138 days of the year.

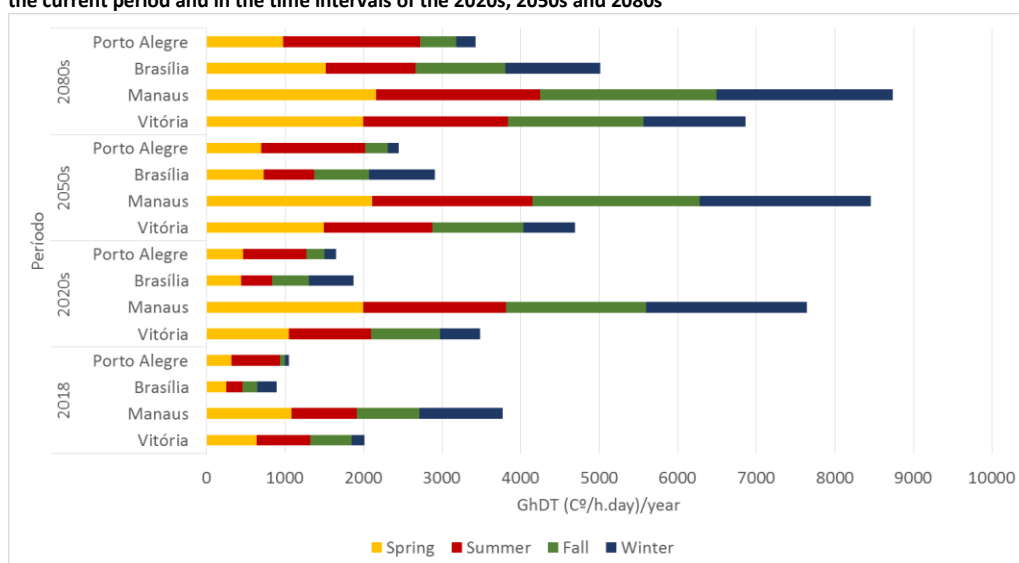
In Vitória, the incorporation of more efficient windows to the EVSS of the MOt entails, in the current period, a reduction of more than 186 full days of discomfort due to heat during a year. Considering the 2020s, 2050s and 2080s, the decrease in occupant discomfort would be greater than 176, 153 and 76 days, respectively.

In Manaus, the municipality that spends the most heat discomfort among the cities in the sample, changing the openings and EVSS in the current period could provide a decrease of more than 201 days of discomfort. For the 2020s period, the reduction in discomfort would exceed 45 days. In 2050s, the minimization of discomfort would correspond to about 12 days and in the 2080s, only 1 day.

Thus, the constructive adaptations proposed according to NBR 15575-2021 are able to provide the minimization of thermal discomfort due to heat in the residential building evaluated. However, the progressive reduction in the capacity to alleviate thermal discomfort over time is notorious, especially in cities with a hot and humid climate, such as Manaus and Vitória, currently located in the ZB8. These data indicate that even passive strategies recommended by specific regulations, such as NBR 15575 (2021), will become obsolete and insufficient for the proper conditioning of buildings considering the rigor of the impacts of climate change.

Figure 13 demonstrates that, even implementing changes in openings and EVSS, in future climate contexts, seasons that are often characterized by milder climates in terms of heat, such as fall and winter, will lose this characteristic, becoming as rigorous as spring and summer for thermal comfort conditions, mainly in Manaus and Vitória.

Figure 13 - Minimization in the trend of thermal discomfort by heat in the Optimized Model (MOt) in Vitória, Manaus, Brasília and Porto Alegre, in the current period and in the time intervals of the 2020s, 2050s and 2080s

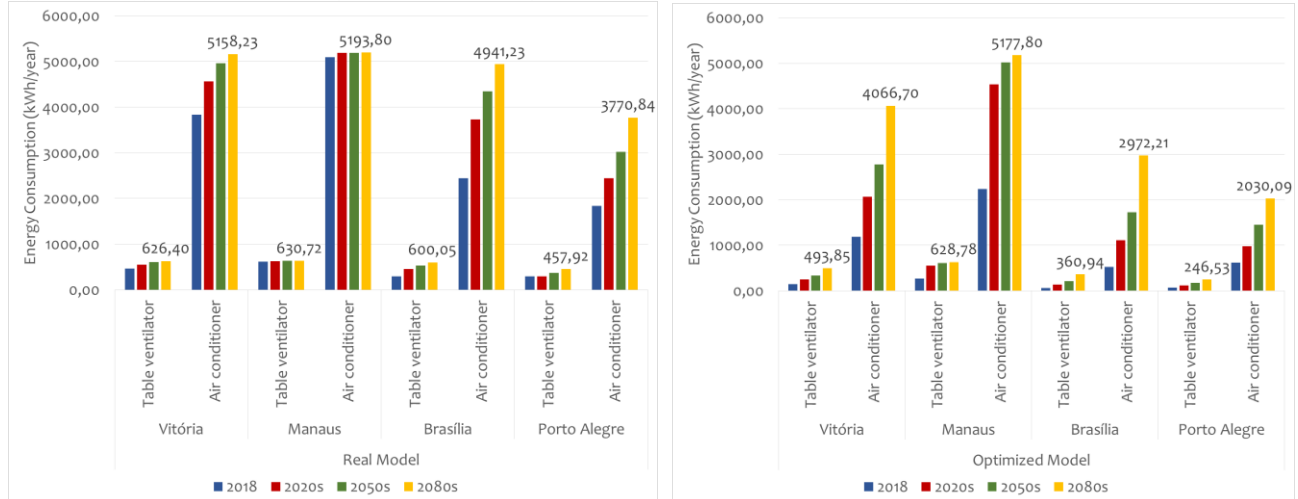


Source: authors.

Analysis of the energy efficiency of the models

Figure 14 illustrates a graph showing annual electricity consumption (kWh/year) of the Real Model (MReal) and the Optimized Model (MOt), emphasizing that the MOt is also characterized as advantageous in relation to the MReal, in terms of energy consumption electricity (kWh/year) for the operation of the ventilator or the air conditioning, whose nexus corresponds to the significant reduction of the thermal discomfort caused by heat by the users. For the time intervals of the 2020s, 2050s and 2080s, the annual consumption represents the average consumption of the years encompassed by each interval.

Figure 14 – Graph of annual electricity consumption (kWh/year) of the Real Model (MReal) and the Optimized Model (MOt)



NOTE: the consumption values were extracted from the 'Table of estimated average monthly consumption of household appliances according to a hypothetical use' (ELETROBRÁS, 2015), considering the items 'Table ventilator' and 'Split air conditioning less than or equal to 10,000 BTU', due to the lower consumption of equipment. Source: the authors.

The ventilator operation entails a lower consumption of electrical energy compared to the air conditioner. The highest demands for energy for this purpose occur in Manaus and Vitória, respectively, as they have the longest periods of discomfort due to heat among the municipalities in the sample. Even with constructive adaptation actions, Manaus and Vitória maintain the proportion of consumption in relation to Brasília and Porto Alegre.

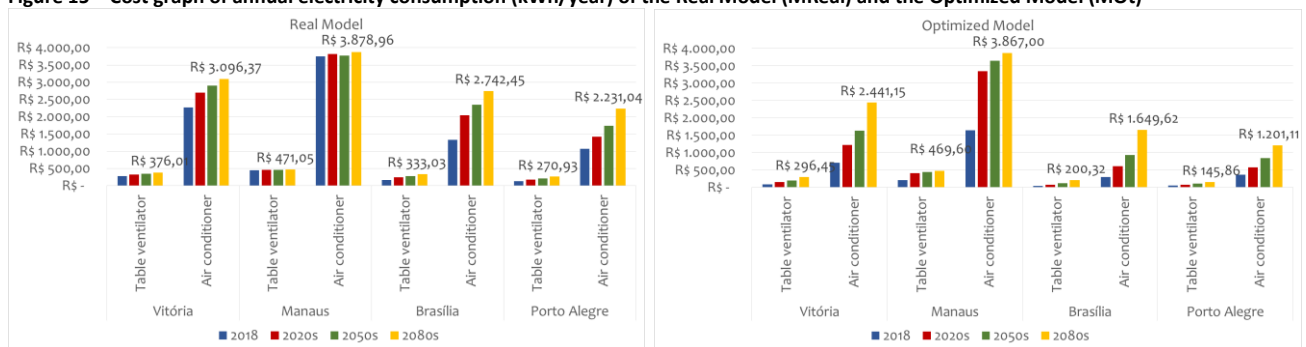
Despite the improvement in comfort conditions attributed to the MOt, the trajectory of power consumption indicates the obsolescence of passive conditioning strategies given the temperatures projected for the next decades. In some scenarios, especially from the time interval of 2050s, there is probably a need to use air conditioning to obtain comfort indices in the indoor environment.

Thus, the increase in temperatures in the cities considered in this research, over the next decades, will lead to an increase in electricity consumption for the operation of equipment that provides thermal comfort in the residence. This panorama is directly reflected in the energy costs of housing units for the operation of artificial thermal conditioning devices. Based on current calculation standards, the projection of energy distribution costs also indicates that the MOt can provide savings to residents of all evaluated cities.

However, even adapting the construction to the present climate, according to the normative recommendations in force in Brazil, the houses would not be considered adequate considering climate changes, also considering the high costs of operating the appliances, whose demand would be even greater over the decades. (Figure 15).

Although projections of monetary and inflationary readjustments have not been considered, the estimate represents the trend towards an increase in housing operating costs.

Figure 15 – Cost graph of annual electricity consumption (kWh/year) of the Real Model (MReal) and the Optimized Model (MOt)

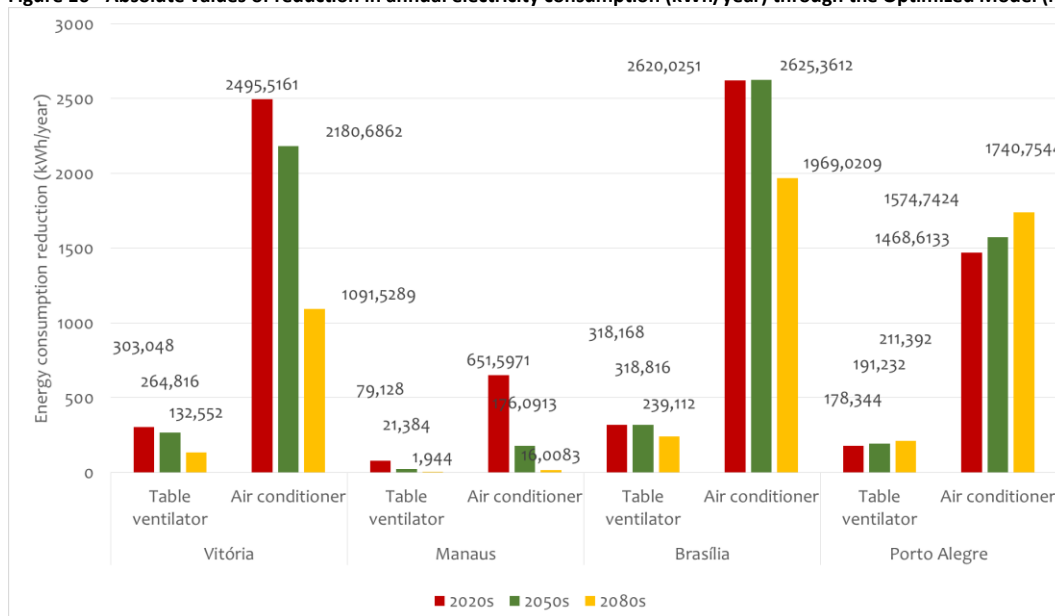


Source: authors.

Noting the energy efficiency of the MOt proposal, there was a reduction in electricity demand also in the time intervals of 2020s, 2050s and 2080s, demonstrated, in absolute values, in Figure 16. The greatest reductions in energy consumption are projected for Vitória and Brasília.

These data can be understood, since, despite the reduction of discomfort in Manaus, the high GHR still entails a high demand for the use of active conditioning, which would be even greater without using strategies applied through constructive adaptations in the MOt. Finally, Porto Alegre has the lowest levels of discomfort in the survey, highlighting, however, that these are still high, justifying the smaller reduction in energy demand.

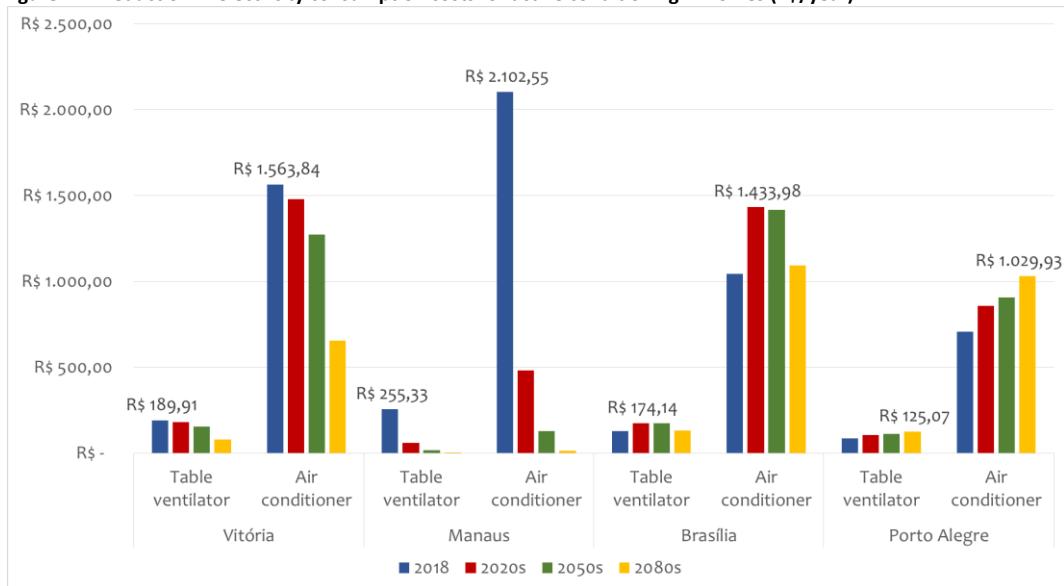
Figure 16 - Absolute values of reduction in annual electricity consumption (kWh/year) through the Optimized Model (MOt)



Source: authors

Given the above, it can be said that the implementation of actions to adapt buildings to climate change can provide a reduction in costs related to the conditioning equipment considered, that is, ventilators and air conditioners (Figure 17).

Figure 17 - Reduction in electricity consumption costs for active conditioning in homes (R\$/year)



Source: authors.

In the current period, the biggest differences between MReal and MOt costs were observed in Manaus and Vitória, respectively, using air conditioning. In the time interval of 2020s, Brasília will surpass Manaus in terms of cost reduction and will come in second place, behind Vitória.

These data can be understood by the progression of discomfort in Manaus, already in 2020s, indicating that, in this period, even a more efficient model - such as the MOt, compared to the MReal - would already require a high energy consumption for the active conditioning of homes. This trend is also reflected in Vitória, Brasília and Porto Alegre, respectively, especially from the 2050s onwards.

It is confirmed, therefore, that even the implementation of passive conditioning strategies for buildings, consistent with NBR 15575 (ABNT, 2021), can be considered beneficial, but will become obsolete considering the rigor of the future climate, demanding artificial air conditioning to thermal comfort in buildings and highlighting the need for periodic updating of regulations so that the behavior of buildings meets the new requirements proposed by the climate in transition.

Final considerations

Brazilian buildings are often characterized by project replication regardless of where they are located and by the consequent inadequacy to the local climate. Several national standards, such as NBRs 15220-3 (ABNT, 2005) and, especially, NBR 15575 (ABNT, 2021), have been revised and improved so that their effective application to building design provides significant improvements.

The computer simulations allowed the calculation of the ΣGHR in each scenario, demonstrating that the proposed constructive adaptation actions contributed to the reduction of periods of thermal discomfort inside the house, reducing the need to activate ventilators and split air conditioners, minimizing the energy consumption in all scenarios.

However, it is important to highlight that, despite the reduction in discomfort - especially in the 2020s period, from the time interval of 2050s, with a peak in 2080s, the results pointed out that, considering the severity of climate change, there will be an

inability to maintain comfort in the building's internal environment only through the implementation of passive conditioning strategies adopted at work. In this scenario, among the major impacts projected for the future climate throughout the Brazilian territory, it was found that the mechanical thermal conditioning will be mandatory for the habitability in the dwellings, within the standards addressed in the research, and the absence of this could pose risks to the physiological limits and the thermal well-being of residents.

It is confirmed, therefore, that in addition to implementing technologies for the constructive improvement of the envelope, special attention must be given to the thermal properties of the systems and materials, considering the analysis of current and future conditions, especially regarding air temperature and the relative humidity of the air, in addition to the patterns of occupancy of the environment by the user. Faced with rapid climate changes and also the trend of new types of use of housing spaces, the design process must take into account the useful life of the building, both in terms of meeting current and future conditions and needs.

Therefore, two pillars of more adequate development of design processes and, consequently, of constructive standards can be mentioned: first, the adaptation of buildings to the local climate, in the present time, considering the extension of their useful life, characterizing an instrument of preparation from constructions to future climate scenarios; and second, the containment of anthropogenic climate change – stimulated, for example, by high GHG emissions and deforestation – since, from certain future scenarios of high emissions, passive conditioning strategies will be obsolete. Thus, the inclusion of parameters for projecting future climate conditions in NBR 15575 would make it an important tool for defining strategies for adapting buildings to climate change in the 21st century.

The selection of a restricted number of municipalities is pointed out as a limiting factor for the research. Thus, the inclusion of a greater number of cities, which present different climatic conditions, may allow a more extensive overview of the thermal behavior of buildings in different locations of the national territory, under the conditions of climate change. Moreover, the research considered only the climate scenario RCP 8.5 of the IPCC-AR5. Using more climate scenarios can generate different results regarding the impacts of climate change on the performance of the envelope, in the parameters adopted in the research.

In the simulations, only one APP, a standard behavior of users in relation to the operability of the building and a set of adaptive proposals were evaluated. Other configured behaviors and different constructive solutions can modify the expressed results. The results presented should be considered as a portrait of a trend, and not as absolute values as they are based on the hypothesis of the most critical scenario projected for future climate changes, which is still a conjecture of a trend.

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