v. 23 n. 1 2023

cadernos pós
cadernos de pós-graduação
em arquitetura e urbanismo

Adaptações construtivas em habitações de interesse social no Cerrado brasileiro frente às mudanças climáticas

Constructive adaptations in social dwellings in the Brazilian Savannah region in the face of climate change

Adaptaciones constructivas en viviendas sociales en el Cerrado brasileño frente al cambio climático

Emeli Lalesca Aparecida da Guarda, Mestre em Engenharia de Edificações e Doutoranda em Arquitetura e Urbanismo, Universidade Federal de Santa Catarina.
E-mail*: emeliguarda@gmail.com* *http://orcid.org/0000-0001-7536-4448*

Luciane Cleonice Durante, Doutora em Física Ambiental, Universidade Federal do Mato Grosso.
E-mail*: luciane.durante@hotmail.com* *http://orcid.org/0000-0002-4998-4587*

Ivan Julio Apolonio Callejas, Doutor em Física Ambiental, Universidade Federal do Mato Grosso.
E-mail*: ivancallejas1973@gmail.com* *http://orcid.org/0000-0001-7877-7029*

To cite this article: GUARDA, E. L. A. da; DURANTE, L. C.; CALLEJAS, I. J. A. Adaptações construtivas em habitações de interesse social no Cerrado brasileiro frente às mudanças climáticas. *Cadernos de Pós-Graduação em Arquitetura e Urbanismo*, São Paulo, v. 23, n. 1, p. 36-54, 2023.
DOI 10.5935/cadernospos.v23n1p36-54

Submissão: 2022-06-18
Aceite: 2023-01-11

Resumo

As mudanças climáticas são reconhecidas como um desafio global chave para o século 21. O objetivo deste trabalho é analisar, por meio de simulação computacional, os efeitos do aquecimento global no desempenho térmico e energético de uma habitação social implantada no cerrado brasileiro. A metodologia consiste em preparação dos futuros arquivos climáticos; elaboração de propostas de intervenção no objeto de estudo, definindo seis tipologias (Tbase, T1 a T5); classificação da eficiência energética; análise do conforto térmico e estimativa da carga térmica para refrigeração. Sob os efeitos do aquecimento global, T5 apresentou o melhor comportamento térmico em 1.148 horas no Cenário Base e 6.841 horas, em 2080. Tbase e T5 possuem classificação de eficiência energética de "C" e "A" no Cenário Base, respectivamente, e ambas são "E", em 2080. Conclui-se que, considerando a vida útil das edificações, é necessário repensar as especificações atuais de construção para absorver os impactos das mudanças climáticas. Apontam-se orientações sobre como construir hoje para garantir habitabilidade nos cenários climáticos futuros.

Palavras-chave: Desempenho termoenergético; Sustentabilidade; Estratégias bioclimáticas.

Abstract

Climate change is recognized as a critical global challenge for the 21st century. This work aims to analyze, through computer simulation, the effects of global warming on the thermal and energy performance of social housing implanted in the Brazilian Savannah. The methodology consists of preparing future climate files; preparation of intervention proposals in the object of study defining six typologies (Tbase, T1 to T5); classification of energy efficiency, analysis of thermal comfort, and estimation of the thermal load for cooling. Under the effects of global warming, T5 showed the best thermal behavior - 1,148 hours in the Base Scenario and 6,841 hours in 2080. Base and T5 have energy efficiency ratings of "C" and "A" in the Base Scenario, respectively, and both are "E" in 2080. It is concluded that considering the useful life of buildings, it is necessary to rethink current construction specifications to absorb the impacts of climate change. Guidance is provided on how to build today to ensure habitability in future climate scenarios.

Keywords: Thermoenergetic performance; Sustainability; Bioclimatic strategies.

Resumen

El cambio climático es reconocido como un desafío global clave para el siglo 21. El objetivo de este trabajo es analizar, a través de simulación por computadora, los efectos del calentamiento global en el desempeño térmico y energético de una vivienda social implantada en el cerrado brasileño. La metodología consiste en preparar archivos de clima futuro; elaboración de propuestas de intervención en el objeto de estudio definiendo seis tipologías (Tbase, T1 a T5); clasificación de la eficiencia energética, análisis del confort térmico y estimación de la carga térmica para refrigeración. Bajo los efectos del calentamiento global, T5 mostró el mejor comportamiento térmico – 1.148 horas en el Escenario Base y 6.841 horas en 2080. Tbase y T5 tienen calificaciones de eficiencia energética de "C" y "A" en el Escenario Base, respectivamente, y ambas son "E" en 2080. Se concluye que, considerando la vida útil de las edificaciones, es necesario repensar las especificaciones constructivas actuales para absorber los impactos del cambio climático. Se proporciona orientación sobre cómo construir hoy para garantizar la habitabilidad en escenarios climáticos futuros.

Palabras clave: Desempeño termoenergético; Sustentabilidad; Estrategias bioclimáticas.

Introduction

Several scientific studies have shown the occurrence of global warming. Marengo and Soare (2003) estimated an increase of +0.85 °C every 100 years for the same Amazon region. According to NOAA (2021), 2020 was the second warmest year in 141 years (period 1880-2020), with a global land and ocean surface temperature of +0.98 °C. Furthermore, the seven warmest years have been occurring since 2014. South America's annual temperature has increased by approximately +0.14 °C per decade since 1910.

On the urban and building scale, one concern regarding the theme is the energy consumption of buildings to maintain comfortable conditions. Studying the consequences of this phenomenon has gained worldwide importance. It starts with the problem of the current housing models, which are already built with inadequate thermal insulation, asking how the conditions of internal ambiance will be affected in future climate change scenarios. In Savannah's climate, heating conditions are predicted due to its location between the tropic's regions. Wang *et al*. (2021) warned that there is a growing need to clarify the challenges posed by climate change to limit thermal discomfort by applying bioclimatic design strategies. Therefore, it is necessary to update the climatic data from the prospect established by the IPCC emission scenarios and verify the current buildings' behavior in future environmental conditions.

In this context, the concept of building resilience emerges and is understood in this study as the capacity of buildings to adapt to changes that may impact the functioning of their systems and the conditions of habitability (ROAF; FUENTES; THOMAS-REES, 2014). The AR4 (IPCC, 2021) presents resilience as the ability of systems to absorb disturbances while maintaining their normal functioning, alerting society to the vulnerability and risks to which the population is subject. Rana *et al.* (2022) cite vulnerability and exposure in homes, where millions of people face multiple risks due to climate change.

In this way, this research aims to assess the constructive adaptations in social dwellings by incorporating passive strategies and measures to mitigate climate change impacts according to the A2 emission scenario described in the IPCC Fourth Assessment Report (AR4), considering its implantation location in the Brazilian Central-Western region (Savannah Tropical climate).

Methodology

This study develops through a scenario approach: the first named Base Scenario, without the influence of global warming on climatic variables, and the others, Future scenarios, in which the projections established in AR4 (IPCC, 2007) are considered, evaluated by the HadCM3 global model based on scenario A2, presented in (GUARDA *et al*., 2020).

Regarding the delineations of this study, it can be considered that to guide the construction of constructive design guidelines for housing incorporating the effects of global warming and, consequently, climate changes for the 21st century, it is necessary to simulate the climate through models of general circulation (GCM), downscaling and emission scenarios. These procedures can generate uncertainties and limitations in the variability and future climate projections. However, the CCWorldWeatherGen tool is widely used for building future climate files due to its ease of handling and unrestricted license. This tool predicts climate change based on the GCM HadCM3 and the A2 emissions scenario. Thus, for this research, issue scenario A2 of the Fourth Report (AR4) of the IPCC was restricted, as it is widely consolidated in the scientific literature and the CCWorldWeatherGen tool due to the ease of generating future climate files in EPW format, which can be used to investigate the energy and thermal performance of houses, which is the focus of this research.

Study Object

The city of Cuiabá-MT, located in the Brazilian Savannah, also named Cerrado (central region), has a climate profile classified as tropical (Aw), according to the Koppen-Geiger classification (PEEL, 2007). To analyze climate evolution, the three climatological normals available for 1931-1960, 1961-1990, and 1981-2010 by INMET were investigated, considering the meteorological data of Cuiabá city as a reference to represent the Savannah climate in the region. INMET climate files were obtained from the BDMET database for the most historical year periods and 2019 (INMET, 2020) (Figure 1). Comparing historical data from Climatological Normal (NC – 1931-1960) and INMET (2018 and 2019), an increase in the annual average air temperature of 0.57 °C in Cuiabá city has been observed over approximately 60 years. This fact corroborates the projections presented by the IPCC, whose average global temperature increase is 0.15°C to 0.30°C per decade (IPCC, 2014).

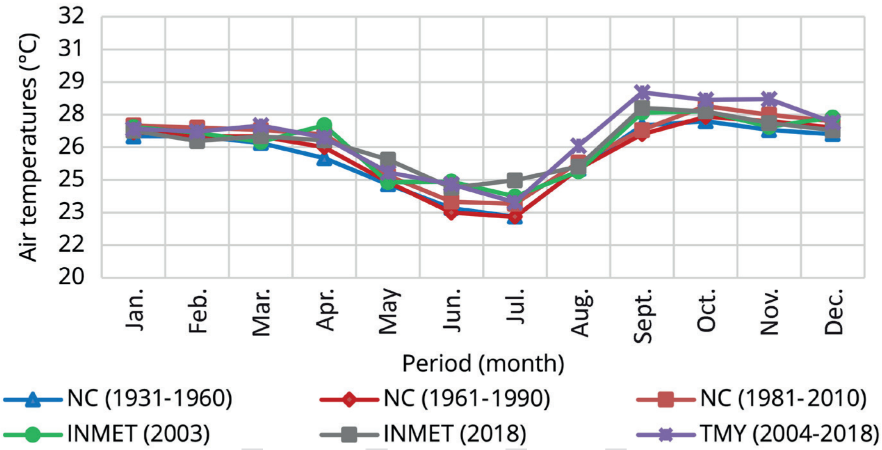
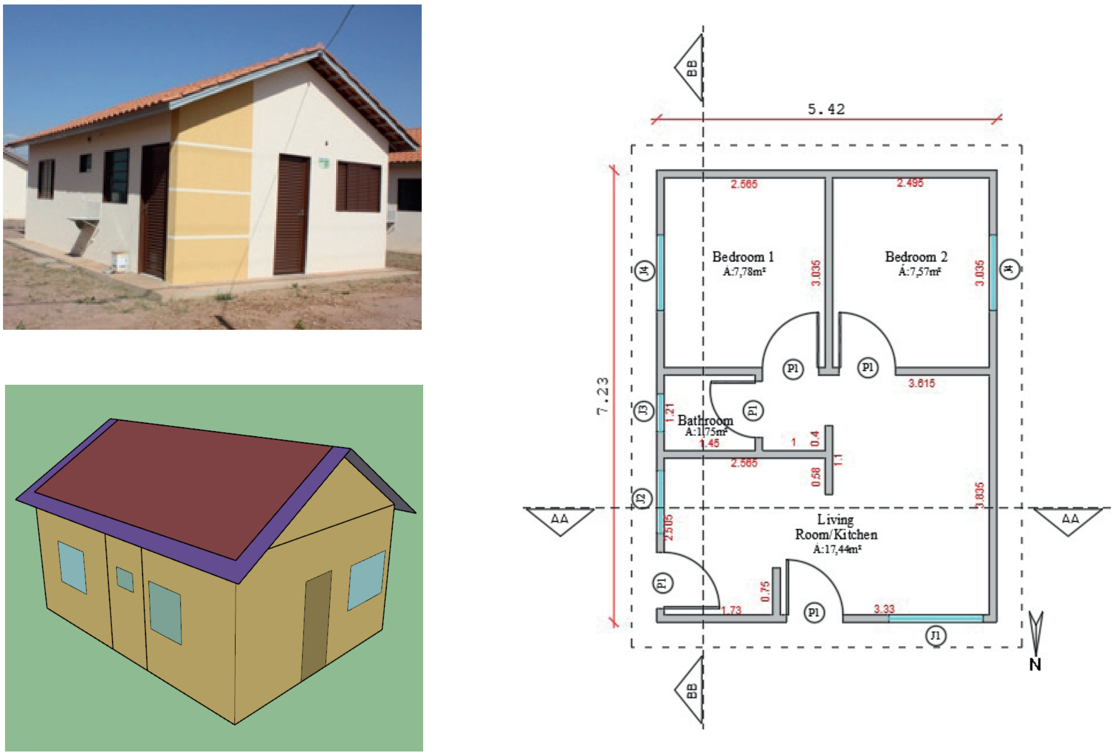


Figure 1: Climatic characterization of the study region. Source: The authors (2022).

Particularly in Brazil, there is still a deficit of 6,355 million households (FJP, 2021). To reduce it, the Brazilian government established a policy for the low-income population, implementing a national social housing program called "My House, My Life," with approximately five million housing units built by 2019 (Brasil, 2020). However, the units tend to prioritize lower costs, executing low-income housing with similar typologies, with the same design and materials throughout the country, despite the climate variations exhibited in Brazil.

For this study, it was selected a building project implemented in many Brazilian states. Its choice was based on the fact that these dwellings are handed out without any adaptation concern about the climatic conditions of the implantation region, resulting in buildings with poor thermal and energy performance (TRIANA, 2016). The built area is composed of 39.18 m^2 (Figure 2). In the analyses conducted in this research, the residential dwelling was implanted with the main facade facing north (0°), the most exposed facade at this latitude (GUARDA, 2019).

The bedrooms and living room windows are composed of metal frames with two opaque sliding panels and a single glass 3mm thick. In the kitchen, a tilting-type model with a single glass 3mm thick was utilized. The external doors are made of metal plates, and the internal doors are made of wood (Figure 3). The percentages of functional areas of ventilation and natural lighting follow guidelines established in the Brazilian regulation for energy efficiency in buildings (RTQ-R) (INMETRO, 2012) and the Brazilian standard NBR 15.575-4 (ABNT, 2013).

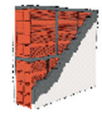
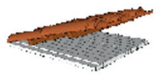
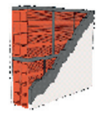
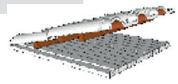
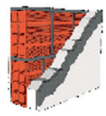
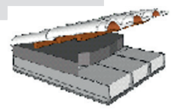


(a) Picture and perspective of Housing of Social Interest (HIS) implanted in the region.

(b) Floor plan (dimensions in meters).

Figure 2: Picture and architectural characteristics of the social dwelling. Source: Rios (2015).

Brazil's Federal Government approves the construction systems, and their thermal properties can be visualized in Figure 3, based on the standards NBR 15.220 (ABNT, 2003) and NBR 15.575 (ABNT, 2013) expressed in Thermal Resistance (R), Total Thermal Resistance (Rt), Thermal Transmittance (U) and Thermal Capacity (C). Based on the literature review, individual measures cannot neutralize the impacts on habitability in the typology of social dwelling (GUARDA *et al*., 2020; TRIANA, 2016). Therefore, combinations of passive strategies are necessary to increase the resilience of this building to the potential effects of climate change, such as thermal inertia, thermal insulation, low solar absorption, shading of the openings, and selective ventilation. Thus, the original building envelope was redesigned (in this study, it is named Tbase), taking the previous strategies as a reference. Five typologies were defined as studied cases, which were named T1 to T5, according to the properties shown in Table 1.

	Changes applied in the Tbase typologies	R	U	Rt*	U*	C	
T1**	External walls: similar Tbase with solar absorption modification (0.2 – light color).	0.129	7.74	0.299	3.344	164.61	
	Roof system	0.854	1.17	1.064	0.939	41.92	
T2**	External walls: mortar internal layer (0.025 cm), brick (0.09 m), expanded polystyrene (EPS) (0.04 m), and mortar external layer (0.025 cm).	1.128	0.886	1.298	0.770	169.38	
	Roof system: similar Tbase with solar absorption modification (0.2 – light color).	0.847	1.18	1.057	0.946	41.92	
T3**	External walls: mortar internal layer (0.025 cm), brick (0.14 m), EPS (0.04 m), and external and mortar external layer (0.025 cm).	1.176	0.85	1.346	0.7429	179.11	
	Roof system	Similar to T2					
T4***	External walls	Similar to T2					
	roof system: ceramic tile, attic, concrete layer (0.05 m), EPS slab layer (0.06 m), and an internal mortar layer (0.015 m).	1.785	0.56	1.995	0.501	159.42	
T5***	Internal walls: mortar internal layer (0.025), brick (0.19 m), and mortar external layer (0.025 cm).	0.176	5.65	0.346	2.890	176.82	
	External walls: mortar internal layer (0.025 cm), brick (0.19 m), EPS (0.06 m), and external and mortar layer (0.025 cm).	1.677	0.596	1.847	0.541	180.15	
	Roof system	Similar to T4					

**Considering external surface resistance (0.04), internal surface resistance horizontal flow (0.13), and internal surface resistance upward flow (0.17).*

***Low emissivity due to the implementation of barrier insulation radiant (0.61 m^2K/W).*

**** high emissivity (0.21 m^2K/W).*

Table 1: Thermal properties of the vertical panel and roof systems. Source: EnergyPlus HTML Report.

Exterior window shutters are present in all typologies studied in this research, allowing residents to control the entry of sunlight. The combined measures to enhance building resilience were based on the criteria that redesigned envelopes must reach the energy efficiency classification "A" for Brazilian bioclimatic zone 7, which considers that the indicator named cooling degree hours (CDH) must be below 12,566 °Ch (INMETRO, 2012).

Building thermal, energy simulation and adaptive thermal comfort

For operational reasons, the OpenStudio plugin was used to model the dwelling project for thermal, energy, and comfort simulation. Its 3D model was imported into the thermal and energy simulation software EnergyPlus developed by the US Department of Energy. This software can model multizone buildings' performance and energy consumption considering their design, local climate data, and other parameters. It allows simulations of naturally ventilated and artificially conditioned buildings. Energy Plus Weather Files (EPW) containing current data and future climate scenarios were used to conduct the simulation with and without the impact of climate change. The future data were generated by the CCWorldWeatherGen Tool, presented in (GUARDA *et al*., 2020). The simulation comprises the following stages: geometry modeling (made in the OpenStudio plugin), thermal insertion properties of the materials, the introduction of indoor occupancy patterns and lighting systems, natural ventilation and equipment parameters, and finally, determination of the soil temperature.

The building occupancy, lighting patterns, and internal heat gains (equipment's internal loads) were taken from (INMETRO, 2012). Soil temperature significantly influences the thermoenergy simulation; thus, the "ground domain slab" from EnergyPlus software was used to estimate temperatures under the dwellings for the basis and future climate scenarios.

Standard 55 (ASHRAE, 2013) establishes the adaptive thermal comfort index proposed by (DEAR; BRAGER, 1998) to conduct thermal comfort analyses applicable to naturally ventilated buildings. After determining the neutral temperature, 90% user satisfaction was established, in line with previous research (SÁNCHEZ-GARCÍA *et al*., 2018).

Estimated Thermal Load

According to Standard 55 (ASHRAE, 2013), energy consumption can be estimated using thermal balance according to the magnitude of the internal load and the heat exchanges by the building's vertical and horizontal envelopes systems (PEDERSEN; FISHER; LIESEN, 1997). The estimated thermal load for the baseline (1961-1990) and future climate change scenarios (2020, 2050, and 2080) are expressed in kWh/month for each type of survey (Tbase and T1 to T5).

The Cooling Degree Hours (CDH) were adopted as indicators of building thermal performance under natural ventilation conditions following the recommendation of the RTQ-R (INMETRO, 2012). The base temperature used to calculate the cooling degree hours was set at 26 °C. To classify the energy efficiency of the building, the indicator proposed for bioclimatic zone 7 (Cuiabá is set as a city located in Savannah's climate, as previously mentioned) is described in RTQ-R. In this way, energy efficiency should present cooling degree hours for level "A" (best efficiency), ≤12566 °Ch, level "B"≤18.622 °Ch, level "C"≤24.679 °Ch, level "D"≤30.735 °Ch and, level "E" (worst efficiency)>30.735 °Ch.

Results

Adaptative Thermal Comfort in the Base Scenario and Futures

The combined adaptation measures implemented in the standard typology envelope (Tbase) effectively improve the building's thermal performance in the current scenario, increase comfort, and reduce hot discomfort hours inside the building (Figure 4a). Regarding monthly thermal comfort, in Tbase in October and December, the mean indoor temperature was over the adaptive thermal comfort range (22.54 to 29.26 °C). This typology presents annual hours of thermal discomfort of 16.6%. In contrast, in the other typologies, the mean annual air temperature inside the building remains between the upper and lower thermal comfort ranges (Figure 3a).

Even considering that the thermal adaptation of the comfort range will be shifted by + 0.58 °C in the 2020 scenario (comfort range between 23.01 and 29.84 °C), thermal comfort conditions in the Tbase and T1 typologies are not reached inside the indoor environment from August to April, increasing the annual percentage of thermal discomfort to 66.6 and 58.3%, respectively. It represents an increase of +50% concerning the Base Scenario. For the other typologies (T2 to T5), they present hours of thermal discomfort in 16.6% of the year, in October and December (Figure 3b). Thus, Tbase and T1 cannot provide suitable habitability to their users (thermal discomfort is greater than 50%).

In the 2050 scenario, the thermal comfort range also increased by +1.15 °C compared to the Base Scenario (comfort range between 23.51 and 30.41 °C). In Tbase and T1, thermal comfort conditions are only observed in June and July, with thermal discomfort reaching 91.6 and 83.3% of the year, respectively. This increase is also seen in the other typologies, showing discomfort hours in 58.33% of the year in T2, T3, and T4. T5 is the only one to be resilient to the impact of climate change predicted for this period, presenting annual thermal comfort hours equal to the discomfort (50% of the year) (Figure 3c).

The 2080 scenario followed the same behavior as the previous time frames, even elevating thermal adaptive comfort ranges (24.41 at 31.25 °C). The proposed building adaptation measures cannot counterattack the indoor effects predicted by global warming in the tropical savannah climate. All typologies will display 91.66% of thermal discomfort yearly, with thermal comfort conditions only in July (Figure 3d). This increase in thermal discomfort of the typologies can be justified by the significant increase in external average air temperature of + 5.5 °C, resulting in mean internal air temperatures over 30 °C.

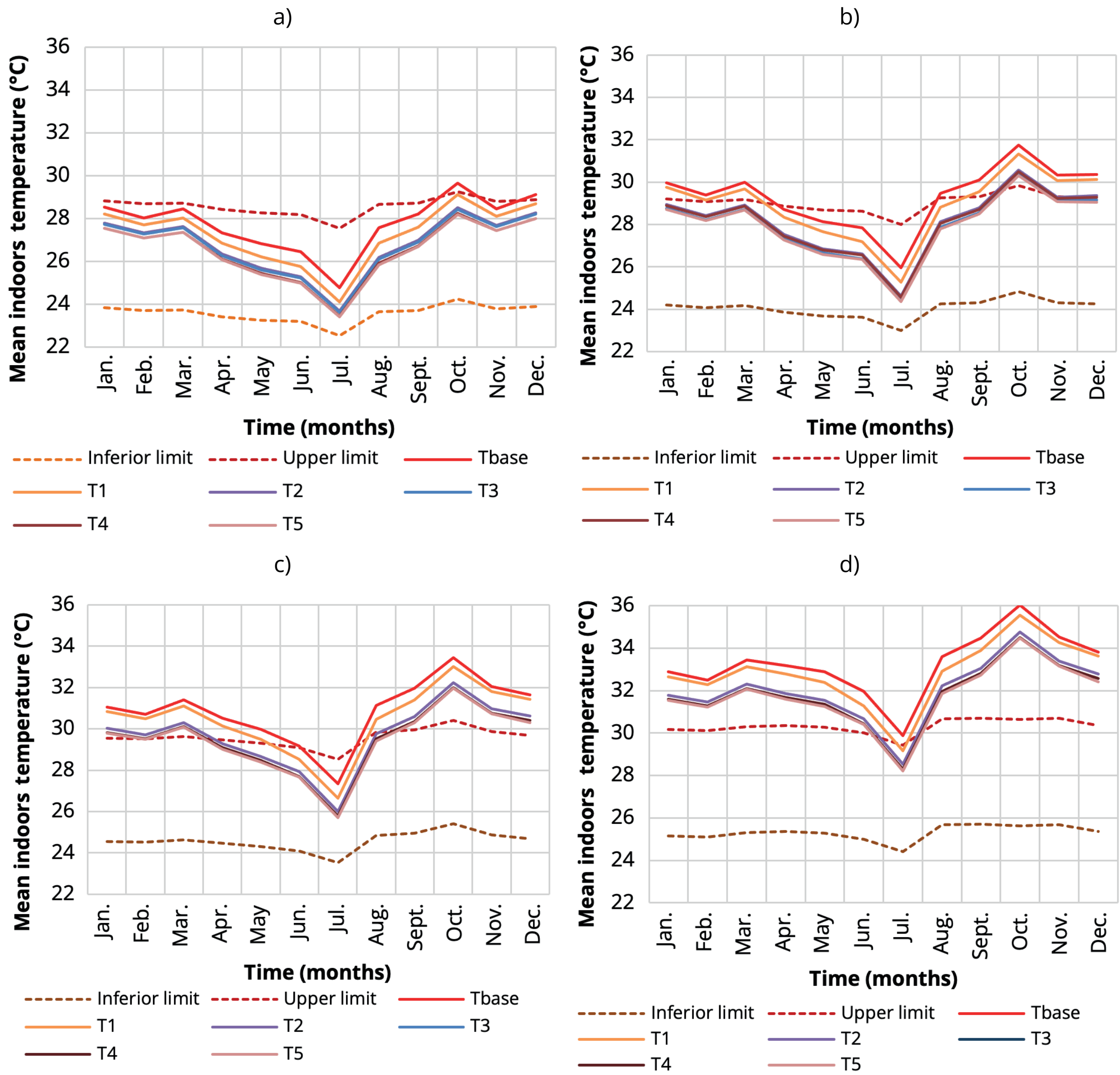


Figure 3: Thermal conditions in a) the base scenario, b) 2020 scenario, c) 2050 scenario, and d) 2080 scenario. Source: Elaborated by the authors.

Thus, even considering the possibility of people adapting to the new weather conditions imposed by climate change, a gradual dissatisfaction increase and reduction is provided by hot and cold weather conditions, respectively, and a reduction in thermal comfort is observed. Thus, further constructive interventions are necessary to improve building thermal resilience to improve thermal comfort conditions for the 2050 and 2080 scenarios.

Estimated Thermal Load

Thermal load for heating was disregarded in this study, as the primary consumption in typologies comes from cooling demand in the long permanence rooms.

In the Base Scenario, the thermostat was set based on the adaptive thermal comfort range (between 22.54 and 29.26 °C). Although the range is elastic, a high thermal load for cooling is observed to maintain the Tbase's comfort conditions (annual thermal load of 2.447 kWh). With the measure of reduction in solar absorption of the external walls of T1, energy consumption is reduced by 37% compared to Tbase (1.530 kWh). Improving the thermal insulation on the outer walls of T2 and T3 reduces the thermal load to 68%; the thermal load drops to 831 and 735 kWh, respectively. Finally, by improving the thermal insulation of the roof (T4) and the thermal insulation of the roof and external/internal walls (T5), it is possible to achieve the lowest average annual load, with a reduction of 83% in Tbase (422 and 413 Wh, respectively) (Figure 4). Thus, the measures implemented can improve the building envelope, drastically reducing the demands for thermal refrigeration loads to maintain the building's thermal habitability in the research region.

In the 2020 scenario, the thermostat was regulated between 23.01 and 29.84 °C. Even with the improvement in the T1 typology envelope, which promoted a 44% reduction in thermal load compared to Tbase, the thermal load is drastically affected, almost doubling due to the climate changes projected for the period (5,616 in Tbase and 3,122 kWh in T1). Typologies T2, T3, and T4 are also affected by global warming, despite showing improvements in the thermal energy performance provided by the passive measures applied in the building envelope (an average reduction of 73% in Tbase, with an average annual thermal load of energy 1,501 kWh) In the T5 typology, the drop in thermal load is more significant compared to the previous ones, with a reduction of 78% (1,227 kWh). Note that the load in the typologies is lower than that observed in the current scenario in the Tbase typology. Thus, thermal insulation measures, whether applied to the external walls (T2 and T3), the roof (T4), and the walls and roof (T5), have the potential to improve the building's resilience in the face of the impacts of global warming in the 2020 scenario.

Considering people's adaptive capacity in the 2050 scenario, the thermostat was set between 23.51 and 30.41 °C. Nevertheless, the thermal demand for cooling in the long permanence rooms of the research typologies increases even more. Following the previous scenario, the Tbase and T1 typologies presented higher values of annual cooling demand (7,170 and 4,531 kWh, respectively, a reduction of 37% in Tbase). Thermal insulation measures applied in the T2, T3, T4, and T5 typologies reduced energy demand. However, its impacts stabilize as the building envelope progressively improves, reaching an average annual thermal load of 2,447 kWh (a reduction of 66% concerning Tbase). This demand is similar to that quantified for Tbase in the current scenario. In this sense, the proposed measures can provide resilience to the building due to the effects of climate change predicted in the 2050 scenario.

In the 2080 scenario, the average external temperature increases by +5.75 °C, drastically influencing the cooling thermal load in the typologies, even elevating the thermal comfort range (24.41 to 31.25 °C). The Tbase and T1 typologies exceed the annual load of 8,000kWh, while in T2, T3, T4, and T5 Typologies, it surpasses 5.000 kWh. The constructive intervention measures cannot bring the annual consumption to the base scenario levels (<2,447 kWh in Tbase). For this reason, despite the improvement provided by the passive constructive strategies adopted for the building envelope, building resilience cannot ultimately be achieved, and other complementary measures must be adopted.

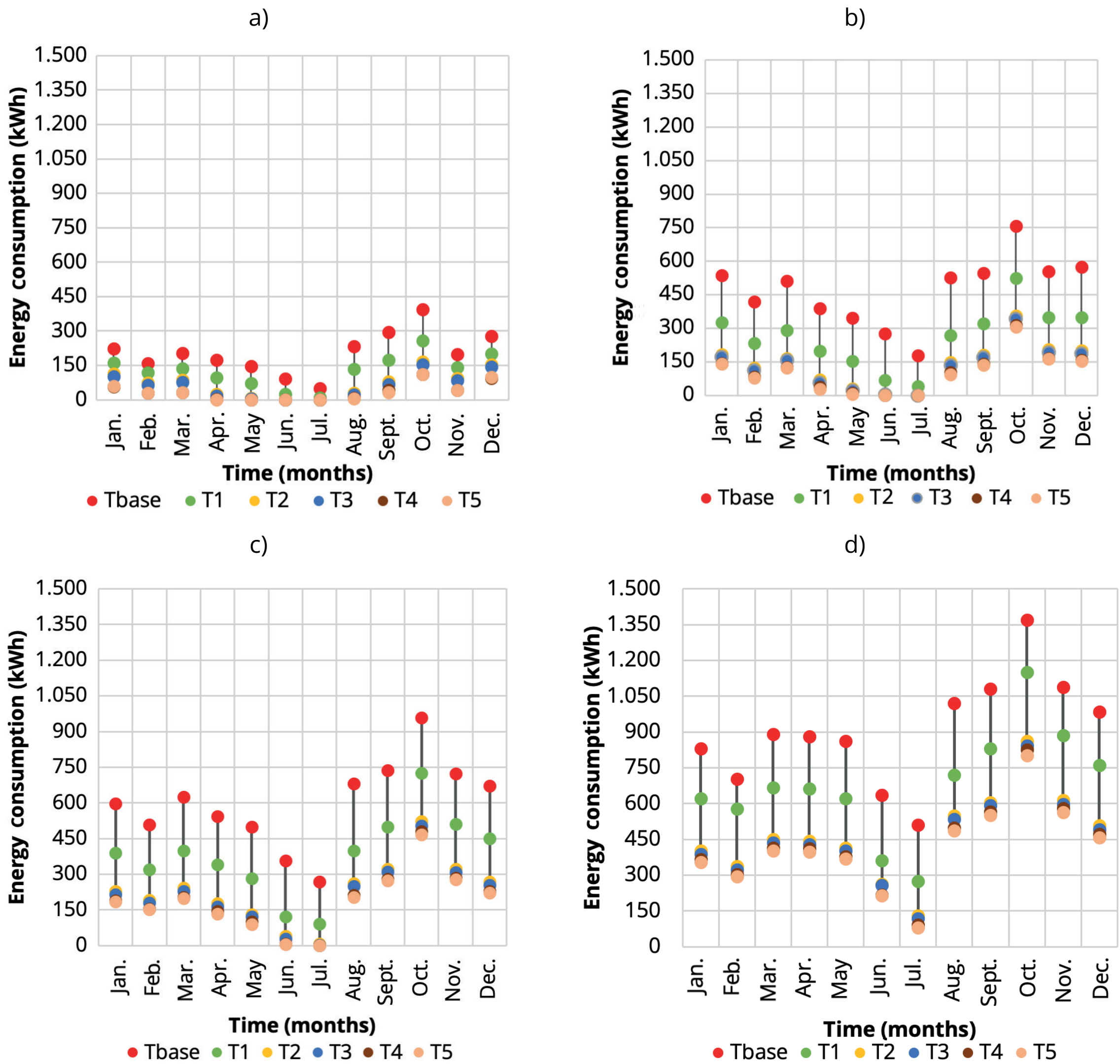


Figure 4: Energy thermal cooling demand in building typologies a) in the base scenario, b) 2020 scenario, c) 2050 scenario, and d) 2080 scenario. Source: Elaborated by the authors.

Typologies Energy Efficiency Classification

The typologies Tbase and T1 had the worst classifications in the base scenario (energy efficiency levels "C" and "B", respectively). As previously described, the low performance is related to the building envelope characteristics, which have low thermal insulation. As thermal insulation is increased in the typologies, with improvements in thermal insulation, first, in the external wall system and, posteriorly, in the roof system, superior energy performance is enhanced from T2 to T5 (Level "A"). From T2 to T5, the energy performance, quantified in cooling degrees-hours (CDH), is similar. The T5 typology obtained the lowest CDH values in the base scenario (10,443 °Ch), a reduction of 13,412 °Ch when compared to the Tbase (Figure 5a).

The global warming predicted for the 2020 scenario impacts the thermal efficiency of the typologies surveyed. Even considering adaptive thermal comfort criteria by raising the thermostat temperature, CDH is increased. Tbase is the most affected typology, reaching the worst performance level foreseen in the Brazilian RTQ-R (Level "E"), followed by the T1 typology (level "D"). In the other typologies, the impact is less expressive, but an average increase of +10,000 °Ch is quantified, degenerating the energy efficiency level from "A" to "C" (Figure 5b).

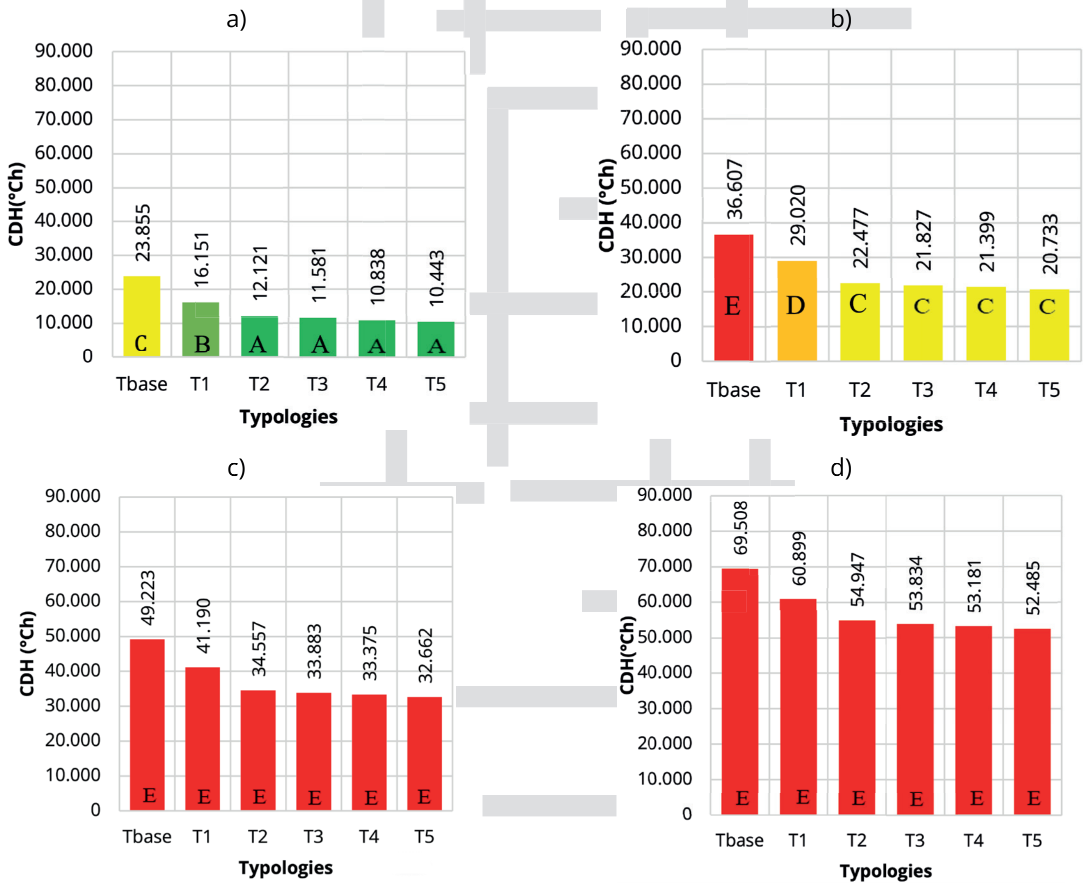


Figure 4: Energy efficiency of the housing envelope: a) base scenario, b) 2020 scenario, c) 2050 scenario, and d) 2080 scenario. Source: Elaborated by the authors.

For the 2050 and 2080 scenarios, the CDH exceeds 32,000 °Ch, driving all typology efficiencies to the worst level of Brazilian RTQ-R (Level "E") (Figure 5c and d). Despite building envelope improvement, the actual building efficiency levels established in the Brazilian RTQ-R are challenging to achieve. Thus, complementary passive measures should be considered for this purpose.

Consolidation of the Constructive Guidelines for Normative Terms and Parameters

Building resilience gradually increases from base (Tbase) to T5 typology in the four scenarios analyzed when considering CHD. This behavior can be linked to the improvement of the building envelope, associated with the elevation of its thermal capacity, as well as the thermal transmittance reduction of external walls and roof systems.

When the thermal transmittance in the roof system is reduced to 0.939 W/m²K in the T1 typology, a decrease of 7,704 °Ch in the CHD was observed compared to Tbase. In turn, when the external walls' thermal transmittance is reduced to 0.770 W/m²K, and the thermal capacity increases to 169.38 kJ/m²K due to the installation of the EPS layer (0.04m) (T2 typology), better thermal insulation in the building is achieved, decreasing 11,734 °Ch in the CHD compared to Tbase, representing a double the reduction compared to T1 in 1960-1990.

The typology T3 has a thermal capacity of 179.11 kJ/m²K and lower CHD values in the scenarios, with an average of 30,281 °Ch, obtaining a reduction of 14,517 °Ch about the Tbase average. It is noteworthy that the thermal transmittance of the external walls decreased slightly (0.7429 W/m²K) about Tbase, justified by the 0.09 m increase in the thickness of the construction system for Tbase.

Typologies T4 and T5 obtained similar CHD values in the scenarios, showing a difference of 1,000 °Ch between the typologies in the four scenarios. The typology T4 has a thermal transmittance of 0.770 (walls) and 0.501 W/m²K (roofs) and the T5 of 0.541 (walls) and 0.501 W/m²K (roofs), with the average of GHR in the scenarios 29,698 and 29,081 °Ch, respectively. The difference obtained by the increase in thermal capacity is justified, being 169.38 in T4 and 180.15 KJ/m²K in T5, characterizing T5 as more resilient to the effects of global warming (Figure 6).

Tbase obtained the worst levels of thermal performance, with maximum internal temperatures of 35.08, 37.23, 38.31, and 41.08 °C in the 1961-1990, 2020, 2050, and 2080 scenarios, respectively.

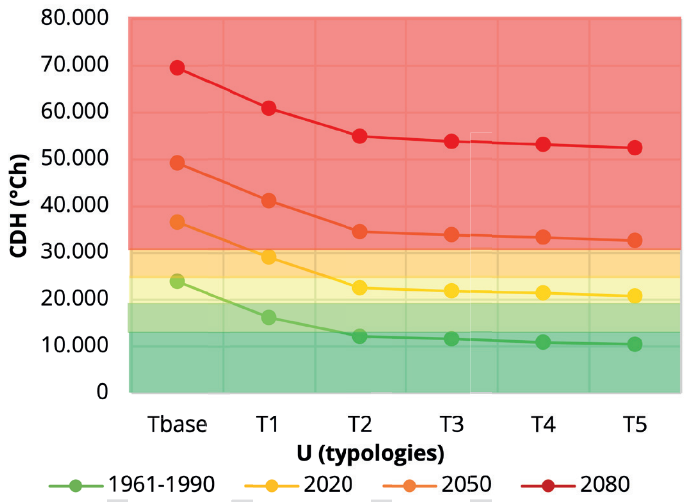


Figure 6: Consolidation of CDH by typology. Source: Elaborated by the authors.

With the increase in the thermal resistance of the vertical and horizontal construction systems, there was a reduction in the maximum internal temperature inside the types, as well as the adaptation between the upper and lower limits, increasing the hours of thermal comfort from T1 to T5. Among the types with interventions, T1 had the highest maximum internal temperature, 32.68, 34.84, 36.15, and 38.96 °C in the 1961-1990, 2020, 2050, and 2080 scenarios, respectively. The internal temperature difference between T1 and Tbase was 2.12 °C in the 2080 scenario.

Typologies T2 to T5 achieved an average increase in the maximum internal temperature of 2.25, 3.78, and 6.55°C in 2020, 2050, and 2080 scenarios, respectively. With the insertion of thermal insulation in the external walls, T2 and T3 showed similar behavior. The external walls' thermal transmittance and thermal capacity are 0.77 and 0.7429 W/m²K and 169.38 and 179.11 KJ/m²K, respectively. In this way, both types obtained an average annual maximum internal temperature of 30.81, 33.08, 34.64, and 37.40 °C in the Base and 2020, 2050, and 2080 scenarios, which represent values higher than the upper limit of thermal comfort by 5%, 10%, 12%, and 18%, respectively.

With the insertion of ceiling tiles in T4 and T5, there was a reduction in thermal transmittance and an increase in the thermal capacity of the roof to 0.50 and 159.42 KJ/m²K, respectively, with the lowest average values of maximum internal temperature of 30.68, 32.97, 34.57, and 37.34 °C in the Base, 2020, 2050, and 2080 scenarios, respectively.

In the Base Scenario, typologies T4 and T5 obtained internal temperatures above the upper limit of comfort at +1.48 °C and +1.36 °C, respectively, increasing the maximum internal temperature to 6.58°C above the upper limit comfort in both types in the 2080 scenario, requiring active strategies to achieve thermal comfort (Figure 7).

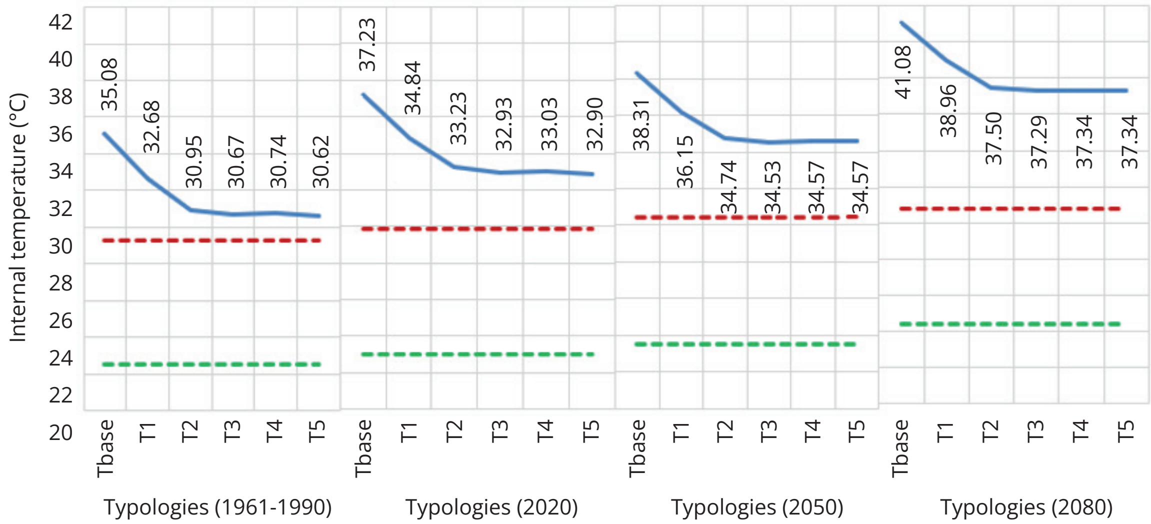


Figure 7: Consolidation of maximum internal temperature and upper and lower limits by typology. Source: Elaborated by the authors.

It was observed that the typologies that presented thermal transmittance of the external walls above 0.770 and the roofs above 0.946 W/m²K obtained worse classifications of energy efficiency of the envelope and conditions of thermal comfort. With the increase in the thermal capacity of the external walls to 180.15 and the coverage to 159.42 kJ/m²K, the T5 typology obtained a better thermoenergetic performance and a more significant number of hours of thermal comfort inside. Notably, the increase in the thickness of the external walls from 0.14 m in Tbase to 0.02 m in T5 directly influenced the improvement in thermal comfort conditions.

Conclusions

The findings demonstrated that users' thermal comfort and building thermoenergetic performance would be aggravated by the global warming predicted for the region. Given the future scenarios studied, studies in the building design phase are essential to make buildings resilient and adapt to climate change.

It was also verified that the comfort conditions, the energy consumption for cooling, the energy efficiency, and the thermal performance of the houses currently built on a large scale in the country are already influenced by the high temperatures of the region today, presenting low thermal envelope quality. Incorporating the effects of global warming, current conditions are even more compromised, contributing negatively to thermal comfort conditions and, consequently, to habitability.

Deficiency in the thermal performance analysis criteria established by current Brazilian standards and regulations was observed, which allows buildings with internal temperatures above 36.0°C. Adequacy of the thermal performance classification of current standards and regulations and regular updates are of fundamental importance to obtain adequate considerations in habitability in the face of future climate projections.

The intervention proposals for the Tbase building envelope have improved its thermoenergetic performance and building thermal comfort conditions. The typologies that presented wall and roof system thermal higher than 0.770 W/m²K and 0.946 W/m²K, respectively, were those that obtained worse building energy efficiency ratings and internal thermal comfort conditions, with worse levels of adaptability in future climatic scenarios. Based on the findings, it is possible to conclude that the proposed measures of adaptation by the use of passive constructive interventions become an essential key to achieve building the highest level of energy efficiency classifications for the climatic conditions that will prevail in the future in the savannah region; however, with the significant increase predicted for the outdoors temperatures, the use of active cooling interventions will be essential to provide adequate thermal comfort conditions in the savannah climate.

Future work is recommended to analyze the costs arising from implementing constructive adjustments since the national housing policy imposes limits on financial resources for Brazilian social dwellings.

References

ABNT NBR 15575-4. ABNT NBR 15575-4:2013 – Edificações habitacionais – Desempenho Parte 4 : Sistemas de vedações verticais internas e externas Associação Brasileira de Normas Técnicas.

ABNT. ABNT NBR 15220-1 Desempenho térmico de edificações Parte 1: Definições, símbolos e unidades. Associação Brasileira de Normas Técnicas, p. 1-66, 2003.

AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS (ASHRAE). *ASHRAE Standard 55*: thermal environmental conditions for human occupancy. Atlanta: ASHRAE, 2021.

BRASIL. Ministério do Planejamento, Orçamento e Gestão. 6° Balanço do Programa de Aceleração do Crescimento (PAC) 2015-2018. Brasília: MP, 2020. Disponível em: http://pac.gov.br/pub/up/relatorio/11fbe9b2f7cbecb3ec5c1f9f67b5f3be.pdf. Acesso em: 15 maio 2021.

DEAR, R. J.; BRAGER, G. S. Developing an adaptive model of thermal comfort and preference. *ASHRAE Transactions*, v. 104, n. Pt 1A, p. 145-167, 1998.

DEPARTMENT OF ENERGY, DOE. EnergyPlus. Disponível em: https://energyplus.net. Acesso em: 16 maio. 2020.

FUNDAÇÃO JOÃO PINHEIRO (FJP). Estatística e Informações: demografia e indicadores sociais – Déficit Habitacional no Brasil 2015 (Diretoria de Estatística e Informações (DIREI), Ed.) Belo Horizonte Fundação João Pinheiro, 2021.

GUARDA, E. L. A. *Resiliência de habitação de interesse social unifamiliar em região de savanna frente às mudanças climáticas*. Dissertação (Mestrado em Engenharia de Edificações e Ambiental) – Universidade Federal de Mato Grosso, Cuiabá, 2019.

GUARDA, E. L. A., *et al*. The influence of climate change on renewable energy systems designed to achieve zero energy buildings in the present: A case study in the Brazilian Savannah. *Sustainable Cities and Society*, v. 52, p. 1-9, February 2019, 2020.

INSTITUTO NACIONAL DE METEOROLOGIA (INMET). Banco de dados 2018 e 2019. Disponível em: https://bdmep.inmet.gov.br/. Acesso em: 27 abr. 2023.

INSTITUTO NACIONAL DE METEOROLOGIA (INMET). Banco de dados 2020. Disponível em: https://bdmep.inmet.gov.br/. Acesso em: 27 abr. 2023.

INSTITUTO NACIONAL DE METEOROLOGIA (INMET). Normais Climatologias 1931-1960. Disponível em: https://clima.inmet.gov.br/NormaisClimatologicas/1961-1990/precipitacao_acumulada_mensal_anual. Acesso em: 27 abr. 2023.

INSTITUTO NACIONAL DE METROLOGIA QUALIDADE E TECNOLOGIA (INMETRO). Requisitos técnicos da qualidade para nivel de eficiencia energética de edificios residenciais. 2012.

INSTITUTO NACIONAL DE METROLOGIA QUALIDADE E TECNOLOGIA, I. Requisitos técnicos da qualidade para nivel de eficiencia energética de edificios residenciais. 2012.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC). Climate Change Synthesis Report: contribution of working groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Core Writing Team; Pachauri, R. K.; Reisinger, A. (ed.)]. Geneva, IPCC, 2007. p. 104.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC). Climate Change 2014: Synthesis Report Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In: Core Writing Team, Pachauri RK, Meyer LA (eds) IPCC, Geneva, Switzerland, 151 p., 2014.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC). Climate Change Synthesis Report Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In: Core Writing Team, Pachauri RK, Meyer LA (eds) IPCC, Geneva, Switzerland, 151 p. 2007.

MARENGO, J. A.; SOARES, W. R. *Impacto das Mudanças Climáticas no Brasil e Possíveis Futuros Cenários Climáticos*: Síntese do Terceiro Relatório do IPCC 2001. Clima e Recursos Hídricos, p. 209-233, 2003.

NOAA, National Centers for Environmental Information. Global Temperature Trends, Updated through 2020 | Annual 2020 Global Climate Report. [S. l.], 2021. Disponível em: https://www.ncei.noaa.gov/access/monitoring/monthly-report/global/202013. Acesso em: 12 jul. 2022.

PEDERSEN, C. O.; FISHER, D. E.; LIESEN, R. J. Development of a heat balance procedure for calculating cooling loads. *ASHRAE Transactions*, v. 103, n. pt 2, p. 459-468, 1997.

PEEL, M. C.; FINLAYSON, B. L;. MCMAHON T. A. Updated world map of the Köppen-Geiger climate classification. Hydrology and Earth System Sciences Discussions, European Geosciences Union, v. 11, p.1633-1644, 2007.

RANA, I. A. A localized index-based approach to assess heatwave vulnerability and climate change adaptation strategies: A case study of formal and informal settlements of Lahore, Pakistan. *Environmental Impact Assessment Review*, v. 96, p. 106820, 2022. DOI: https://doi.org/10.1016/j.eiar.2022.106820

RIOS, G. A. A. *Desempenho termoenergético de habitação de interesse social*. 2015. Tese (Doutorado em Engenharia Elétrica) – Universidade Estadual Paulista, Ilha Solteira, 2015.

ROAF, S.; FUENTES, M.; THOMAS-REES, S. Ecohouse: A casa ambientalmente sustentável. Bookmann: Porto Alegre, 2014.

SÁNCHEZ-GARCÍA, D. *et al*. Adaptive comfort models applied to existing Dwellings in Mediterranean climate considering global warming. *Sustainability (Switzerland)*, v. 10, n. 10, 2018.

TRIANA, M. A. Abordagem integrada no ciclo de vida de habitação de interesse social considerando mudanças climáticas. Tese (Doutorado em Engenharia Civil) – Universidade Federal de Santa Catarina, Florianópolis, 2016.

WANG, S. Applicability of passive design strategies in China promoted under global warming in past half century. Building and Environment, v. 195, p. 107777, 2021. https://doi.org/10.1016/j.buildenv.2021.107777