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Thermal comfort and air renewal in social housing: a case study in Uberlândia, Brazil

Conforto térmico e renovação de ar em habitação de interesse social: estudo de caso em Uberlândia, Brasil

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ABSTRACT: The COVID-19 pandemic has highlighted aspects that require greater attention in residential buildings, especially in social housing developments. For example, thermal comfort and air renewal, play an important role in the environmental quality of housing and control of spreading pathogens, including coronavirus. The challenge is adequately providing these attributes in Brazilian social housing (SH) as naturally ventilated buildings where predominantly low-income families live. Considering it, a study was developed using computational simulation to evaluate the interaction between the indicators of thermal comfort (using the adaptive model) and air renewal (in air changes per hour - ACH) in a horizontal semi-detached typology of social housing provided by the Brazilian government program Minha Casa, Minha Vida, located in Uberlândia city, Minas Gerais state, Brazil. Ventilated roofs, variable window opening patterns, effective ventilation areas, and horizontal window shadings were the behavioral and physical interventions suggested to comparative analyses according to their performance to the indicators. The paper aims to present and discuss the main results obtained in terms of positive trends for the analyzed indicators' performance and for the typology and location studied, seeking the achievement of better ventilated and thermally comfortable habitats. Additionally, a brief study on the most appropriate adaptive thermal comfort model for studies in the city of Uberlândia is presented, contributing to the future performance of more accurate thermal comfort analyses in SH, aiming at more assertive and resilient provision of guidances for renovations.

Keywords: Social developments, Adaptive thermal comfort models, Air changes, Ventilation, Computational simulation.

RESUMO: A pandemia de COVID-19 evidenciou aspectos que exigem maior atenção em edifícios residenciais, especialmente em conjuntos habitacionais de interesse social. Por exemplo, o conforto térmico e a renovação do ar desempenham um papel importante na qualidade ambiental das moradias e no controle da propagação de patógenos, incluindo o coronavírus. O desafio é fornecer adequadamente esses atributos em habitações de interesse social (HIS) brasileiras, que são edifícios com ventilação predominantemente natural onde vivem famílias de baixa renda. Levando isso em consideração, um estudo foi desenvolvido utilizando simulação computacional para avaliar a interação entre os indicadores de conforto térmico (usando o modelo adaptativo) e renovação do ar (em trocas de ar por hora - ACH) em uma tipologia horizontal de habitação social geminada, fornecida pelo programa governamental brasileiro Minha Casa, Minha Vida, localizado na cidade de Uberlândia (MG), Brasil. Telhados ventilados, padrões variáveis de abertura de janelas, áreas efetivas de ventilação e sombreamento horizontal de janelas foram as intervenções comportamentais e físicas sugeridas para análises comparativas de acordo com seu desempenho para os indicadores. O artigo tem como objetivo apresentar e discutir os principais resultados obtidos em termos de tendências positivas para o desempenho dos indicadores analisados e para a tipologia e localização estudadas, buscando a criação de habitats mais bem ventilados e termicamente confortáveis. Além disso, um breve estudo sobre o modelo adaptativo de conforto térmico mais adequado para estudos na cidade de Uberlândia é apresentado, contribuindo para o futuro desenvolvimento de análises de conforto térmico mais precisas em HIS, visando a orientação mais assertiva e resiliente de reformas.
Palavras Chave: Habitação Social, Modelos de Conforto Térmico Adaptativo, Trocas de Ar, Ventilação, Simulação Computacional.

1. INTRODUCTION

The COVID-19 pandemic has highlighted the mandatory attributes of the residential built environment that ensure the well-being and health of its occupants. The dilution of contaminants provided by an adequate air renewal and the guarantee of thermal comfort in the performance of habitual and new activities (quarantines, work, study, leisure, physical activity, and others) were some of these attributes that gained relevance with the increase of hours at home (NAVARATNAM et al., 2022; NAVAS-MARTÍN, OTEIZA and CUERDO-VILCHES, 2022; MUIANGA et al., 2021; VOORDT, 2021). Those are considered especially relevant in the context of Brazilian social housing (SH), where a significant portion of vulnerable people live (VILLA et al., 2022a).

The measures of social isolation imposed by the pandemic expanded the role of the entire house as a long-occupancy environment. This intensified pre-existing conflicts with people who live in the same house and neighbors due to the unpreparedness of houses to face new demands of the moment. Risks of transmission of airborne diseases occur especially in indoor environments in several situations, including residences, especially those overcrowded (NISHIURA et al., 2020). There are strategies to improve air quality, such as the use of air conditioners, capable of filtering and returning the air to proper conditions for breathing (MORAWSKA et al., 2020). This measure represents higher operating costs with electricity, which makes it less inviting for low-income contexts, such as social housing in Brazil, increasing the interest in passive thermal conditioning and ventilation alternatives.

In this sense, some studies have demonstrated the central role of building designs that favors opportunities for environmental control and adaptation (TORRIANI et al., 2023) aligned with current requirements of thermal comfort and healthiness.

Cheshmehzang (2021) analyzed inequity in perceived thermal comfort in 10 different residential typologies in the United Kingdom. He found that the most compact ones, with fewer openings (considered as windows and doors) and no access to common balconies or gardens, usually destined for low income, had the lowest satisfaction votes in general, especially regarding the indicators of privacy, lighting, and airflow. Thapa et al. (2020), in turn, observed that during the pandemic the Indians dissatisfaction with the temperature of their homes accentuated proportionally to the increased number of days of confinement, choosing to keep windows closed during the day to avoid heat gains by convection and to make earlier use of the ventilator, compared to a pre-pandemic study - which favored a reduction in air renewal and an increase in energy bills.

In a study involving field measurements and computational simulation of a student residence in Egypt, Elshafei et al. (2017) found that the built environment does not provide thermal comfort conditions at any time of the year, whether with closed or opened windows. Proposed variations in positioning and dimensions of the effective ventilation area, using computer simulation, increased air speed, and thermal comfort considerably.

Malta, Rabbi, and Nico-Rodrigues (2022) studied the potential of the roofing system and percentages of effective ventilation areas on improving the thermal comfort and air velocity in Brazilian social housing located in the Bioclimatic Zone 8. The strategies considered the recommendations established by the Standard NBR 15.220 (ABNT, 2003) and the Standard NBR 15.575 (ABNT, 2021). The better results combined for roofs were thermoacoustic tiles of 30 mm with PVC lining, ventilated attic, windows with two vertical slats, and effective ventilation area of 20%.

SH offered by the Brazilian program Minha Casa, Minha Vida (MCMV) has especially failed in terms of an adaptation to the climate. Recent research has shown that plans and constructive specifications are repeated in different Brazilian climatic regions, often causing thermal discomfort and resource expenditure in the search for comfort during the use and operation phase (VILLA et al., 2022a; BORTOLI, 2018; VASQUEZ, 2017; BRASILEIRO, MORGADO and LUZ, 2017; TRIANA, LAMBERTS and SASSI, 2017; AMORE, SHIMBO and RUFINO, 2015).

In SH, after a few years of occupancy and use, self-construction without technical guidance is a recurrent practice (VILLA et al., 2017). The inflexibility of the architectural designs is associated with the constructive rigidity characterized by the use of load-bearing masonry (VILLA et al., 2022b). This limitation results in the obstruction of windows when performing expansions and, therefore, the creation of hot rooms that are poorly ventilated and illuminated, representing health risks for their residents (SIMÕES, LEDER and LABAKI, 2021).

Considering this scenario, Triana, Lamberts, and Sassi (2017) put in perspective the long life-cycle of buildings and the need to prepare them for changes expected in the face of future climatic and environmental challenges. This is an issue especially discussed by the authors in the context of Brazilian social housings' current design. Loche, Fonseca, and Carlo (2018), in turn, assumed it as a fact given the tendency of self-construction and complete occupancy of urban lots with enlargements. They highlighted the importance of recognizing and considering passive constructive techniques of the local population to contribute to the expansion of thermal comfort and the reduction of energy consumption (ROAF and NICOL, 2017).

With that in mind, for this work, a theoretical study was carried out on the influence of physical suggested interventions (ventilated roofs, variable effective ventilation areas and horizontal window shadings) and behavioral suggested changes (variable window opening patterns) on thermal comfort and air renewal in a horizontal social housing (SH) typology as delivered by the governmental program Minha Casa, Minha Vida (MCMV) in the city of Uberlândia, Minas Gerais state, Brazil. The study was based on computational simulations using the EnergyPlus software package, 8.7 version.

The adaptive models of thermal comfort established by Standard 55 (ASHRAE, 2014) and De Dear, Kim, and Parkinson (2017) and the Standard 62.2 on ventilation and acceptable air quality in residential buildings (ASHRAE, 2016) were the normative parameters adopted for the study.

The main purpose was to measure the impact of suggested physical and behavioral interventions on thermal comfort and air renewal indicators through a computational model with standardized configurations. The procedure allowed comparisons among the potential of each proposed intervention on envelope and building use. Performance trends were thus observed in the case study.

The investigation was developed based on the following key questions:

KQ 1) Which is the most appropriate adaptive model for analyzing thermal comfort in the city of Uberlândia (Minas Gerais state): Standard 55 (ASHRAE, 2014) or De Dear, Kim and Parkinson (2017).

KQ 2) How do physical interventions (namely ventilated roof, horizontal window shading and effective ventilation areas) and behavioral interventions (variable window opening patterns) influence the renewal of air and the thermal comfort in a standardized horizontal social housing typology in Uberlândia city? and

KQ 3) Which interventions result in better trends for the indicators analyzed in the specific context of social housing in Uberlândia city?

Thus, this article aims to present and discuss the trends of performance resultant from different interventions on thermal comfort and air renewal rates. Additionally, a brief study on the most appropriate adaptive thermal comfort model for studies in the city of Uberlândia is presented. These are conclusions that can be applied to the context of new SH projects and, especially, to the orientation of renovations in existing ones. The intention is to contribute to the future performance of more accurate thermal comfort analyzes in SH, as well as to the promotion of well-being and resilience in the habitats of most vulnerable audiences, regardless of whether there is a pandemic context or not.

2. NORMATIVE REFERENCES

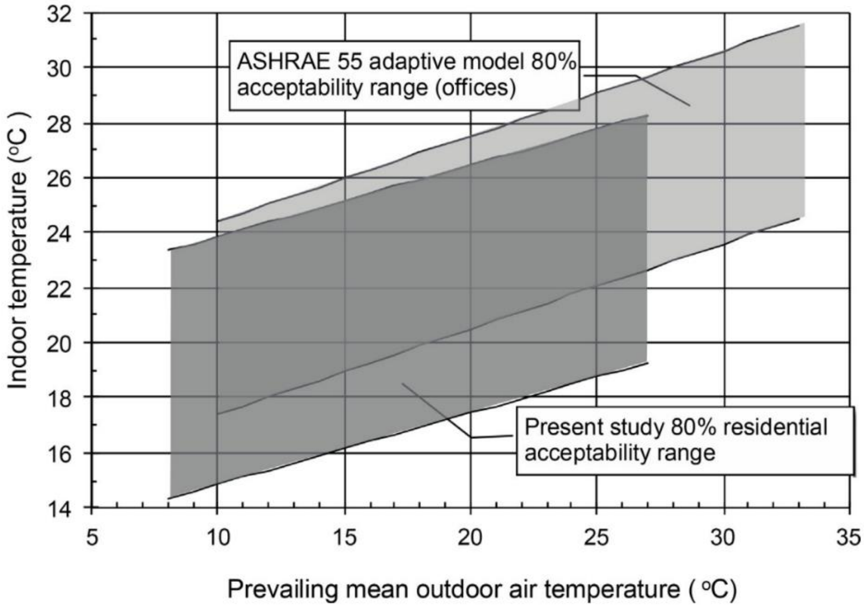
Different models and analysis methods are applied to understand the sensation, perception, satisfaction, and/or thermal preference of occupants of different categories of buildings (TORRIANI et al., 2023; SHAHZAD, 2018). The so-called adaptive model has been widely used as an indicator of thermal comfort. It is based on the idea that people can achieve thermal comfort within a longer range of internal temperatures around a neutral temperature, a range that varies according to external temperatures (ASHRAE, 2014; DE DEAR, BRAGER and COOPER, 1997).

The premise is that humans have physiological, psychological, and behavioral strategies to adapt to the thermal environment. Changes in clothing and positioning in the environment, the control of windows or doors and air conditioning devices, and the adjustment of thermal expectations are some examples of adaptive opportunities (SOUSA and LEDER, 2019; DE DEAR, BRAGER and COOPER, 1997). Hybrid or naturally ventilated environments, such as SH, are more consistently evaluated from an adaptive approach. As advantages of this approach, the following can be cited: the potential for optimizing energy consumption and increasing user satisfaction with the thermal environment. According to De Dear et al. (2013), the interaction of the occupant with the building interferes simultaneously in the satisfaction with the thermal environment and in the final thermal performance of the building. For them, “the greatest threat to user satisfaction occurs when a building and its subsystems are too complicated, difficult to understand or not responsive to adaptive behaviors of its occupants”.

The Standard 55 (ASHRAE, 2014) is the main reference for determining comfort assessment procedures through the adaptive model and is widely used in any building categories. A more recent study by De Dear, Kim, and Parkinson (2017) discussed the applicability of the adaptive model defined by Standard 55 (ASHRAE, 2014) for residential buildings. The recommendations in this Standard were drawn based on field surveys conducted in various regions globally, but with office buildings as the object of study, where behavior and clothing codes tend to be more restrictive. According to the authors, the flexibility and adaptive opportunities at home are greater, allowing for adjustments of clothing, metabolism, environmental settings, among other strategies.

Based on this assumption, it is natural to consider that the ranges of acceptability in residential buildings are wider when compared to office buildings. De Dear, Kim, and Parkinson (2017) developed 2-year field studies in 42 homes in Australia's hot and humid climate that underpinned the development of a strictly residential adaptive model, in which the acceptability range is wider when compared to office buildings. It was also observed that this range shifted to a cooler region, with neutrality being achieved at lower ambient temperatures, relative to the office model, as illustrated in Figure 1 and equations 1 and 2 (ASHRAE, 2014) and 3 and 4 (DE DEAR, KIM and PARKINSON, 2017). Any occurrences of temperatures above or below the limits set by both models indicate the hours in discomfort due to heat (in summer) and cold (in winter), respectively.

Figure 1 - Office vs. Residential Adaptive Model.



Source: De Dear, Kim and Parkinson (2017).

$$Upper\ limit\ for\ 80\%\ acceptability\ (°C) = 0.31 \times T_{pma\ (out)} + 21.3 \text{ (Eq. 1)}$$
$$Lower\ limit\ for\ 80\%\ acceptability\ (°C) = 0.31 \times T_{pma\ (out)} + 14.3 \text{ (Eq. 2)}$$

$$Upper\ limit\ for\ 80\%\ acceptability\ (°C) = 0.26 \times T_{pma\ (out)} + 21.25 \text{ (Eq. 3)}$$
$$Lower\ limit\ for\ 80\%\ acceptability\ (°C) = 0.26 \times T_{pma\ (out)} + 12.25 \text{ (Eq. 4)}$$

In which,

$T_{pma\ (out)}$ refers to the prevailing external air temperature in the last 7 to 30 days.

The adaptive model of De Dear, Kim, and Parkinson (2017) considered in its elaboration the pattern of air conditioners activation in all rooms of the houses studied throughout the day as well as air temperatures measured by sensors. The air temperatures at the time of air-conditioning activation/shutdown were considered as limits of acceptability for heat and cold. Using this criterion, the De Dear, Kim, and Parkinson (2017) model analyzed the behavior and preferences of people at home over 2 years for all hours of the day for any metabolic levels and values of clothing insulations.

In contrast, Standard 55 (ASHRAE, 2014) considers metabolic rates, dress conditions, and thermal preferences compatible with office building activities to propose a temperature range limit of thermal comfort. While Standard 55 (ASHRAE, 2014) comprises greater climate variability, but a very restricted use class, the De Dear, Kim, and Parkinson (2017) model comprises only the reality of domestic environments for a specifically hot and humid climate and considers the culture and preferences of Australian subjects. With this, one model differs essentially from the other, determining different situations for its applicability.

The Brazilian standard for evaluating the thermal performance of residential buildings, NBR 15.575, in its revised version (ABNT, 2021), has as one of its evaluation criteria the percentage of hours in which the internal temperature is within an operative range from the analysis of degrees-hours of cooling and heating, which indicate the demand for correction of the thermal environment in the face of heat and cold. The upper and lower limits are defined according to the annual mean external temperature at the analyzed locality. Thought for the Brazilian context, even for the analysis of thermal performance and not thermal comfort, NBR 15.575 (ABNT, 2021) standard provides possible parameters for comparing results obtained through the adaptive thermal comfort models here presented. After all, according to Krelling et al. (2020), the lower and upper limits for evaluating thermal performance demonstrated coincidences with perceptions of thermal comfort raised by the field work of De Dear, Kim and Parkinson (2017), allowing to discuss these concepts together.

Despite many building codes limit minimum opening areas for ventilation in the residential sector, there are no current Brazilian regulations on air renewal for naturally ventilated residential environments. The parameters established by Standard 62.2 (ASHRAE, 2016) are often used, which defines the functions and minimum requirements for mechanical and natural ventilation systems, and the envelope characteristics intended to provide acceptable indoor air quality in residential buildings (WALKER et al., 2021; NG et al., 2019; CLARK et al., 2019). This Standard edition is previous to the pandemic period and has not yet been updated, offering a parameter on minimum acceptable air quality conditions in a residential environment. On its fourth item - *Dwelling-Unit Ventilation*, sub-item 4.1.1 - *Total Ventilation Rate*, the Standard requires a total ventilation rate (Q_{tot}) given by Equation 5.

$$Q_{tot} = 0.15\ x\ A_{floor} + 3.5\ (N_{br} + 1) \quad \text{(Eq.5)}$$

In which,

Q_{tot} refers to the total ventilation rate required in L/s;
A_{floor} refers to the floor area of the housing unit in m²;
N_{br} refers to the number of bedrooms in the house (not less than 1).

This equation considers two individuals for each bedroom and 1 for each additional bedroom. When a higher occupant density is known, the rate found should be increased by 3.5 L/s for each additional person. The air flow entering the environments, Q_{tot}, is often called in research and performance analyses in terms of air changes per hour (ACH, given in m³/h). The ACH expresses the ratio between the volume of air added or removed from a space in an hour and the volume of the space. To use the ventilation rate provided by Standard 62.2 (ASHRAE, 2016), it is necessary to convert the value Q_{tot} for each zone, according to Equation 6:

$$ACH_{zone} = 3.6 \times Q_{tot} \div Vol_{zona} \quad \text{(Eq. 6)}$$

In which:

$ACH_{zone} =$ air exchanges per hour required for the thermal zone, ACH
$Q_{tot} =$ total ventilation rate required for housing, L/s
$Vol_{zone} =$ Thermal zone volume, m³
3.6 = constant expressing conversion of l/s into m³/h

With the value of ACH_{zone}, it is possible to evaluate the rate of ventilation and air renewal in each thermal zone evaluated (room and bedrooms, for example). ACH is an indicator of indoor air quality that has gained relevance in the context of a pandemic caused by viruses whose main route of transmission is respiratory. The air renewal in an environment occurs through the openings (windows and doors) and their cracks, and the larger the effective area of an opening and its infiltration coefficients, the greater the potential for air renewal of an environment – which can be undesirable in cold weather conditions, favoring situations of conflict between natural air renewal and thermal comfort, for example. In this study, ACH is used as an indicator of air renewal.

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3. MATERIALS AND METHODS

The investigation is based on a computational simulation of an MCMV's SH horizontal typology, comprising a semi-detached plan existing in the city of Uberlândia (Minas Gerais state, Brazil) – delivered between 2010 and 2011. The houses are located at Shopping Park neighborhood, which comprises 3600 housing units of the MCMV (Figures 2a and 2b), benefiting homeowners with family incomes between 0 and 3 minimum wages[1]. Autonomous housing units are connected from their bedrooms wall, as can be seen in Figure 2c. The 3D geometry was modeled using the graphical interface of Sketchup Make 2017 software and Euclid 9.3 extension for communication with the EnergyPlus simulation engine, version 8.7. This software allows the determination of the thermal behavior of buildings under dynamic conditions of exposure to the weather, being able to reproduce the effects of thermal inertia, as well as natural ventilation through the AirFlowNetwork module built into the program, being validated by ASHRAE Standard 140.

The eaves were modeled for shading purposes, and the surrounding environment was not taken into account in this simulation, as depicted in Figure 2d. The patterns of occupancy, lighting, and equipment, as well as ventilation/infiltration parameters were based on the prescriptions of NBR 15.575 (ABNT, 2021), while the thermal properties of materials were obtained from Weber *et al.*, 2017 and NBR 15.220 (ABNT, 2005). Tables 1 to 6 summarize the key information used to set up the base case model (standardized) and the proposed alternatives.

According to NBR 15.575, these values consider an amount of two occupants per bedroom. Thus, the maximum of four occupants is set for the living room. All windows and external doors of the rooms and kitchens were configured with simple 3 mm thick glasses, solar transmittance of 0,837, and solar reflectance of 0,075 (ABNT, 2021). Aluminum slats were set up for the bedroom windows and the kitchen's external door, along with 5 cm thick frames in the bathroom and kitchen windows and on the outside door of the living room.

Table 7 describes the configuration of the base case (BC) and six generated alternatives. All models were simulated considering the main façade the one with the living rooms (Figure 2C), sun oriented as they exist in the SH development: to North, South, East, and West. The average values of the analyzed indicators (thermal comfort and ACH) allowed the identification of the best/worst performance of the alternatives.

The simulation was carried using the weather file from Climate.OneBuilding.Org: BRA_MG_Uberlandia.867760_INMET, which contains hourly information of the test reference year (TRY) for the variables: dry bulb temperature, dew temperature, relative humidity, atmospheric pressure, radiation, illuminance, wind direction and speed, among others.

[1] The minimum wage when the development was delivered (2010/2011) was R$510,00.

Figure 2 – Shopping Park neighborhood and its semi-detached houses.

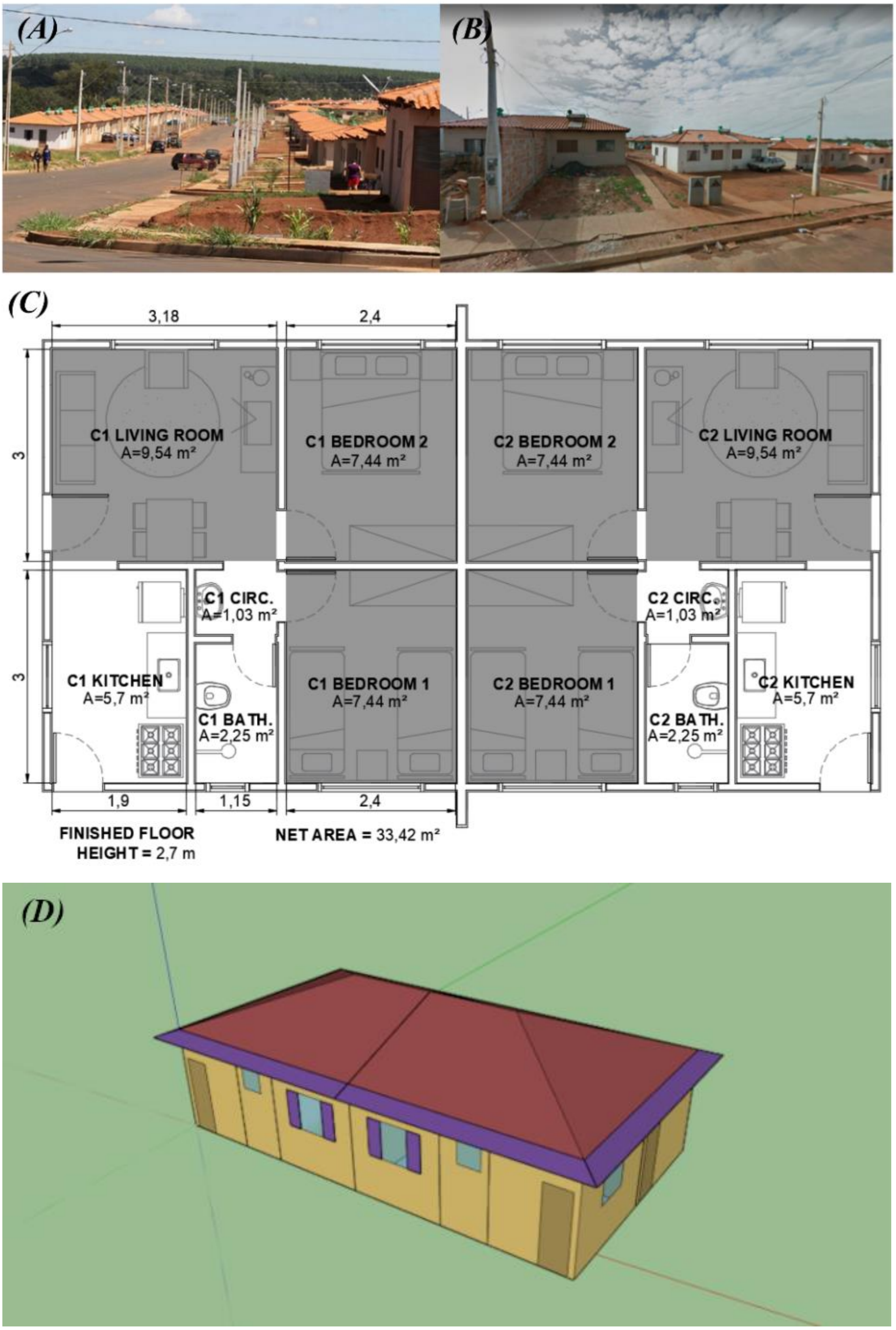

Table 1 - Period of use and heat generation for long occupation rooms (LOR).

Room	**Periods of use/occupation**	**Activity performed**	**Heat produced by body surface area (W/m²)**	**Heat produced by a person with 1,8 m² of body surface area (W)**	**Radiant fraction**
Bedroom	00:00 - 7:59 and 22:00 - 23:59	Sleeping or resting	45	81	0,30
Living room	14:00 – 21:59	Sitting or watching TV	60	108	0,30

Source: NBR 15.575 (ABNT, 2021).

Table 2 – Natural ventilation parameters.

Parameters	**Doors**	**Windows**
Airflow coefficient through cracks when the opening is closed (kg/(s.m))	0,0024	0,00063
Airflow exponent through cracks when the opening is closed (dimensionless)	0,59	0,63
Discharge coefficient of the opening (dimensionless)	0,60	0,60

Source: NBR 15.575 (ABNT, 2021).

Table 3 - Occupancy and lighting routines for weekdays and weekends.

	Bedroom (%)	**Living room (%)**
Occupation	100% - 22:00 - 7:59	50% - 14:00 - 17:59 100% - 18:00 - 21:59
Lighting	100% - 6:00 - 07:59 and 22:00 - 23:59	100% - 16:00 - 21:59

Source: NBR 15.575 (ABNT, 2021).

Table 4 - Installed power density, radiant fraction and visible fraction for lighting system at long occupation rooms (LOR).

Room	**Installed power density (W/m²)**	**Radiant fraction**	**Visible fraction**
Bedroom	5,00	0,32	0,23
Living room	5,00	0,32	0,23

Source: NBR 15.575 (ABNT, 2021).

Table 5 - Period of use, density of internal loads and radiant fraction of long occupation rooms (LOR) equipments

Room	**Periods of use**	**Power (W)**	**Radiant fraction**
Bedroom	14:00 – 21:59	120	0,30
Living room	14:00 – 21:59	120	0,30

Source: NBR 15.575 (ABNT, 2021).

Table 6 - Thermal properties of the materials used in the simulation.

Material	**Thickness (m)**	**Conductivity - λ [W/m.K]**	**Density - ρ [kg/m3]**	**Specific Heat - c [J/kg. K]**
Brick 9x19x19 + 0,18 m² air chamber. K/W	0,013	0,9	1600	920
Brick 12x19x19 + 0,8 m² air chamber. K/W	0,013	0,9	1600	920
External mortar absorptance 0,29	0,0175	1,15	2000	1000
External mortar absorptance 0,11	0,0175	1,15	2000	1000
Internal mortar absorptance 0,11	0,0125	1,15	2000	1000
Mortar of shared wall (between bedrooms)	0,0175	1,15	2000	1000
PVC lining	0,01	0,071	273	960
Ceramic tile	0,01	1,05	2000	920
Tile floor	0,0075	1,05	2000	920
Subfloor	0,07	1,75	2200	1000
Wood door	0,03	0,15	650	2300

Source: NBR 15.220 (ABNT, 2003) and Weber *et al.* (2017).

Table 7 - Base case and alternative models' settings.

Model Identification	Description
Base Case	- Windows' opening conditioned to occupation, internal operative temperature (open when higher than 19ºC) and when internal temperature is higher than the external - Maximum width factor of all windows = 45% - All windows either completely closed or completely opened (0 and 1)
Alternative 1 - BC + AlwaysOnLOR	- Same as the base case settings, except: - Long occupation rooms windows' opening in 100% of the hours of the year, regardless of external or internal temperatures and occupancy.
Alternative 2 - BC + VentRoof	- Same as the base case settings + ventilated roof (with 46% of the side walls area that support the roof always open)
Alternative 3 - BC + VentRoof_AlwaysOnLroom	- Same settings as the Alt. 2 + windows of living rooms open in 100% of the hours of the year, regardless of external or internal temperatures and occupancy.
Alternative 4 - BC + VentRoof_90SLroom_ StpBedroomV	- Ventilated roof + - Opening of windows conditioned to occupancy, internal operative temperature (open when higher than 19ºC) and when internal temperature is higher than external - Maximum width factor of living rooms' windows = 90% (completely closed or completely opened - 0 and 1) - Maximum width factor of bedrooms' windows = 45% (completely closed, partially opened, and completely opened - 0, 0.5 and 1) - Maximum opening of the bedrooms' windows when the difference between internal and external temperature is 0, and minimum when it is ≥ 6ºC, with opening fractions in the range - variable closing setpoint.
Alternative 5 - BC + VentRoof_StpBedroomV	- Same settings as Alternative 2, except: - Maximum width *factor of the rooms* windows = 45%, being opening options: completely closed, partially open and completely open - 0, 0.5 and 1 - Maximum opening of the bedroom windows when the difference between internal and external temperature is 0, and minimum when it is ≥ than 6ºC, with opening fractions in the range - variable closing setpoint.
Alternative 6 - BC + VentRoof_StpBedroomV_ HShading	Same settings as Alt. 5, + - Horizontal solar shading with 60 cm in living rooms, horizontal angle of shading = 31°

All rooms of the two autonomous semidetached houses were simulated, for all existing solar orientations in the neighbourhood (north axis 5º, 95º, 185º and 275º) Onlythe long occupancy rooms (living rooms and bedrooms – highlighted in gray in Figure 2c) were analyzed and the average values found for these rooms are expressed in the next session. The raw data were analyzed using a Python script made for this purpose, indicating the following information:

- Operative temperatures - maximum and minimum;
- Occupancy schedule;
- Degrees-hours of heating and cooling (for all year and occupied hours) according to Standard NBR 15575 upper and lower limits for the Interval 1 of external temperatures – 18ºC < To_{APP} < 26ºC (ABNT, 2021);
- Percentage of hours and absolute hours in thermal comfort and discomfort according to Standard 55 (ASHRAE, 2014) and Dear, Kim, and Parkinson (2017) (for all year and occupied hours);
- Hourly air changes per hour (ACH), by frequency of occurrence, in hours and percentage (all year and occupied hours).
- Percentage of hours and absolute hours with sufficient ACH, according to Standard 62.2 – Equation 6 (ASHRAE, 2016) (for all year and occupied hours).

In real experiments, in which measurements of physical properties of objects are made, it is usual to express the uncertainties derived from inaccuracies of the measurement equipment itself, giving greater reliability to the results (SILVA, ALMEIDA and GHISI, 2016). At the same time, in theoretical experiments, such as computational simulation, there are also uncertainties derived from geometric simplifications, inaccuracy of thermal and optical properties, inaccuracies in the weather file, limitations of the simulation program itself, among others (WESTPHAL and LAMBERTS, 2005). In these cases, it is usual to express uncertainties through indicators such as the Coefficient of Variation of the Root-Mean-Square Error – CV(RMSE), or the Normalized Mean Bias Error (NMBE) (ASHRAE, 2014).

According to Furbringer and Roulet (1999), it is not correct to consider numerical results of experiments as the "absolute reality", as the author recommends caution regarding its reporting and consideration of inaccuracies. Aware of these recommendations, the present study assumes the possible inaccuracies derived from the previously mentioned aspects without prejudice to the fulfillment of the proposed objectives.

It should be noted that the study aims to demonstrate trends in a standard horizontal typology of SH, using complementary inputs based on Brazilian regulations of recognized credibility. Thus, it allows the comparison among the proposed interventions through the verification of better trends for the studied indicators.

4. RESULTS AND DISCUSSIONS

4.1 Base case: initial diagnosis and adaptive thermal comfort model adopted

Figure 3 illustrates the indicators analyzed according to the operative temperatures simulated for the case and the results of the tree analytical methodologies contrasted. According to the Standard 55 (ASHRAE, 2014), the percentages of hours in thermal discomfort in summer and winter in long occupied rooms (LOR) throughout the year are practically the same, while De Dear, Kim, and Parkinson (2017) overestimate heat discomfort and virtually cancel out discomfort in winter in LOR, as can be seen in Table 8. The cooling and heating degree-hours indicator was used as a parameter for comparison between the adaptive comfort models studied here. This is an indicator used by NBR 15.575 standard, adopting lower and upper limit temperatures for the thermal comfort range in the city of Uberlândia of 18º and 26ºC, respectively (ABNT, 2021).

The limit temperatures for the comfort range of NBR 15.575 (ABNT, 2021) were derived from the Standard 55 (ASHRAE, 2014), incorporating adaptations in the face of the findings of Eli (2020), De Vecchi et al. (2014) and Ramos et al. (2020) on patterns of occupancy and behavior of users, and their interference in the thermal performance of residential and corporate buildings. As mentioned, the Brazilian standard measures thermal performance by obtaining degrees-hours of cooling and heating, which indicate the demand for correction of the thermal environment in the face of heat and cold. Although the direct equivalence between the thermal performance of buildings and human thermal comfort is not guaranteed, similarities were identified between the limit values of the Brazilian standard and perceptions of comfort raised in fieldwork performed by Eli (2020), De Vecchi et al. (2014), Ramos et al. (2020) and even De Dear, Kim and Parkinson (2017), allowing to discuss these concepts together (KRELLING et al., 2020).

In its turn, the adaptive model of De Dear, Kim, and Parkinson (2017) enhanced Standard 55 method by considering in more detail the specific routines of use and occupancy of the residential reality. When analyzing the values of discomfort in winter and summer obtained according to De Dear, Kim, and Parkinson (2017), there is a greater similarity with those verified using the limit temperature range proposed by the Brazilian standard (as can be seen in Table 8). Therefore, it was considered coherent, for the present investigation, to adopt the adaptive model of De Dear, Kim, and Parkinson (2017) for the analyses.

Figure 3 - Thermal comfort indicators analyzed in the base case.

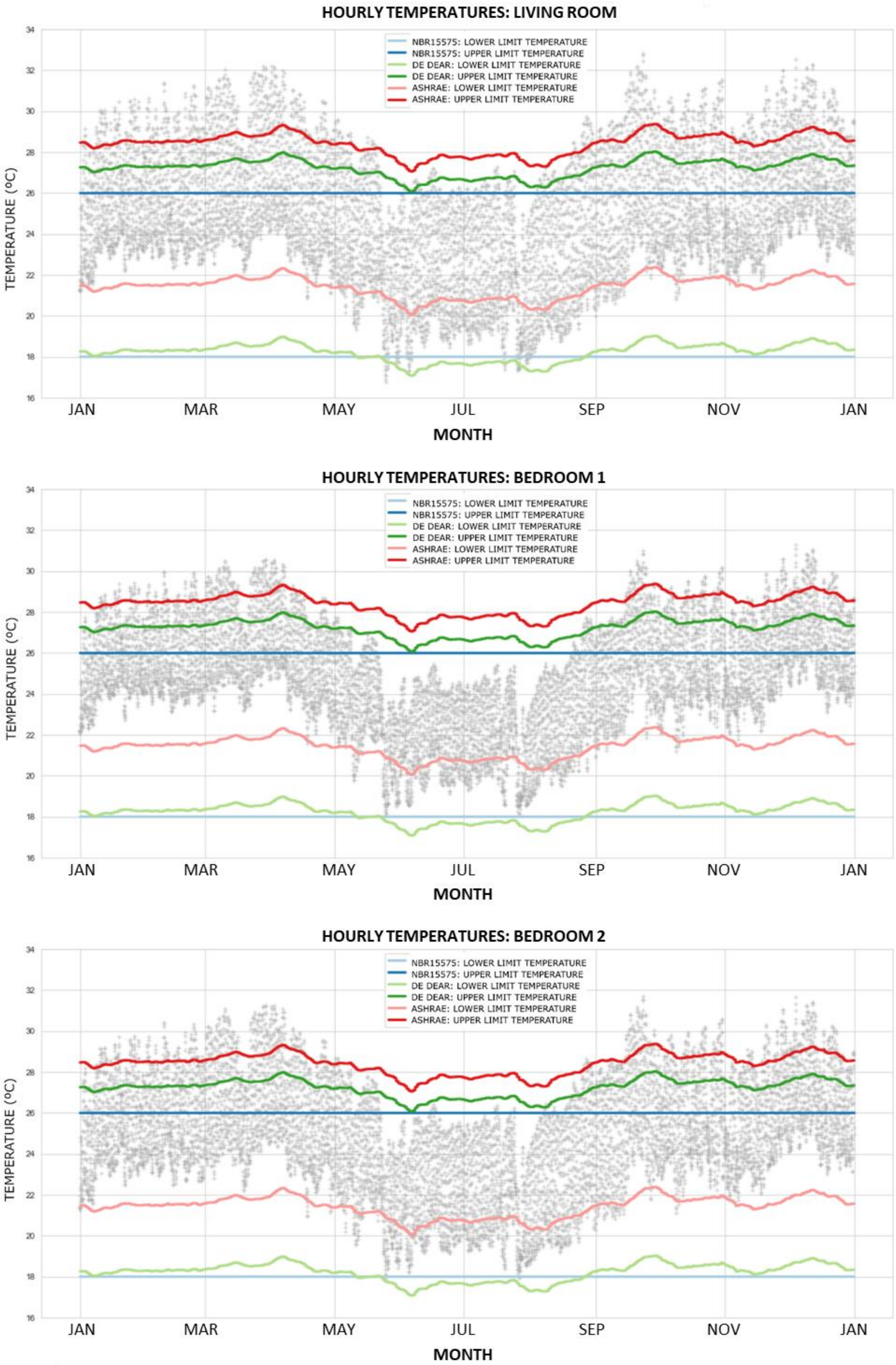

Table 8 - Relation between adaptive models and degrees-hours methods.

Model identification	***Base case (BC)***		
Rooms	***LIVING ROOM***	***BEDR. 1***	***BEDR. 2***
Standard 55: discomfort in summer [%]	12,52%	5,89%	8,55%
Standard 55: discomfort in winter [%]	10,50%	7,75%	8,65%
De Dear: discomfort in summer [%]	22,96%	16,30%	19,66%
De Dear: discomfort in winter [%]	0,25%	0,00%	0,00%
NBR 15575: Cooling degree-hours [ºC]	6755,90	4710,00	5551,79
NBR 15575: Heating degree-hours [ºC]	21,25	0,00	0,43

Legend: HIGHERLOWER

With regard to air renewal in the base case, ACH values were obtained for the long occupancy rooms of the building design by adopting the minimum requirements of Standard 62.2 (ASHRAE, 2016), by considering the net areas declared in official project documentation[2], and by applying Equation 6 (as seen in session 2).

- Living room (9.54 m² x 2.7 m = 25.76 m³) – 2,66 ACH
- Bedrooms 1 and 2 (7.44 m² x 2.7 = 20.1 m³) – 3,41 ACH

4.2 Relations observed between thermal comfort and ACH

Table 9 presents the percentage of hours in thermal discomfort and comfort and the sufficient ACH obtained in the base case and in the selected alternatives. Assuming the pandemic reality in which the occupancy length of stay at home has increased, as well as the multifunctionality and stay in unusual hours in the rooms, the indexes of thermal comfort and air renewal at all hours of the year were also considered for analysis, in addition to occupied hours.

Regarding the base case, it was possible to observe that the total of occupied hours in thermal comfort is high, being equally high for all hours of the year. The exception is the living room, which when compared to the bedrooms presents less thermal comfort. This may be related to the fact that the living room has two exterior-facing facades, which increases its thermal gains and losses during the day – and that is why this is the only room in which some discomfort in winter is observed.

In the base case it is observed that the air renewal is sufficient for most of the occupied hours, but significantly smaller when all hours of the year are considered – since its configuration assumes the opening of windows only when the environment is occupied, including the contribution through infiltrations. This is the most common scenario to the reality of most Brazilian households, and for this reason it is adopted by NBR15.575 (ABNT, 2021) – as in Table 2.

Alternative 1 assumes the same settings as the base case with the implementation of a behavioral change: the windows opening of long occupied rooms in 100% of the time throughout the year, regardless of occupancy and external and internal temperatures. This alternative seems more coherent to the reality of increasing and diversifying the use of domestic environments during the social restrictions imposed by the pandemic. In this alternative, there is an average 3,28% increase in the percentage of total hours in comfort, with a significant increase in air renewal in all hours of the year. This alternative was the one that most significantly reduced the percentage of total hours in discomfort in summer, by an

[2] Provided by Uberlândia City Hall in 2016 (see Figure 2).

average of 24% compared to the base case. However, it caused a small increase in hours of discomfort in winter that, although small, previously did not exist in the bedrooms, demonstrating the impact of ventilation not only on the renewal of air but also on the change in internal temperatures. It is worth noting that the scenario stipulated by alternative 1 may be difficult to implement, since the control of the windows also has the function of ensuring safety against unwanted entrances (dust, insects, larger animals and/or human invaders), which deserves some consideration.

Table 9 - Results of thermal comfort and air changes per hour for the base case and alternatives.

Model identification	***Base Case (BC)***								
Room	***LIVING ROOM***	***BEDR. 1***	***BEDR. 2***						
De Dear: discomfort in summer [%]	22,96%	16,30%	19,66%						
De Dear: discomfort in winter [%]	0,25%	0,00%	0,00%						
De Dear: total hours in comfort [%]	76,79%	83,70%	80,34%						
De Dear: total of comfort when occupied [%]	50,62%	99,67%	99,67%						
ASHRAE 62.2: Sufficient ACH [%]	28,72%	28,71%	36,75%						
ASHRAE 62.2: Sufficient ACH when occupied [%]	86,16%	68,90%	88,19%						
Model identification	***Alternative 1 - BC + AlwaysOnLOR***			***Alternative 2 - BC + VentRoof***			***Alternative 3 - BC + VentRoof_AlwaysOnLroom***		
Room	***LIVING ROOM***	***BEDR. 1***	***BEDR. 2***	***LIVING ROOM***	***BEDR. 1***	***BEDR. 2***	***LIVING ROOM***	***BEDR. 1***	***BEDR. 2***
De Dear: discomfort in summer [%]	18,17%	12,33%	14,58%	20,41%	13,49%	16,54%	19,85%	12,90%	15,90%
De Dear: discomfort in winter [%]	2,85%	1,54%	1,53%	0,25%	0,00%	0,01%	0,70%	0,07%	0,13%
De Dear: total hours in comfort [%]	78,98%	86,13%	83,89%	79,34%	86,51%	83,45%	79,45%	87,03%	83,97%
De Dear: total of comfort when occupied [%]	63,29%	97,23%	97,13%	55,17%	99,81%	99,70%	56,20%	99,67%	99,56%
ASHRAE 62.2: Sufficient ACH [%]	97,88%	39,52%	78,71%	27,15%	28,09%	36,62%	88,50%	23,92%	36,85%
ASHRAE 62.2: Sufficient ACH when occupied [%]	96,71%	55,01%	82,74%	81,44%	67,42%	87,89%	89,42%	57,40%	88,44%
Model identification Room	***Alternative 4 - BC + VentRoof_90SLroom_ StpV Bedroom***			***Alternative 5 - BC + VentRoof_StpBedroomV***			***Alternative 6 - BC + VentRoof_StpBedroomV_ Hshading***		
De Dear: discomfort in summer [%]	***LIVING ROOM***	***BEDR. 1***	***BEDR. 2***	***LIVING ROOM***	***BEDR. 1***	***BEDR. 2***	***LIVING ROOM***	***BEDR. 1***	***BEDR. 2***
De Dear: discomfort in winter [%]	20,80%	14,93%	17,71%	22,03%	15,98%	18,82%	21,38%	15,51%	18,37%
De Dear: total hours in comfort [%]	0,10%	0,00%	0,00%	0,08%	0,00%	0,00%	0,09%	0,00%	0,00%
De Dear: total of comfort when occupied [%]	79,10%	85,07%	82,29%	77,89%	84,02%	81,18%	78,53%	84,49%	81,63%
ASHRAE 62.2: Sufficient ACH [%]	55,68%	99,59%	99,59%	52,29%	99,53%	99,51%	53,39%	99,56%	99,51%
ASHRAE 62.2: Sufficient ACH when occupied [%]	29,17%	3,57%	13,17%	28,13%	3,36%	12,51%	27,81%	3,48%	12,72%
Model identification	87,50%	8,58%	31,62%	84,38%	8,05%	30,03%	83,42%	8,36%	30,52%

Legend: HIGHER LOWER

Alternative 2 differs from the base case only by inserting openings in the side walls that support the roof and surround the attic – creating a ventilated roof. With openings of 46% of the available wall area, an average increase of 3,21% in the percentage of total hours in comfort was observed, in relation to the base case, as well as a small reduction in air renewal throughout the year and the occupied hours. This alternative reduces, on average, by 14.6% the total hours in discomfort in summer in the house, in relation to the base case. With lower occurrence of internal high temperatures, the thermal balance of the building changes, reflecting on the air movement by difference of pressure between indoor and outdoor atmospheres. This may explain the small reduction observed in the rate of air renewal, which does not make this alternative less interesting, but indicates that, alone, it does not represent a great advantage for both indicators studied, when compared to the previous one.

Alternative 3 is a combination of the first two, associating the benefits of the ventilated roof with the opening of windows of the living room in 100% of the time during the year. While discomfort in summer was reduced by 17,8% from the base case, the reduction in total hours in discomfort was 3,83%, on average, the highest so far. At the same time, there was a small increase in air renewal in living room and bedroom 2, while bedroom 1 had air renewal reduced by 16,69% compared to the base case, a value lower than that observed in alternative 1. Moreover, in this alternative, constant ventilation in the living room had a minimal impact on discomfort in winter, which makes this strategy also interesting when compared to the previous ones. However, it should be noted that, although this alternative presents good results, it involves higher implementation costs when compared to the Alt. 1, as residents may have to invest in a ventilated roof.

In Alternative 4, it was checked the impact of the expansion of the effective ventilation opening area in the living room to 90%, associated with the addition of an intermediate opening area to the bedrooms windows which results in ventilation effective areas of 45%, 22,5%, or closed. The value of 22,5% is a partial opening condition dependent on the difference between internal and external temperature, being the closest value to 6ºC the maximum difference tolerated for minimum opening. This alternative yielded the lowest expansion of the total hours in comfort, with an average of 2,3% improvement over the base case. This alternative virtually nullified the discomfort in winter that existed only in the base case living room, though it greatly reduced the air renewal in the bedrooms. Bedroom 1 had air renewal reduced by 87,55%, bedroom 2 by 64,15%, and the living room was practically unaffected. The results show, on the one hand, little effectiveness in changing the type of frame of the living room to enlarge its effective opening area and, on the other hand, the negative effect of this strategy associated with the variable closing setpoint of the bedrooms windows in its rate of air renewal and thermal comfort when compared to the previous alternatives.

Alternative 5 had the same settings as Alternative 2 but associated with a variable temperature setpoint for closing the bedroom’s windows. This option resulted in an even greater impact on the reduction of air renewal compared to Alt. 4, but in all analyzed rooms, in addition to a light increase in the annual average percentage of hours in thermal comfort (+ 0,94% in relation to the base case), which discourages this strategy.

Finally, Alternative 6 used the same settings as Alternative 5, adding horizontal solar shadings of 60 cm in the living room window trying to reduce the contribution of solar radiation to discomfort in summer. The reduction of discomfort in summer in the base case was negligible, negatively impacting the renewal of air such as alternatives 4 and 5, indicating that the investment in it does not compensate.

Analyzing Alternatives 4, 5, and 6, it is noticed that the combined changes in effective opening area (without interfering in the absolute area of the wall available for the installation of windows) with variable opening patterns and window shading are ineffective on increasing thermal comfort and air renewal inside the environments. These results are an indication that other issues related to the project, such as the geometry of the wrap, the compartmentalization and sectorization of rooms, the materiality of internal vertical seals, among others, may be exerting a greater influence on the indicators in question (thermal comfort and ACH).

The evidence for this statement is that the implementation of a ventilated roof in Alternative 2 was the factor that most favorably influenced the annual percentage of hours in thermal comfort. In parallel, the constant opening of the window in the living room and bedrooms during the entire day provided the best average performance for both indicators, making Alternative 1 (which mainly involves behavior change in the use of windows) the best

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option in terms of improvement in thermal comfort and less impact on the ACH. Next there's Alternative 3 and others involving behavioral changes and constructive interventions, presenting greater investments and difficulties for effective implementation.

Figure 4 - Thermal comfort indicators analyzed in the base case.

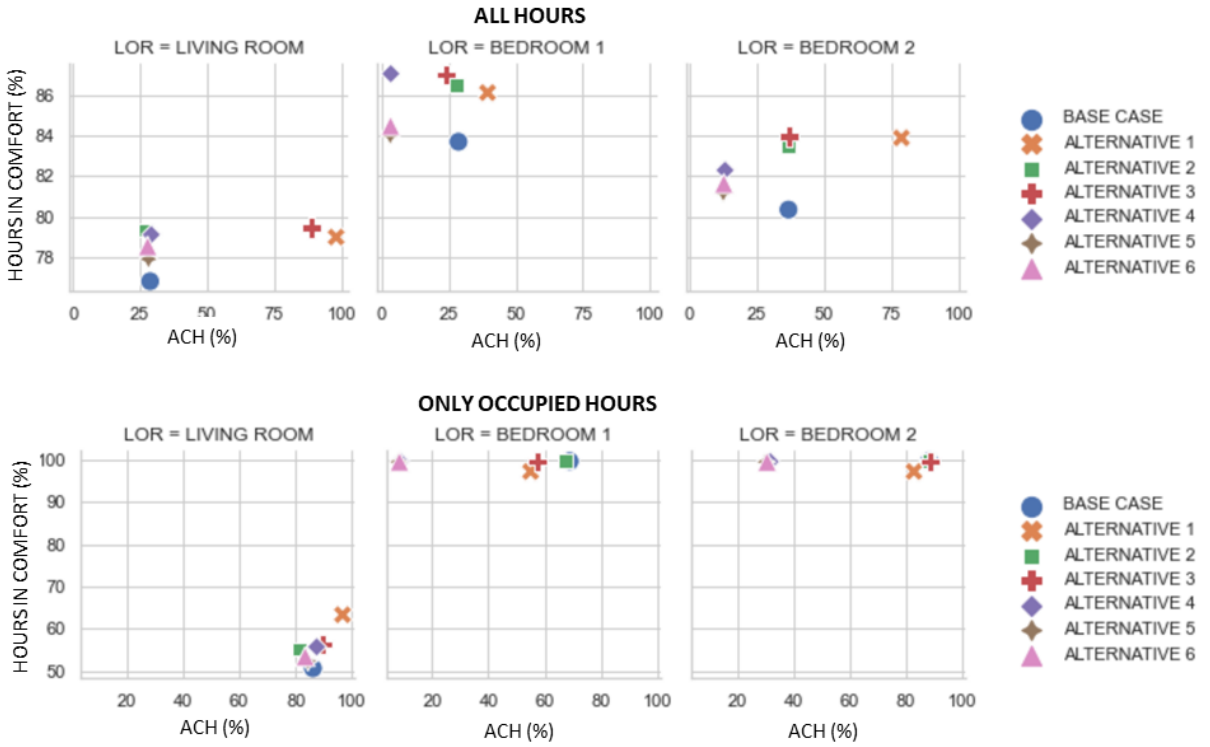


Figure 4 summarizes the findings reported above for the base case and its six studied alternatives. The vertical Y-axis organizes the percentage of hours in comfort for each of the alternatives and the horizontal X-axis the percentage of hours in sufficient air renewal in ACH.

4.3 Observed trends for the indicators analyzed

The six alternatives to the base case presented were elaborated aiming the smallest possible financial impacts, which involved the adoption of adaptive behaviors in the manipulation of windows and physical interventions, such as alteration of window models, insertion of solar shadings, and openings in the attic to ventilated roofs. The simulation of these alternatives allowed a discussion about the impact of behavioral and physical interventions on the analyzed indicators, for a housing typology, as it was delivered by PMCMV.

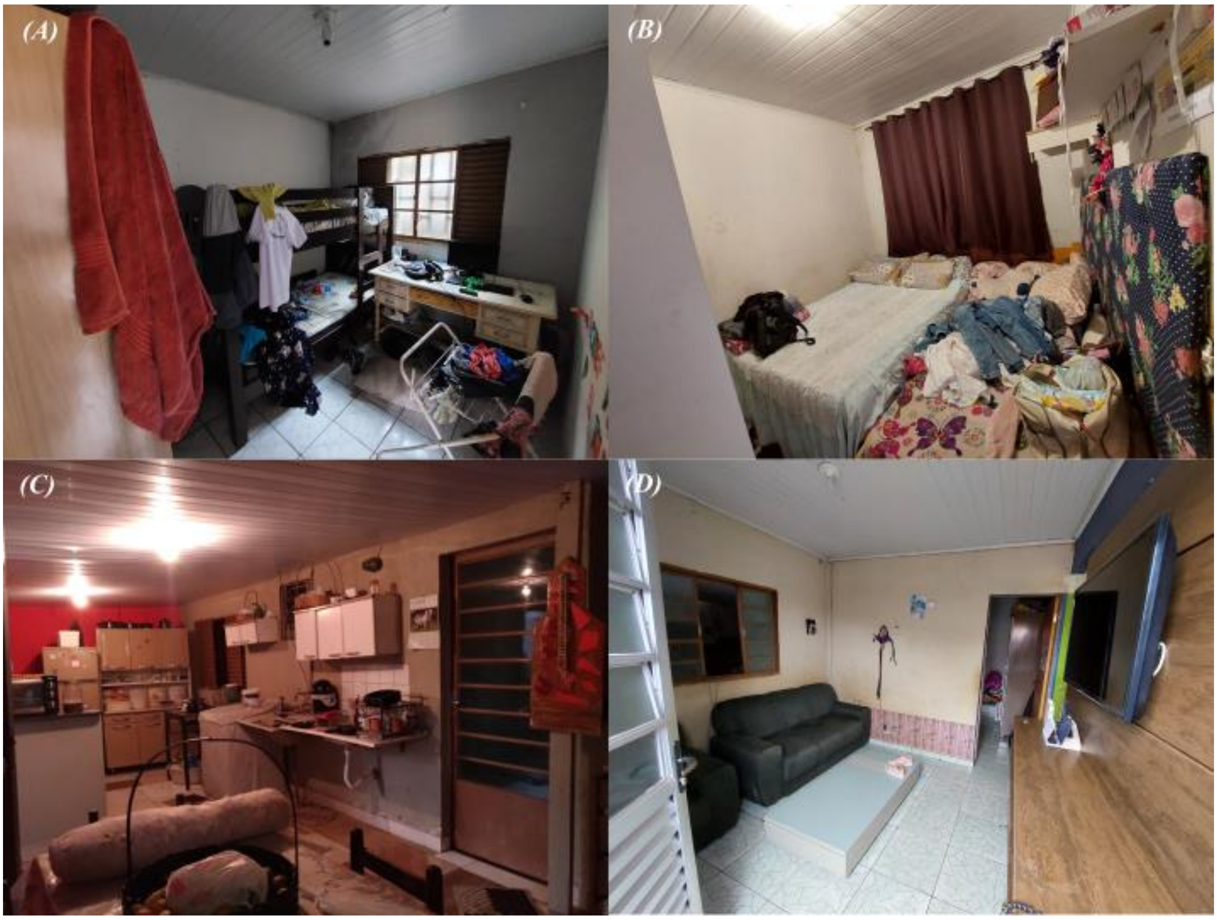
The results from the base case to alternative 6 show a high percentage of total hours in thermal comfort, remaining close to 80%. In the occupied hours, this value is almost always even higher, getting close to 100%. Although in most cases thermal comfort throughout the year remained almost unchanged or went from one already good situation to another even better (with the expansion of total hours in thermal comfort and the reduction of hours in discomfort in summer), the same was not observed regarding air renewal.

From the base case, the air renewal considered sufficient is less frequent when observing the whole year, since the opening of windows in this case is conditioned to the occupancy. The only alternative that combined the best results for both indicators (thermal comfort and air renewal), was the nº 1, in which the passage of air through the windows is unimpeded throughout the entire day and in all rooms during the whole year - involving thus the adoption of an adaptive behavior. Such adaptive behavior relates to the new observed patterns of staying at home imposed by the pandemic.

The behavior of leaving the living room windows opened also throughout the night, as well as the bedrooms windows also opened throughout the day - which would define a use not conditioned by occupancy – raises some reflections. In the living room, the window faces the street and not all residents were already able to build front walls (Villa *et al.*, 2022a). This can make them feel insecure about leaving the windows fully opened at night. Regarding all rooms in the house, including the bedrooms, previous research has shown that many residents feel uncomfortable with dusty winds entering the house (Villa *et al.*, 2022a) and, consequently, the higher demand for hygiene, which can also discourage the opening of windows, even in occupied hours.

Moreover, it is observed, in practice, that the reduced dimensions of the houses, added to the inability to accommodate the uses demanded and the density of rooms (Bortoli and Villa, 2020) cause situations of obstruction of windows by furniture (Figure 5a and 5b), hindering their access and manipulation.

Figure 5 - Obstruction of windows by the furniture in the bedrooms (a and b) and Obstruction of windows by the construction of contiguous rooms (c and d).

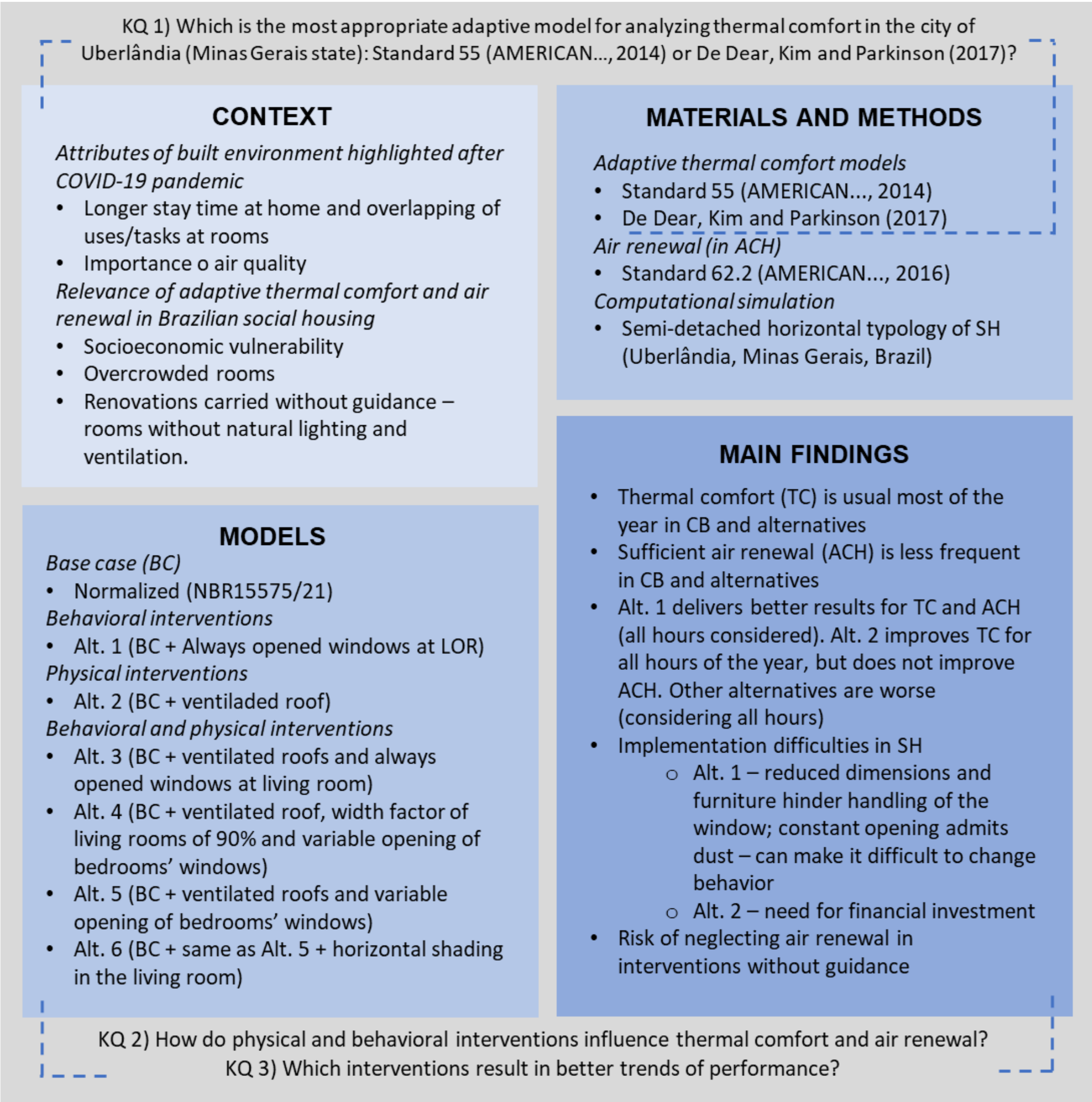


The results showed that there is a close relation between air renewal and thermal comfort, indicating, however, that in a scenario where thermal comfort is high, air renewal can be overlooked - as demonstrated by the comparison between alternatives 1 and 2, in which thermal comfort was improved for both, but the same did not apply to air renewal.

That is, in a context where thermal comfort is already good and where there are difficulties and complications for the handling of windows beyond the usual (busy hours), the renewal of air can be neglected, which is alarming, whether in a pandemic scenario or not. Air quality is related to its renewal, when current practices (conditioned by the characteristics of things, according to Gram-Hansen (2009) and current climatic conditions do not evidently impair thermal comfort, the healthiness of the air can be underestimated - favoring the accumulation of moisture, mold, and the proliferation of the most diverse pathogens.

It is also worth mentioning that the present work was carried out considering the initial configuration of the houses delivered by the MCMV and that after a few years of occupancy, the residents perform interventions without adequate guidance that can negatively alter the perception of the indicators analyzed - compromising thermal comfort and, even more, the renewal of air. As an example, there is the building of contiguous rooms to the delivered house, isolating windows from the light inlet or natural ventilation (Figure 5 – c and d).

Figure 6 - Research path according to key questions (KQ) and main findings.



In this sense, alternative 1 stood out and further investigations are needed to enable the expansion of natural ventilation through openings beyond occupied hours. Interesting trends were observed to obtain good results of thermal comfort and air renewal in SH simultaneously, recommending:

- Need for greater knowledge about the action of the resident in the face of the climate (and its changes) x characteristics of the building x behavior x air quality - aiming at the awareness of the resident;
- Expand understanding of the influence of renovations with enlargement on thermal comfort and air renewal in horizontal SH;
  Improvement of projects delivered by government programs such as MCMV - with provision for enlargement considering ensuring adequate conditions of thermal comfort and air renewal, balancing the effects of the physical transformations undertaken on the two indicators;
- Expansion of the participation of architects and urban planners in the study process for better transformations/renovations of SH, using the prerogatives brought by the Brazilian law of free technical assistance (Law nº 11.888/2008) to owners of low-income popular housing.

After all, Figure 6 summarizes the course of the research and its main findings, according to the key questions enunciated in the introduction.

5. CONCLUSIONS

This article described and provided a discussion on the results of a study that measured the influence of ventilated roofs, solar protections, variable patterns of windows' opening, and effective areas of ventilation of windows on thermal comfort and air renewal in a semi-detached horizontal typology of SH, located at Uberlândia city (Brazil). A normative base case and six alternatives with the proposed interventions were simulated.

The base case showed high rates of thermal comfort, in the occupied hours and all hours of the year, presenting low performance regarding the air renewal for all hours of the year. It was found that the interventions in the base case altered the temperature of the environments and, therefore, the pressure and air movement inside the house, either favoring or impairing the performance of the analyzed indexes.

Alternative 1, which provides for opening windows in the room 100% of the time throughout the year, regardless of occupancy and external and internal temperatures, was the one that brought the best results, providing an average 3.28% increase in the percentage of total hours in comfort, with a significant increase in air renewal in all hours of the year. This alternative is assuming only the need for a behavioral change and possible investment in devices for window safety. In parallel, it was found that the use of ventilated roofs (Alternative 2) brought high improvement of thermal comfort, an average increase of 3.21% in the percentage of total hours in comfort was observed, in relation to the base case. However, without sufficient expansion of the air renewal in relation to the base case, demanding greater investments when compared to alternative 1.

It was observed that, although the gains from increasing the hours of thermal comfort were low in the alternatives if compared to the base case, Alternative 1 is the one that increased the most the air renewal. However, some difficulties for its effectiveness were noticed - such as insecurity, dust and obstruction of openings by furniture and by expansions without technical guidance.

Moreover, the findings indicate a risk to underestimate air renewal when thermal comfort conditions are favorable, since all interventions had a positive impact on thermal comfort and the same did not apply to air renewal. This is alarming in a context of COVID-19 pandemic and even after. In the analyzed scenario, in which residents make expansions without technical assistance that results in impairing natural lighting and ventilation, it is fearful that the concern with air renewal will only occur when the conditions of thermal comfort deteriorate considerably.

The reflections raised in this study expect to contribute to guide more accurate thermal comfort analyses in SH located in the city of Uberlândia (Minas Gerais state, Brazil). Consequently, it contributes to the promotion of more resilient, better ventilated, and more thermally comfortable *habitats*, especially for vulnerable populations benefiting from government housing programs.

6. ACKNOWLEDGEMENTS

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7. ABBREVIATIONS

SH - social housing
MCMV - *Minha Casa, Minha Vida* habitational government program
LOR - long occupied rooms (bedrooms and living rooms)
BC - base case

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