The influence of envelopes in the thermal performance of residential buildings, from the perspective of bioclimatic architecture

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Abstract
Energy efficiency measures (EEMs) and their impact on the thermal performance of buildings as well as on the user’s thermal comfort, have become the focus of several studies. Bioclimatic strategies can contribute to improving thermal performance while increasing indoor thermal comfort for users. This paper aims to verify the bioclimatic potential of two types of dwellings in three Brazilian cities. The first one is the baseline, with basic construction systems. The other includes EEMs. The method consists of the verification of bioclimatic potential by psychometric charts for indoor and outdoor conditions. The results show significant indoor discomfort caused by heat in both dwellings—thermal comfort conditions during more than 95% of annual hours in Manaus, and during 85% in São Paulo. Therefore, energy efficiency strategies such as shading, ventilation and HVAC systems are necessary to promote thermal comfort conditions in hot climates.

1. Introduction
It is well known that buildings account for a considerable amount of total energy use. Considering the global scenario, the buildings and construction industry are responsible for 36% of the final energy use and 39% of the greenhouse gases emitted [1]. In Brazil, approximately 52% of the electricity consumed in 2019 is due to buildings [2]. An effective way to reduce energy consumption and maintain or increase the occupants’ comfort is the application of bioclimatic strategies [3,4]. The utilization of bioclimatic strategies—long-term measures for improving energy efficiency—to reach the nearly Zero Energy Building (nZEB) standard is presented by Stasi et al. [5]. The application of passive solutions and the analysis of the local climate is essential when designing energy efficient buildings [6,7].

The adaptation of buildings through bioclimatic strategies can be accomplished through the utilization of psychometric charts, like the one developed by [8] to address the limitations indicated in Olgyay’s charts [9]. Givoni based his studies on the linear relationship between vapour pressure and temperature amplitude of outdoor air to address the appropriate strategy [10]; through different phases, it incorporates comfort indexes and offers a simple and popular application in Brazil [11]. Also, Givoni’s charts are used especially for hot and humid climates, with graphical climate data analysis interpretation.

Some studies have applied Givoni’s charts to study human comfort conditions in South America, as in [11], to analyze the impact of comfort in elevated temperatures in Brazil; in [12] with the analysis of bioclimatic strategies, the similarities and differences for eight regions inserted in Cfa climates; and in [13] correlating the role of bioclimatic strategies in the Argentinian energy labelling program.
This method application could also provide an interesting analysis when considering the indoor temperature of buildings. Generally, Givoni’s method uses external temperatures to analyze indicated passive strategies. However, when Givoni conceived the idea of the psychometric charts, the intention was to use the indoor temperatures to evaluate effective strategies for reaching optimal comfort conditions for occupants. Silva and Abreu [14] verified by measurements the indoor temperatures of a building in the South of Brazil and used Givoni’s psychometric charts to compare the recommended bioclimatic strategies using indoor and external temperature data. Guarda et al. [15] investigated the bioclimatic potential for Cuiabá, Brazil, considering the application of Givoni’s charts and future climate projections for the A2 scenario of the fourth IPCC report [16]. The results showed an increase in the average temperature and a decrease in relative humidity, which affects the passive strategies over the years. A similar approach is performed by Liu et al. [17] and Roshan, Oji, and Attia [18]. This article aims to verify the bioclimatic potential of a reference dwelling in (1) the baseline case (BL) and (2) the high-performance case (HP), with energy efficiency strategies included in the envelope, in three different Brazilian cities. The motivation is based on the lack of studies for Latin America concerning the use of indoor temperatures as per Givoni’s bioclimatic charts.

2. Method
This study considered three Brazilian cities in the analysis, located in different biomes: Cuiabá with Brazilian hot-dry cerrado; Manaus with Amazonian hot-humid climate; and the Atlantic Forrest of São Paulo with mild temperatures. ASHRAE Standards [19] classify Manaus and Cuiabá as extremely hot humid (0A), and São Paulo as hot humid (2A). According to the climate files, the Heating and Cooling Degree Hours (HDH and CDH) are, respectively, 1.08 hours and 1,425 hours for Cuiabá, 0hrs and 909.33 hours for Manaus, and 19.58 hours and 73.5 hours for São Paulo. The base temperature considered were 18.3°C (HDH) and 26.7°C (CDH) in all cases.

2.1. Bioclimatic potential
Considering the close relationship between the usage of passive design strategies within dwellings that adopted them and their thermal comfort conditions, the impacts of the bioclimatic potential, through Givoni’s bioclimatic charts [20], was quantified. The tool Analysis Bio [21] supported the investigation. It uses 12 strategies divided by zone: ventilation, ventilation/high inertia, ventilation/high inertia/evaporative cooling, high inertia to cooling, high inertia/evaporative cooling, high inertia/solar heating, thermal comfort, mechanical heating, passive solar heating, mechanical cooling, evaporative cooling, and humidification. The data transcription in the bioclimatic chart has as input the climate file for the analyzed location, converted in a comma-separated values (CSV) file.

The .csv file’s header is standardized, respecting the following order: month, day, hour, dry-bulb temperature (°C), wet-bulb temperature (°C), dew point (°C), atmospheric pressure (Pa), absolute humidity (Kg/Kg), relative humidity (%), enthalpy (BTU/Lb), wind speed (m/s), total cloud cover (decimals), extraterrestrial horizontal radiation (Wh/m²), global horizontal radiation (Wh/m²), direct radiation (Wh/m²), direct normal radiation (Wh/m²), and diffuse horizontal radiation (Wh/m²). Consequently, the climate files are not compatible with the .csv file, requiring the calculation of the wet-bulb temperature (°C), absolute humidity (Kg/Kg), and enthalpy (BTU/Lb). The calculation methods have been described by some authors [15,22].

The results are expressed by the percentage of annual hours of comfort and discomfort computation and the strategies with greater frequency applied to the dwellings analyzed. Considering the external conditions, the strategies taken into account are ventilation, ventilation/high inertia, high inertia/solar heating, mechanical cooling, and shading. In order to calculate the wet-bulb temperature (°C), the following variables were inserted in the .csv file: mean indoor temperature (°C) and indoor relative humidity (%), both values weighted by the total floor area of living room and bedrooms. Finally, the results of the bioclimatic potential, considering indoor conditions, were presented for strategies involving ventilation, mechanical cooling and heating, and shading.
2.2. Representative social housing model

The dwelling used in this study was adapted from the model characterized by Triana, Lamberts and Sassi [23]. The house has two bedrooms, one bathroom, and one kitchen integrated with the living room, with a total floor area of 43.24m².

In order to verify the percentage of annual hours of comfort and discomfort caused by heat or cold, the dwelling was evaluated considering EEMs, i.e., the “high-performance model” (HP), and the “baseline model” (BL), with basic construction characteristics (Figure 1). The HP model includes 4cm rock wool thermal insulation in the external walls, which reduces thermal transmittance to 0.78W/m².K when compared to the BL model. Also, the internal walls were improved with perforated clay brick and the absorptance reduced to 0.3.

Figure 1. Construction characteristics from the representative social housing.

Once the construction characteristics were defined, energy simulations were performed, using the EnergyPlus v.9.4 tool. The outputs obtained were mean air temperature (°C) and air relative humidity (%). The occupation, lighting, and equipment operation were defined as typical for social housing in the Brazilian context, as described in NBR 15,575 [24]. The dwelling is evaluated in the natural ventilated condition, considering two people in the living room, between 2:00 PM and 6:00 PM, four between 6:00 and 10:00 PM and two people per bedroom between 10:00 PM and 8:00 AM. The lighting and equipment were 5W/m² and 120W, respectively.

3. Results

The results were presented following the methodological process described before, divided in: (1) bioclimatic potential considering the external and (2) indoor conditions. The aim was to verify the percentage of required hours of bioclimatic strategies in both cases.

3.1. Bioclimatic Potential considering external conditions

In hot climate cities such as Cuiabá and Manaus, ventilation is required for longer time spans, i.e., 42.7% of the time (3,741 hours) and 76.5% (6,701 hours), respectively. In mild climates, like São Paulo, ventilation is required during 17.6% of annual hours (1,542 hours). When the heating strategies are considered, such as high inertia/solar heating, the results for Manaus, Cuiabá, and São Paulo are 0%, 4.9% and 37.7%, respectively. The same behavior is observed in the ventilation/high inertia strategy, with greater percentage values for Cuiabá (Figure 2).

A shading strategy is needed during significant lengths of time — 93% in Cuiabá and 100% in Manaus, i.e., this strategy is required throughout the year for both cities. In São Paulo, shading is required during 49% of annual hours (4,275 hours), i.e., the shading strategy is recommended for half
of the year to reach superior comfort conditions (Figure 2). The mechanical cooling strategy was not required in São Paulo but was in Cuiabá (i.e., 9%), and Manaus (i.e., 13%).

Initially, the comfort and discomfort hours are considered in the external conditions, using the climate files applied in building simulation. This first investigation intends to explore the influence of the envelope on the indoor building’s conditions. Thermal discomfort due to heat in Cuiabá was noted 71% of the time, in Manaus 97% of the time and in São Paulo 22% of the time. As observed in Figure 3, Manaus presented higher discomfort percentages due to the heat, none due to the cold and only 2% of annual hours (210 hours) in thermal comfort conditions. This city presents high climatic stability, with high temperatures and humidity throughout the year, characterizing a climate that is extremely hot and humid. Cuiabá presents 24% of annual hours (2,076 hours) of thermal comfort, only 6% of discomfort due to the cold and 71% due to the heat, similar to Manaus. São Paulo shows 31% of annual hours (2,742 hours) in thermal comfort and half of the year (47% or 4,091 hours) in discomfort due to the cold. Therefore, climates with higher climatic stability, such as Manaus and Cuiabá, demand cooling-oriented passive design strategies, e.g. shading and ventilation, and active strategies, e.g. mechanical cooling, to provide better comfort conditions. Cities with a mild climate, such as São Paulo, demand passive design strategies, e.g. high inertia/solar heating.

3.2. Bioclimatic Potential considering dwellings’ indoor conditions

Through the energy simulations, the envelope’s bioclimatic potential investigation was performed for the two situations, for the indoor conditions BL and HP. Both dwellings (BL and HP) present discomfort due to the heat in Manaus, i.e., 97.5% of annual hours (8,541 hours), and thermal comfort in only 1% of annual hours (85 hours). Thus, the implementation of EEMs was not sufficient to mitigate the external temperatures’ impact in the dwellings, demanding more efficient design strategies. In Cuiabá, the implementation of thermal insulation in the walls reduces the hours of thermal discomfort due to the heat by 4.0% (350 hours) and, consequently, increases the hours in thermal comfort (Figure 4). Nevertheless, strategies to mitigate the discomfort due to the heat are still necessary. Discomfort due to the cold was not observed.

![Figure 2. Percentage of required hours of bioclimatic strategies in the external conditions.](image)

![Figure 3. Comfort and discomfort hours in the external conditions.](image)

![Figure 4. Thermal discomfort and comfort hours in the dwellings’ indoor conditions.](image)
São Paulo’s percentages of hours with thermal comfort were superior to 80.0% (7,507 hours) in both building models. The BL model presents higher percentages of thermal discomfort due to the heat, i.e., 12.2%. The application of the EEMs in the building reduces the annual hours of thermal discomfort due to the heat by 2.58%. The annual hours of thermal discomfort due to the cold were less than 5% (413 hours) for both models. Therefore, the implementation of EEMs affected positively only mild climate cities. Cities with hotter climate demand more efficient measures to have a significant impact on the hours of comfort.

The next investigation includes the required hours for both active and passive strategies, considering the dwellings’ indoor conditions. In the cities with a hot climate profile, Manaus and Cuiabá, the percentage of shading hours was significant, i.e., 100% and 99.2%, respectively, for BL and HP. Mechanical cooling was required for more hours in the BL model, with a difference of +5.3% in Cuiabá and +7.2% in Manaus, when compared to the HP model. The ventilation strategy presents similar behavior, +3.6% in Cuiabá and +7.3% in Manaus (Figure 5). The strategies demanded in São Paulo were shading of 76.4% in the BL model and 72.8% in the HP model, and ventilation of 5.8% in the BL model and 5.9% in the HP model. In both models, mechanical cooling was not required.

![Figure 5. Percentage of hours required of bioclimatic strategies in indoor conditions](image)

Lastly, the external conditions such as air temperature and relative humidity directly influence the buildings’ indoor conditions, reflecting on the thermal comfort and discomfort hours. The shading, ventilation and mechanical cooling strategies are required in higher percentages for hotter climates, e.g. Cuiabá and Manaus, which demonstrates that these strategies should be applied in conjunction with the EEMs to reach better thermal conditions in the buildings’ interiors.

4. Conclusions
Through investigations of the bioclimatic potential, it was possible to investigate passive strategies for the analyzed cities and buildings. The envelope modifications included in the high-performance building improved the thermal comfort conditions inside the building and also reduced indoor temperatures, when compared to the base case. However, discomfort due to heat was predominant in the internal rooms in relation to the external environment, for hot climates. The results are partially similar to those observed in [14], performed in the mild climate of Florianópolis, Brazil. The annual hours of comfort due to cold temperatures in the indoor conditions are higher, but the results for discomfort due to heat were differentially higher considering the internal loads. This divergence can be explained by the site measurements performed in [14], which show the limitations of the AnalysisBio.

Finally, it is noted that the comfort strategies most susceptible to improvement were air conditioning and ventilation. This may be justified by new temperature and humidity conditions, which require the use of air conditioning to provide better thermal conditions inside the buildings. It is concluded that incorporating envelope adaptations in the dwellings results in better comfort conditions in their interiors. Research into passive design strategies in dwellings is an important instrument for the coming decades.
to reduce energy demand and improve indoor conditions of buildings. An investigation of the implementation of bioclimatic strategies and its cost analysis should be the focus of future work.

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