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# CLIMATE CHANGE AND THERMAL COMFORT IN COLOMBIAN SOCIAL HOUSING

# CAMBIO CLIMÁTICO Y CONFORT TÉRMICO EN LA VIVIENDA DE INTERÉS SOCIAL COLOMBIANA

# MUDANÇA CLIMÁTICA E CONFORTO TÉRMICO EM HABITAÇÕES SOCIAIS COLOMBIANAS

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# RESUMEN

El cambio climático es una de las problemáticas más relevantes del siglo XXI a nivel mundial y, a pesar del desarrollo de estrategias que buscan minimizar sus consecuencias, es una realidad irreversible. Por consiguiente, es pertinente analizar su impacto sobre la arquitectura colombiana, específicamente en la Vivienda de Interés Social (VIS), tipo de edificación que más se construye en el país. El objetivo de esta investigación fue conocer el desempeño térmico de la VIS actual, en relación con el cambio climático, a partir de un modelo tipo para las ciudades más pobladas de Colombia Bogotá, Medellín y Cali. Dicho modelo se realizó a través de simulaciones computacionales en tres escenarios futuros (2030/2050/2080), los que permitieron diagnosticar cómo el cambio climático tendrá efecto en el confort térmico de sus ocupantes. Dentro de los resultados se demuestra que, del total de los escenarios evaluados (576), tan sólo el 18,9% se encuentra en un rango aceptable de tiempo en confort térmico (>70%). Esto que indica que la mayor parte de la VIS actualmente construida en Colombia no brinda condiciones de confort térmico tanto en un escenario de cambio climático como en el escenario actual, pues en ambas situaciones los casos favorables representan un bajo porcentaje respecto del total de los casos evaluados.



Palabras clave
cambio climático, viviendas de interés social, confort térmico.



# ABSTRACT

Climate change is globally one of the most relevant problems of the 21st century and despite strategies that seek to minimize its consequences, it is an irreversible reality. Therefore, it is pertinent to analyze its impact on Colombian architecture, specifically on Social Housing (SH), the type of building most frequently built in the country. The purpose of this research was to get to know the thermal performance of current SH, in relation to climate change, based on a standard model for the most populated cities in Colombia, namely Bogotá, Medellín, and Cali. This model was made using computer simulations in three future scenarios (2030/2050/2080), which allowed diagnosing how climate change will affect the thermal comfort of the occupants. The results show that, of the total number of scenarios evaluated (576), only 18.9% are in an acceptable range of time in thermal comfort (>70%). This indicates that most of the SH currently built in Colombia do not provide thermal comfort conditions either under a climate change scenario or in the current scenario, since in both situations the favorable cases represent a low percentage with respect to the total number of cases evaluated.



Keywords
climate change, social housing, thermal comfort.



# RESUMO

As mudanças climáticas são uma das questões mais relevantes do século XXI em nível global e, apesar do desenvolvimento de estratégias para minimizar suas consequências, é uma realidade irreversível. Portanto, é pertinente analisar seu impacto na arquitetura colombiana, especificamente na Habitação de Interesse Social (HIS), o tipo de construção mais comum no país. O objetivo desta pesquisa foi conhecer o desempenho térmico da HIS atual em relação às mudanças climáticas, com base em um modelo padrão para as cidades mais populosas da Colômbia: Bogotá, Medellín e Cali. Esse modelo foi criado por meio de simulações computacionais em três cenários futuros (2030/2050/2080), que permitiram diagnosticar como as mudanças climáticas afetarão o conforto térmico dos ocupantes. Os resultados mostram que, dos cenários avaliados (576) apenas 18,9% estão em uma faixa aceitável de conforto térmico (>70%). Isso indica que a maior parte da HIS atualmente construída na Colômbia não oferece condições de conforto térmico tanto em um cenário de mudanças climáticas quanto no cenário atual, pois em ambas as situações os casos favoráveis representam uma porcentagem baixa em relação ao total de casos avaliados.



Palavras-chave
mudanças climáticas, habitação de interesse social, conforto térmico.

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# INTRODUCTION

Climate change is globally one of the 21st century's most relevant environmental problems. Today, it is the 13th Sustainable Development Goal proposed by the United Nations, and despite strategies that seek to combat it and minimize its consequences, it is an irreversible reality (IPCC, 2007). In the specific case of Colombia, phenomena such as El Niño and La Niña are typical examples of how interannual climate variability has been changing (Pabón & Montealegre, 2017). For this reason, it is important to analyze its impact on Colombian architecture, specifically in Social Housing (hereinafter, SH), and reflect on its resilience capacity, since its construction comprises one of the highest indexes in the country.

Colombia is located on the equatorial line in the tropical zone of South America; as a result, it receives a high contribution of annual solar radiation. This specific location means that its climate is determined by its topography, namely that meteorological changes fluctuate depending on the geographical position of the cities (IDEAM & UNAL, 2018). Due to this aspect, the country cannot be categorized within a single specific climate, so sometimes the consequences that climate change has in the national territory are not obvious. Faced with this situation, Pabón (2012) argues that the overwhelming expression of global warming and climate change in Colombia is the shrinking of mountain glaciers and the rising of the average sea level on the Colombian coasts. For this reason, Colombian architecture should consider an adaptation process that prioritizes the country's current and future environmental dynamics.

Colombia has been showing a clear pattern of growth in urban centers since the mid-20th century, in that the country's regional capitals exceed 90% urbanization, while smaller cities show much higher growth compared to rurality (National Administrative Department of Statistics, 2021b). This shows the need to start evaluating the criteria that are currently considered for building design.

According to the intergovernmental panel on climate change, building operation and construction produce 38% of all energy-related $CO_2$ emissions, so these must be halved by 2030 if the construction sector is to move towards climate neutrality by 2050 (IPCC, 2020).

Among the strategies proposed in international studies to address climate change, two possibilities stand out. On one hand, Aleksić et al. (2016) propose "mitigation and adaptation", both applicable to any sector of society. According to the authors, from the architectural point of view, mitigation is addressed through the creation of energy-efficient buildings, the use of renewable energies, and an appropriate selection of materials; meanwhile, climate change adaptation seeks to build energy-efficient buildings that also adapt to the natural conditions of their context. Thus, it is proposed that attention so far in the architectural field has focused on mitigation measures, which has meant that the priority is not implementing strategies that help existing buildings to be resilient to their environment.

Considering this, the authors present several examples of houses that are resilient to extreme climatic conditions such as hurricanes, floods, or unstable terrains, which, through adaptability, resist these situations. By analyzing this in the Colombian context, the need to propose houses and spaces resilient to context-related climatic conditions is ratified and, in this way, apart from responding to climatic adversities, it can contribute to improving people's quality of life. As Eckardt (2011) explains, "resilience enables the coexistence of communities with the risk conditions of a given territory."

Likewise, within the climate change adaptation process, the relevance of thermal comfort to people's health has also been demonstrated, which happens due to long periods spent in enclosed spaces. Gamble et al. (2009) show that a person can spend more than 90% of their life inside a building, demonstrating the impact that its design has on their health. For this reason, the explanations of Soto-Estrada et al. (2016) and Januszkiewicz (2017) are relevant at this point since, despite researching in separate parts of the world, Colombia and Poland, they agree on the importance that the envelope's design has in a building.

In their studies, both mention that resilient buildings, apart from generating thermally comfortable spaces, help people's physical and mental health not to be harmed, ratifying the direct relationship there is between architecture, health, and climate change. Thus, the two studies show that the type of architecture currently being developed in the two contexts analyzed does not respond to its immediate environment, and with this, it is concluded that the architecture we live in is not resilient to climate change. Understanding it as such, it is crucial to start developing homes that guarantee their occupants' well-being from their design, both from their conception and for future scenarios.

Additionally, from the urban point of view, talks have also begun about the importance of

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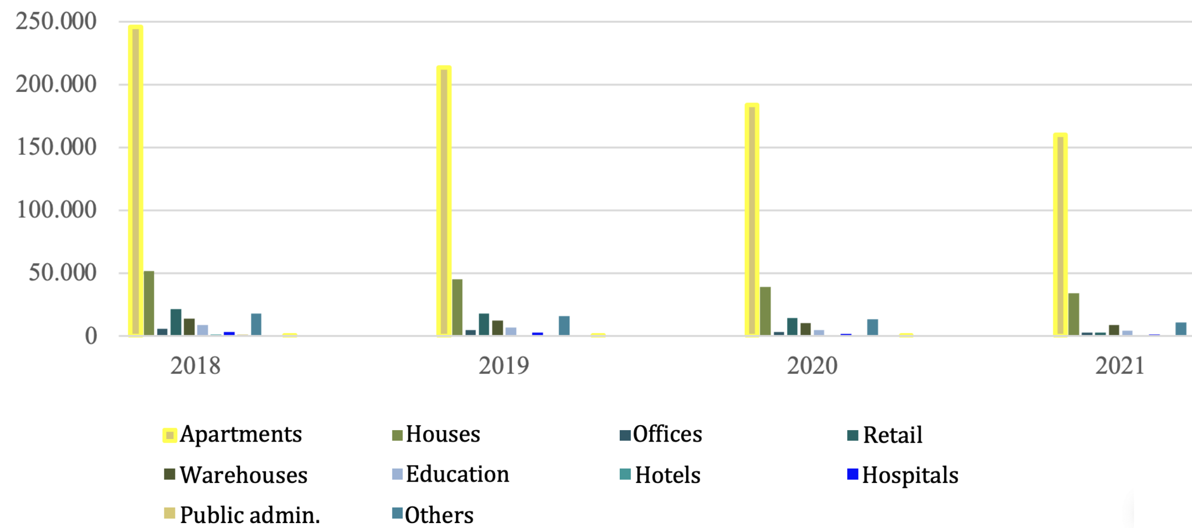


Figure 1. Annual average of the new area by purpose, 2018-2021. Source: Preparation by the authors based on the Buildings Census (CEED).

resilience to climate change and its relationship with sustainability. Alavsi et al. (2021) mention that climate adaptation is one of the most relevant criteria for sustainability and gives, as an example, cities in Asia where they have managed to find harmony between architecture and the environment based on the experience and culture of the local community. Likewise, Gifreu (2018) dares to rethink the definition of sustainable development, stating that it must be "timely to prevent and mitigate the effects of climate change".

In this way, it is essential to understand that climate change is real, as is the need to investigate not only mitigation but also adaptation measures, as the scenario described reaffirms the need to consolidate buildings that are resilient to future climatic conditions.

Bearing this in mind, the main objective of this research was to study the thermal behavior of SH in the face of climate change, located in the three most populated cities of Colombia: Bogotá, Medellín, and Cali, using computer simulations to observe their behavior in three future scenarios (2030/2050/2080).

## HOUSING IN COLOMBIA

Between 2018 and 2021, multifamily housing was the most built construction type in Colombia, accounting for around 68% of the new builds according to a 2021 study conducted by the National Administrative Department of Statistics (2021a), whose data can be seen in Figure 1. This was the main reason why this research focused on Colombian multifamily housing because, by being the most representative, it can lead to a greater social impact. Likewise, within the cited document, SH represented the largest area in the multifamily housing sector, thus further narrowing down the case study.

SH in Colombia is defined by the Ministry of Housing, City, and Territory (2020) as "one that has the elements that ensure its habitability, with quality standards in urban, architectural, and construction design and whose maximum value is 150 current legal minimum monthly salaries (150 SMLMV)".

For 2021, SH has become one of the main strategies to provide a home for Colombian families. However, these houses are not built taking into account environmental conditions or sustainability parameters that guarantee low energy consumption.

Giraldo & Herrera (2017) and Giraldo et al. (2015) explain that passive air conditioning strategies are not implemented in Colombian SH, but mechanical ventilation systems are usually used to help improve the building's feeling of internal comfort, which generates greater energy consumption. Hence, SH in Colombia is not designed to face the context's current or future climatic conditions o without using active strategies that help to improve comfort conditions. Giraldo & Herrera (2017) argue that the scientific management of comfort through passive strategies is disregarded when designing these homes, which consequently, generates decontextualized buildings that do not guarantee the well-being of their inhabitants.

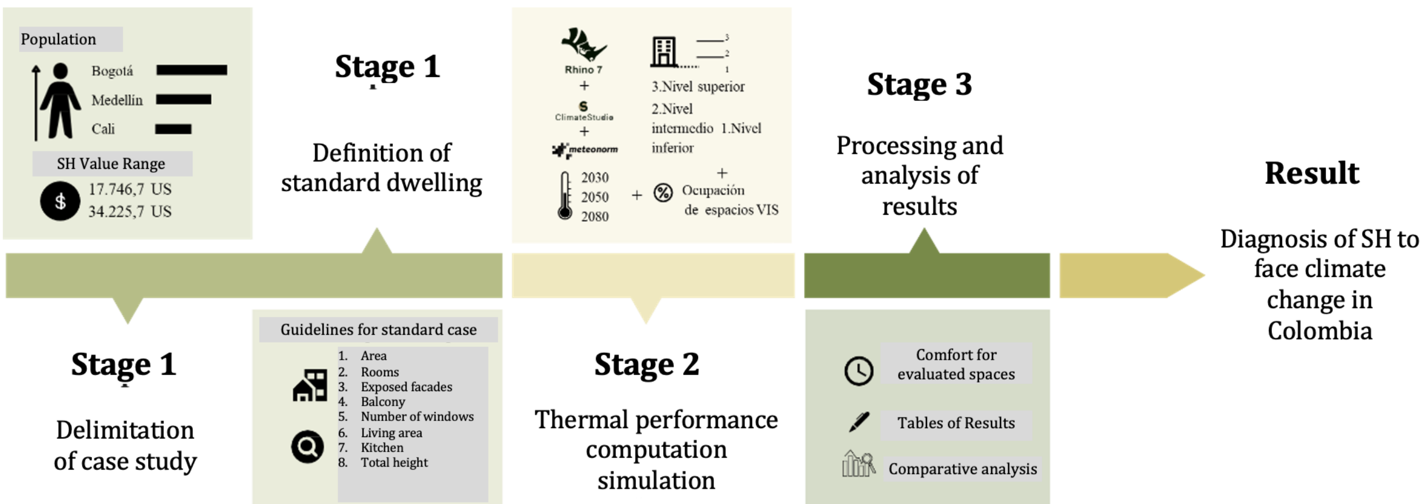


Figure 2. Graphic summary of the methodology implemented for the research. Source: Preparation by the authors.

Table 1. Relative humidity and average temperature for the evaluated cities. Current scenario and future scenarios. Source: Preparation by the authors.

| City | Year | Average temperature* (°C) | Relative humidity (%) | Average Temperature* coldest day (°C) | Average Temperature* hottest day (°C) | Temperature* range in comfort (ASHRAE 55, Comfort 90) |
|---|---|---|---|---|---|---|
| Bogota | Current | 13.2 | 81.7 | 11.9 | 13.8 | 24.4 - 19.4 |
| | 2030 | 14.4 | 80.8 | 12.3 | 15.6 | 24.8 - 19.8 |
| | 2050 | 15 | 80.6 | 12.6 | 16.6 | 25 - 20 |
| | 2080 | 16.3 | 80.4 | 14.1 | 17.3 | 25.4 - 20.4 |
| Data taken from the Bogotá/Eldorado weather station, Latitude: 4.717° Longitude: -74.15°, Altitude: 2,548 masl | | | | | | |
| Medellín | Current | 21.8 | 70.8 | 21.4 | 26.3 | 27.1 - 22.1 |
| | 2030 | 22.1 | 77.2 | 22.7 | 26.2 | 27.2 - 22.2 |
| | 2050 | 22.6 | 77.3 | 23 | 26.4 | 27.3 - 22.3 |
| | 2080 | 23.8 | 77.4 | 23 | 26.9 | 27.7 - 22.7 |
| Data taken from the Medellín/Olaya Herrera weather station, Latitude: 6.217° Longitude: -75.6°, Altitude: 1,499 masl | | | | | | |
| Cali | Current | 23.4 | 76.3 | 21.8 | 25.6 | 27.6 - 22.6 |
| | 2030 | 24.8 | 74.9 | 22.3 | 28.4 | 28 - 23 |
| | 2050 | 25.3 | 74.9 | 23.1 | 28.8 | 28.1 - 23.1 |
| | 2080 | 26.4 | 75.1 | 24.2 | 29 | 28.5 - 23.5 |
| Data taken from Cali CO weather station, Latitude: 3.4°, Longitude: -76.5°, Altitude: 944 masl | | | | | | |

*Dry bulb temperature

# METHODOLOGY

This research implemented an experimental and quantitative methodology that allowed diagnosing the climate change adaptation capacity of SH in Colombia. The methodology included three stages: a first stage to delimit the case study and define the type of housing to be evaluated. A second one, where thermal performance computer simulations were run for standard houses in the three selected cities (Bogotá, Medellín, and Cali), considering future climate projections (2030/2050/2080). Finally, a third stage, which included processing the results obtained and making a comparative analysis, that considers the relationship between time and place.

Table 2. Occupancy patterns and artificial lighting. Source: Preparation by the authors.

| Schedule | Occupation patterns | | Artificial lighting patterns (DPI) (5w/m²) | |
|---|---|---|---|---|
| | Rooms (%) | Living Room/Kitchen (%) | Rooms (%) | Living Room/Kitchen (%) |
| 00:00 - 00:59 | 100 | 0 | 0 | 0 |
| 01:00 - 01:59 | 100 | 0 | 0 | 0 |
| 02:00 - 02:59 | 100 | 0 | 0 | 0 |
| 03:00 - 03:59 | 100 | 0 | 0 | 0 |
| 04:00 - 04:59 | 100 | 0 | 0 | 0 |
| 05:00 - 05:59 | 100 | 0 | 0 | 0 |
| 06:00 - 06:59 | 100 | 0 | 100 | 0 |
| 07:00 - 07:59 | 100 | 0 | 100 | 0 |
| 08:00 - 08:59 | 0 | 0 | 0 | 0 |
| 09:00 - 09:59 | 0 | 0 | 0 | 0 |
| 10:00 - 10:59 | 0 | 0 | 0 | 0 |
| 11:00 - 11:59 | 0 | 0 | 0 | 0 |
| 12:00 - 12:59 | 0 | 0 | 0 | 0 |
| 13:00 - 13:59 | 0 | 0 | 0 | 0 |
| 14:00 - 14:59 | 0 | 50 | 0 | 0 |
| 15:00 - 15:59 | 0 | 50 | 0 | 0 |
| 16:00 - 16:59 | 0 | 50 | 0 | 100 |
| 17:00 - 17:59 | 0 | 50 | 0 | 100 |
| 18:00 - 18:59 | 0 | 100 | 0 | 100 |
| 19:00 - 19:59 | 0 | 100 | 0 | 100 |
| 20:00 - 20:59 | 0 | 100 | 0 | 100 |
| 21:00 - 21:59 | 0 | 100 | 0 | 100 |
| 22:00 - 22:59 | 100 | 0 | 100 | 0 |

Figure 2 outlines and describes in detail the methodological process of the research.

To delimit the case study, the SH located in the country's three most populous cities was considered, which, according to the latest population and housing census of 2018, are Bogotá, Medellín, and Cali (National Administrative Department of Statistics, 2018). Then, the commercial value range defined for SH in the country was identified, which for 2022 ranges from US $17,746.7 (70 SMLMV) to US $34,225.7 (150 SMLMV).

After defining the range and location, data on the current offer in the real estate sector was collated using websites, to determine a typified housing model in each of the cities being studied. In this phase, 20 recently completed multifamily SH projects, or ones under construction, were considered. Of these, eight aspects of the evaluated housing typologies were identified: apartment area, number of rooms, number of exposed facades, the inclusion of a balcony, number of windows per room, living area and kitchen, and total height of the building.

Once each standard dwelling was established, thermal performance computational simulations were run in the Rhinoceros 3D software with the ClimateStudio plug-in, which is supported by the EnergyPlus calculation engine for its thermal performance simulations (Solemma, 2020). This allows making simulations for energy efficiency, daylight access, artificial light performance, and aspects of thermal and visual comfort.

To run the simulations, climate files were taken from the main weather stations for each of the selected cities. Subsequently, these files were processed through the Meteonorm climate projection software

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Table 3. Metabolic rate and internal loads established by city. Source: Preparation by the authors.

| Standard apartment - Bogota | | | | | |
|---|---|---|---|---|---|
| Space | Area ($m^2$) | Num. of people | People/$m^2$ | Metabolic rate | Equipment (kW) |
| Kitchen / Living Room | 15.8 | 4 | 0.25 | 1.8 | 7.59 |
| Master bedroom | 8.25 | 2 | 0.24 | 0.7 | n/a |
| Room 1 | 4.97 | 1 | 0.2 | 0.7 | n/a |
| Room 2 | 6.61 | 1 | 0.15 | 0.7 | n/a |
| **Standard apartment - Medellin** | | | | | |
| Kitchen / Living Room | 18.03 | 4 | 0.22 | 1.8 | 6.66 |
| Master bedroom | 12.08 | 2 | 0.17 | 0.7 | n/a |
| Room 1 | 5.96 | 1 | 0.17 | 0.7 | n/a |
| Room 2 | 5.96 | 1 | 0.17 | 0.7 | n/a |
| **Standard apartment - Cali** | | | | | |
| Kitchen / Living Room | 17.92 | 4 | 0.22 | 1.8 | 6.7 |
| Master bedroom | 9.52 | 2 | 0.21 | 0.7 | n/a |
| Room 1 | 4.95 | 1 | 0.2 | 0.7 | n/a |
| Room 2 | 6.17 | 1 | 0.16 | 0.7 | n/a |

to generate climate files in three future scenarios (2030/2050/2080). The most relevant climate data of the cities evaluated for the current and future scenarios are presented in Table 1.

Along with the analysis of the climatic data, four annual simulations were run (current, 2030, 2050, and 2080) for spaces mainly occupied by the standard housing of each city, varying the orientation of their main facade. The results showed the hourly operating temperature in a given period as the most relevant data, according to the use of the evaluated spaces. Additionally, the variable of dwelling location in relation to the building was considered. Thus, three situations were simulated for each type of house: the first on the first floor, the second on an intermediate floor, and the third on the top floor.

To define occupancy schedules, artificial lighting patterns, the number of people, and the thermal load of equipment, the regulations established by the Brazilian Association of Technical Standards (ABNT) (2013), which manage clear and consistent standards with the Colombian reality, were taken into account (Table 2). Regarding the metabolic rate, the figures determined by the CBE thermal comfort tool were used, which has specific standards for each activity (Table 3). Natural ventilation, as it is a passive space, is considered through the openings, which were assigned an operating temperature, an opening percentage, and a given schedule (Table 4).

On the other hand, for a while now climate change projection scenarios have been created as a tool for research and assessment of the impact and mitigation of climate change. These are defined as "[...] alternatives based on assumptions, of how the world will evolve, so they are not forecasts, since they are not associated with probabilities" (Escoto et al., 2017) and are published by the Intergovernmental Panel on Climate Change (IPCC).

The main objective of these scenarios is to facilitate the research and evaluation of climate change, reducing the range of uncertainty in the efforts made for its mitigation and adaptation (O'Neill et al., 2014). This is why authors such as Kebede et al. (2018) and O'Neill et al. (2014) recommend that the scientific community considers a set of common scenarios.

Notwithstanding this, for this research, it was only possible to generate scenario A2 of the SRES scenarios for the climate files considered, which represents one of the least optimistic scenarios of this set. According to what has been proposed in

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Table 4. Temperature, percentage, and time enabled for window opening. Source: Preparation by the authors.

| City | Year | Operating temperature that enables the opening of a window | Percentage of effective window opening | Schedule enabled for window operation |
|---|---|---|---|---|
| Bogota | Current | 21.9 | 50% (sliding opening system) | Hours of occupancy determined for each space. See Table X |
| | 2030 | 22.3 | | |
| | 2050 | 22.5 | | |
| | 2080 | 22.9 | | |
| Medellín | Current | 24.6 | | |
| | 2030 | 24.7 | | |
| | 2050 | 24.8 | | |
| | 2080 | 25.2 | | |
| Cali | Current | 25.1 | | |
| | 2030 | 25.5 | | |
| | 2050 | 25.6 | | |
| | 2080 | 26 | | |
| Infiltrations considered | | Infiltration renewal rate: 0.5 air changes per hour | | |

Table 5. Characteristics of SRES scenarios. Source: Preparation by the authors based on the translation and adaptation of Quante & Bjørnæs (2016) made by Pereira Ruchansky (2019).

| Scenario | Description |
|---|---|
| A1 | Very fast world economic growth, reaching the maximum world population by mid-century, alternative development of energy technologies. It is divided into three groups, which reflect technological change alternatives: intensive in fossil fuels (A1FI), energies of non-fossil origin (A1T), and balance between the different sources (A1B) |
| A2 | Very heterogeneous world with strong population growth, slow economic development, and slow technological change |
| B1 | Scenario with the same world population as A1, but with a faster evolution of economic structures towards a service and information economy. |

the academic literature, this scenario is equivalent to a midpoint between CPR scenarios 6 and 8.5 (Pereira Ruchansky, 2019). On the other hand, regarding the cumulative total of $CO_2$ emissions between 1990 and 2100 for different scenario groups, it is established that scenario A2 could be close to SSP3 and SSP4 (Pedersen et al., 2021). The scenario considered is described in Table 5.

Next, the results obtained from the described simulations were analyzed, considering the ASHRAE 55:2020 Adaptive Comfort Standard for naturally ventilated buildings. This allowed identifying the thermal comfort level for each of the spaces evaluated in the homes using the percentage of time in comfort established by said standard.

To evaluate thermal performance, multiple standards and norms have been created worldwide, such as the Building Thermal Installations Regulation (RITE), the ISO 7730:2005 Standard, ASHRAE 55:2020, and the UNE-EN 16798-1:2020 Standard. However, within Colombian regulations, there is no national standard that allows objectively evaluating comfort.

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Table 6. Constructive characteristics of standard housing for each city. Source: Preparation by the authors.

| City/characteristic | Cali | Medellín | Bogota |
|---|---|---|---|
| Area ($m^2$ - by ranges) | 50$m^2$ - 60$m^2$ | 50$m^2$ - 60$m^2$ | 50$m^2$ - 60$m^2$ |
| Number of rooms | 2 rooms | 3 rooms | 2 rooms |
| Exposed facades | 1 exposed facade | 1 exposed facade | 1 exposed facade |
| Existence of balcony | With balcony | With balcony | Without balcony |
| Bedroom windows | 1 window | 1 window | 1 window |
| Kitchen windows | without windows | 1 window | 1 window |
| Living room windows | 1 window | 1 window | 1 window |
| Number of floors | 8 floors | 23 floors | 12 floors |
| Indoor ceiling height | 2.24m | 2.20m | 2.30m |
| Interior floor finishing | Exposed concrete (without leveling mortar) | Exposed concrete (with leveling mortar) | Exposed concrete (without leveling mortar) |
| Materiality interior walls | Brick partition walls with an average thickness of 12cm | | |
| Materiality external walls | Exterior walls in reinforced concrete with light colored finish (e.g., white, yellow, light blue) | | Exterior walls in reinforced concrete finished in dark colors (e.g., Dark gray, dark brown) |
| Slab materiality and finish | 10cm thick solid slab. Finished on the underside with white textured paint | | |
| Materiality of the roof | 10cm thick solid slab. Finished on the underside with white textured paint. Finished on the upper side with waterproofing and 5cm mortar | | |
| Window installation | 3mm natural aluminum and clear glass window | | |
| **Thermal transmittance of opaque materials** | | | |
| City | Constructive element | U-Value [W/$m^2$K] | Heat Capacity [[k]/$m^2$k] |
| Bogota - Cali - Medellin | Roof | 3.696 | 272.32 |
| | Walls facades | 3.911 | 367.92 |
| | Interior walls | 2.861 | 227.52 |
| | Mezzanine slab | 4.444 | 229.575 |
| | Subfloor slab | 3.39 | 570 |
| **Characteristics of translucent elements** | | | |
| City | U-Value [W/$m^2$K] | SHGC | Tvis |
| Bogota - Cali - Medellin | 5.82 | 0.818 | 0.877 |
| **Fixed and mobile protective elements** | | | |
| In no case were protective elements considered on the windows, either fixed or mobile (ex: eaves, curtains) | | | |

This research considered the ASHRAE 55:2020 Standard for data processing, as it has been widely cited in related regulations and green building certification systems, in addition to being considered as one of the most appropriate to evaluate the thermal performance of free-running homes (Rubio et al., 2017). This is based on the predicted percentage of dissatisfied people (PPD) and predicted mean vote (PMV) as most of the cited standards. This standard proposes a model to determine the thermal comfort requirements in naturally ventilated buildings and is only applicable when the occupants perform a sedentary activity, with a metabolic rate of between 1 and 1.3 met. It also contemplates two upper and two lower operating temperature limits, which are for an acceptability index of 80% and 90% respectively, by which the comfort range for a certain space is defined (Godoy, 2012). The comfort ranges of 90% acceptability for each evaluated scenario are presented in Table 6.

Regarding the definition of standard housing, based on the search carried out in the real estate sector, the characteristics were defined to establish one for each study city. The aspects evaluated are presented in


Figure 3. Architectural floorplans of standard housing for Cali, indicating the location of openings and obstructions. Source: Preparation by the authors.

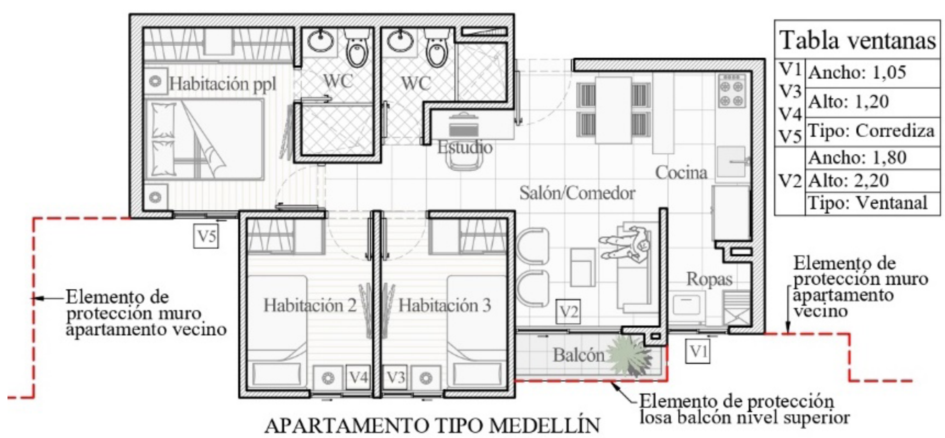


Figure 4. Architectural floorplans of standard housing for Medellin, indicating the location of openings and obstructions. Source: Preparation by the authors.

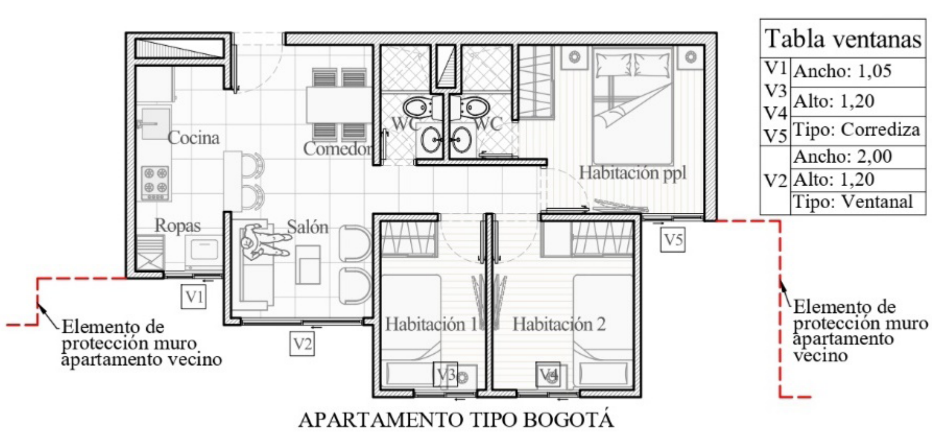


Figure 5. Architectural floorplans of standard housing for Bogota, indicating the location of openings and obstructions. Source: Preparation by the authors.

Table 7. Summary of the results obtained by percentage of favorable scenarios. Source: Preparation by the authors.

| City | Floor | Year | Kitchen and living room | Master bedroom | Bed. 1 | Bed. 2 | Percentage of favorable scenarios by city | Percentage of total favorable scenarios |
|---|---|---|---|---|---|---|---|---|
| Cali | First floor | Current | 100% | 25% | 100% | 50% | 26% | 18.92% |
| | | 2030 | 100% | 25% | 100% | 100% | | |
| | | 2050 | 100% | 25% | 100% | 100% | | |
| | | 2080 | 100% | 25% | 100% | 100% | | |
| | Intermediate floor | Current | 0% | 0% | 0% | 0% | | |
| | | 2030 | 0% | 0% | 0% | 0% | | |
| | | 2050 | 0% | 0% | 0% | 0% | | |
| | | 2080 | 0% | 0% | 0% | 0% | | |
| | Top floor | Current | 0% | 0% | 0% | 0% | | |
| | | 2030 | 0% | 0% | 0% | 0% | | |
| | | 2050 | 0% | 0% | 0% | 0% | | |
| | | 2080 | 0% | 0% | 0% | 0% | | |
| | Percentage of favorable scenarios by space | | 33.33% | 8.33% | 33.33% | 29.17% | | |
| Medellín | First floor | Current | 50% | 0% | 0% | 0% | 14% | |
| | | 2030 | 50% | 0% | 0% | 50% | | |
| | | 2050 | 75% | 25% | 25% | 50% | | |
| | | 2080 | 100% | 50% | 100% | 100% | | |
| | Intermediate floor | Current | 0% | 0% | 0% | 0% | | |
| | | 2030 | 0% | 0% | 0% | 0% | | |
| | | 2050 | 0% | 0% | 0% | 0% | | |
| | | 2080 | 0% | 0% | 0% | 0% | | |
| | Top floor | Current | 0% | 0% | 0% | 0% | | |
| | | 2030 | 0% | 0% | 0% | 0% | | |
| | | 2050 | 0% | 0% | 0% | 0% | | |
| | | 2080 | 0% | 0% | 0% | 0% | | |
| | Percentage of favorable scenarios by space | | 22.92% | 6.25% | 10.42% | 16.67% | | |
| Bogota | First floor | Current | 50% | 25% | 0% | 0% | 17% | |
| | | 2030 | 50% | 25% | 0% | 0% | | |
| | | 2050 | 0% | 0% | 0% | 0% | | |
| | | 2080 | 25% | 0% | 0% | 0% | | |
| | Intermediate floor | Current | 75% | 100% | 0% | 0% | | |
| | | 2030 | 75% | 100% | 0% | 0% | | |
| | | 2050 | 25% | 50% | 0% | 0% | | |
| | | 2080 | 75% | 100% | 25% | 0% | | |
| | Top floor | Current | 0% | 0% | 0% | 0% | | |
| | | 2030 | 0% | 0% | 0% | 0% | | |
| | | 2050 | 0% | 0% | 0% | 0% | | |
| | | 2080 | 0% | 0% | 0% | 0% | | |
| | Percentage of favorable scenarios by space | | 31.25% | 33.33% | 2.08% | 0.00% | | |

Table 8. Consolidated percentage of scenarios where 70% or more of the time in thermal comfort is achieved. Source: Preparation by the authors.

| City | Cali | Medellín | Bogota | Total scenarios |
|---|---|---|---|---|
| Current | 12% | 2% | 9% | 22% |
| 2030 | 12% | 4% | 10% | 25% |
| 2050 | 12% | 6% | 3% | 20% |
| 2080 | 12% | 12% | 9% | 33% |

Table 6 and the most representative characteristics are identified for each of them. On the other hand, Figure 3, Figure 4 and Figure 5 represent their architectural floorplans.

# RESULTS AND DISCUSSION

To process and analyze the results, the starting point was to define a minimum unit of analysis, i.e., one scenario. In total, 576 scenarios were analyzed, which comprise the following analysis parameters: a city, a space, a year, a location in relation to the building, and an orientation. The results of the operating temperatures in the occupancy schedules for each scenario were compared to the comfort range determined for each case, to identify the time that scenario is within thermal comfort.

Subsequently, a minimum value was defined that establishes a scenario as "acceptable" in terms of thermal comfort. Within the academic literature, the limits of acceptability for the predicted mean vote index (PMV) have been investigated, considering variables such as fluctuations in outdoor temperature during the day or year (Lenzuni, 2021), as well as in the validation of indicators to evaluate indoor thermal comfort, such as, for example, the percentage of time a space is within the thermal comfort range (Rueda et al., 2023). However, minimum acceptability related to a space's time in thermal comfort was not found.

Consequently, for the analysis of the obtained results, it was considered that the scenarios with 70% or more of the time within the thermal comfort range would be spaces with an "acceptable" thermal performance. This value is defined by considering that the evaluated scenarios are free running, a condition that makes it difficult to achieve 100% of the time in thermal comfort.

A summary table was obtained (Table 7) with the information obtained, on one hand, that identifies the percentage of scenarios by space, by city, and totals found within that acceptable range of time in comfort. On the other hand, the percentage of favorable scenarios for each year, by city and total scenarios, was summarized in Table 8, identifying the variations between years.

Additionally, the most favorable and unfavorable scenarios for each city are identified in Figure 6, considering the combination of the analysis parameters that yielded the longest and shortest time in comfort.

From the results obtained, particular behaviors by city, and also general trends, are observed. From a general perspective, for Cali and Medellín a differentiated behavior appears between the first, intermediate, and top floors. For the first floor, a higher percentage of time in thermal comfort is seen in most of the analyzed spaces, regardless of orientation or year evaluated. In contrast, for these same cities, apartments on intermediate and upper floors have a higher percentage of time above thermal comfort in the evaluated scenarios, indicating high thermal gains, a situation also found by Murillo et al. (2022) for existing SH in the city of Medellín.

Also, a pattern is observed concerning the times of thermal discomfort. In Medellín and Cali, for most of these scenarios, the main cause is high temperatures. On the other hand, in Bogotá, there are only situations with low temperatures (Table 9). This condition could be evaluated according to research such as that of Pérez-Fargallo et al. (2018), where specific comfort standards are proposed for each case. It is also assumed that the situation described considers the specific climatic conditions of each city.

From analysis by city, it is seen that Cali has only 26% of the scenarios evaluated within an acceptable time in comfort range. However, the variations in the resulting percentages for these do not occur between each year evaluated. This indicates that, for this context, the comfort deficit does not seem to be a consequence of climate change, but rather the current design of SH for Cali. Given this, ensuring a thermally comfortable home for the current scenario should be the priority, which in turn would mean that it would be prepared for the future climate change scenario.

On the other hand, in Bogotá there is a longer time in thermal comfort when the exposed facade faces east and west, compared to the north and south orientation, which do not have a direct solar incidence due to the behavior of the sun in Colombia.

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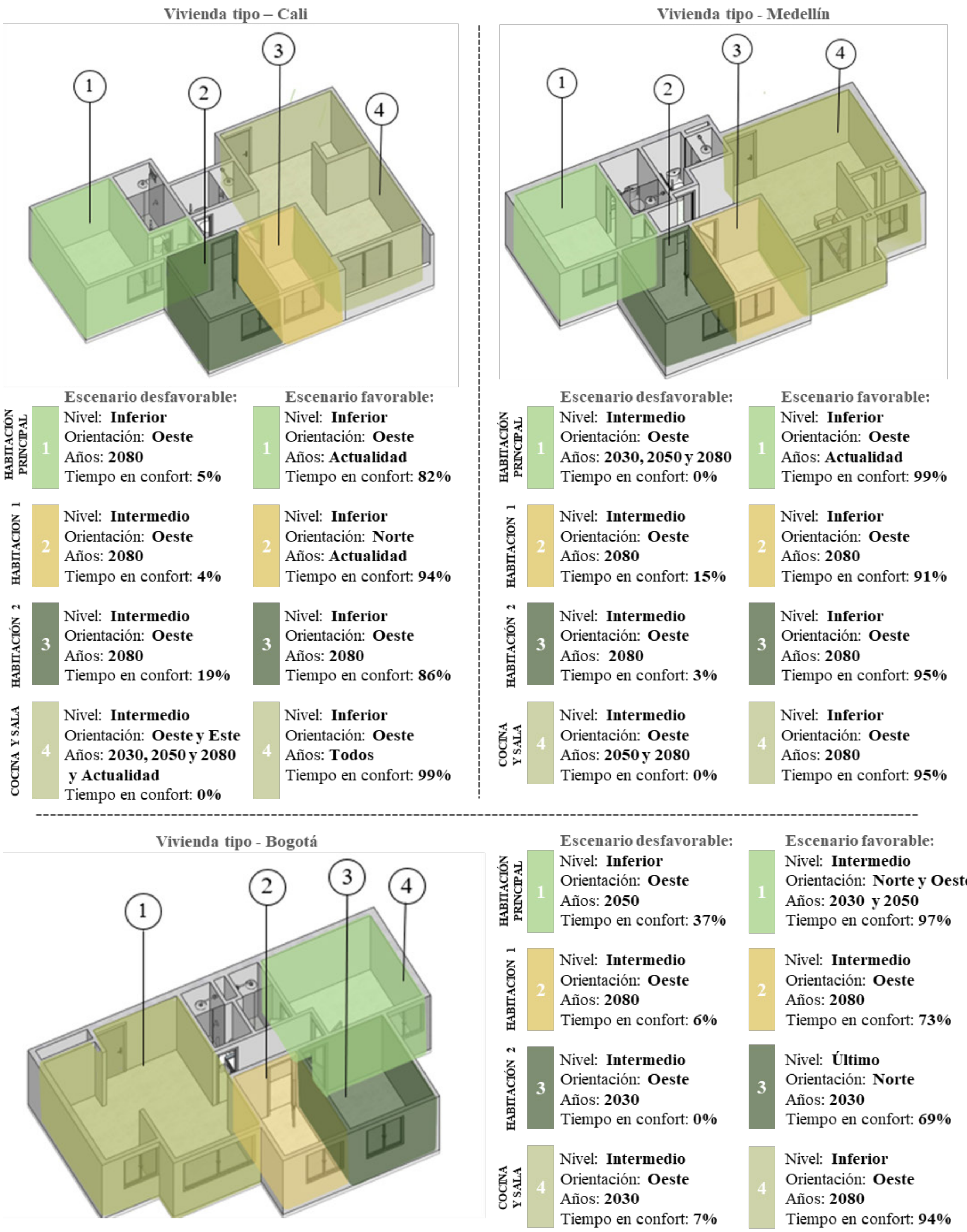


Figure 6. The most unfavorable and favorable scenarios for each analyzed city and space. Source: Preparation by the authors.

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Table 9. Percentage of scenarios in discomfort by city and totals by location within the comfort range. Source: Preparation by the authors.

| City | Space | A higher percentage of time above the comfort range | A higher percentage of time below the comfort range |
|---|---|---|---|
| Cali | Kitchen and living room | 67% | 0% |
| | Master bedroom | 67% | 25% |
| | Bedroom 1 | 67% | 0% |
| | Bedroom 2 | 67% | 0% |
| | Percentage of all scenarios for Cali | 67% | 6% |
| Medellín | Kitchen and living room | 67% | 10% |
| | Master bedroom | 67% | 27% |
| | Bedroom 1 | 67% | 23% |
| | Bedroom 2 | 67% | 17% |
| | Percentage of all scenarios for Medellin | 67% | 19% |
| Bogota | Kitchen and living room | 0% | 65% |
| | Master bedroom | 0% | 67% |
| | Bedroom 1 | 0% | 98% |
| | Bedroom 2 | 0% | 100% |
| | Percentage of all scenarios for Bogota | 0% | 82% |
| Percentage of all scenarios evaluated | | 44% | 36% |

Finally, the space with the greatest impact on climate change is the bedrooms, where the differences in comfort time between the years evaluated are more marked, different from the kitchen where the variations are between 1%-2%.

## CONCLUSIONS

From all the scenarios evaluated (576), only 18.9% are within an acceptable range of time in thermal comfort. Within this figure, Cali is the city where higher percentages of time in thermal comfort are observed, both currently and in the climate change projection, where 26% of the scenarios evaluated for this city are within the comfort temperature range, a low percentage nonetheless. Additionally, it is surprising that, for all the cases evaluated in the three cities, there is a favorable trend over time. For example, by 2080 the percentage of favorable scenarios increases by 11%, compared to the percentage of favorable scenarios for the current climate, for which 78% of the cases evaluated are outside the range in thermal comfort.

This indicates that most of the SH currently built in Colombia do not provide thermal comfort conditions either in a climate change scenario or in the current scenario, because in both situations the favorable cases represent a low percentage of all the cases evaluated. This situation is aggravated by the similarity found between the architectural designs of apartments in different cities, as it evidences a disconnect with the climatic context, which could be one of the main reasons why situations such as those reflected in the results obtained are presented.

For future research, it is urgent to investigate design strategies that respond to climate change for new homes, as well as climate change adaptation strategies for existing homes, considering in both scenarios, as a first measure, satisfying the thermal comfort of the current context. The particular analyses by city, as well as the identification of some trends described in the previous section, can serve as a starting point.

It should also be noted that considerations such as not including pre-existences or neighbors were taken into account within the simulations, since there was no estimated environment because these were hypothetical situations. Additionally, the routines for the user considered are those established by international standards, meaning that they do not adhere to the Colombian sociocultural reality. This is because, at present, there is no profile created that can be studied in this type of specific analysis.

Finally, on being research that does not consider real measurements of the spaces, its conclusions, although they may give indications of possible situations, should be corroborated in future research with on-site measurements and thermal comfort perception surveys.

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