

# Resilient Design Aspects Applied to the Envelope that Determine Thermal Comfort in Social Housing

## Aspectos de diseño resiliente aplicados a la envolvente que determinan el confort térmico en las viviendas sociales

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### Abstract

*City dwellers in South America suffer thermal discomfort inside the buildings because of climate change, a situation that directly affects their health. Resilient design addresses this issue as a response thereto. The objective of the article is to evaluate resilient design characteristics responding to the need for thermal comfort in social housing with regard to the effect of climate change. This was carried out through a theoretical and an empirical stage in two South American cities with opposite characteristics: Passo Fundo in Brazil and Tunja in Colombia. As a result, it was found that CEB is a viable option only in climates with specific conditions given its thermal and environmental properties, according to direct heat gain strategies that tend to be resilient and fit a bioclimatic urban design better. Considering the above, it was concluded that the envelope plays a key role in resilient design in terms of thermal comfort.*

**Keywords:** Climate change adaptation, thermal comfort, resilient design, strategies, affordable housing

### Resumen

Los habitantes de las ciudades en Sur América enfrentan un disconfort térmico al interior de las edificaciones como consecuencia del cambio climático, situación que afecta directamente su salud. Como respuesta a este tema se considera el Diseño Resiliente. El objetivo del artículo es evaluar las características de diseño resiliente que responden a la necesidad de confort térmico en la vivienda social en atención al efecto del cambio climático. Esto se realizó a través de una fase teórica y una empírica en dos ciudades suramericanas con características climáticas opuestas: Passo Fundo en Brasil y Tunja en Colombia. Como resultado se encontró que el BTC es una opción viable solo para climas con condiciones particulares debido a sus propiedades tanto térmicas como ambientales según estrategias de ganancia directa de calor que tienden a ser resilientes y se ajustan mejor a un diseño bioclimático en las ciudades. Teniendo en cuenta lo anterior se concluyó que la envolvente juega un papel fundamental en el diseño resiliente en función del confort térmico.

**Palabras clave:** Adaptación al cambio climático; confort térmico, diseño resiliente, estrategias, vivienda social

## 1. Introduction

Different authors, (Blight and Coley, 2013), (Rodríguez et al., 2019) observe that South American city dwellers suffer thermal discomfort inside their homes, which is related to the increasing climate change phenomenon as a consequence of the accelerated urban growth (IEA and UNEP, 2018). In this sense, it is necessary to design strategies to address the effects of climate change on occupants of indoor environments, but also to minimize the impact of the built environment.

From the health perspective, besides not relying on an optimal housing infrastructure, the lack of adequate temperatures inside the spaces can entail highly negative consequences. The metabolic activities of the body produce heat that must be constantly regulated for comfort and health (Abushakra et al., 2017). Regarding Passo Fundo, the main hospitalization cause is directly related to poor sewage system conditions in certain neighborhoods (Fundação Instituto Brasileiro de Geografia e Estatística, n.d.). Meanwhile, in Tunja, the main morbidity and mortality source in the past decade comes from cardiovascular and cardiopulmonary diseases followed by acute respiratory infections (Ministerios de Salud, 2018).

Thus, according to certain authors, the social housing sector is characterized by high vulnerability levels in the face of realities such as climate change (Barrios and Lazarevski, 2009); (Makantasi and Mavrogianni, 2016). Additionally, around 80% of the total population of South American cities live in this type of housing (DANE, 2019) and predictions indicate that tropical and subtropical countries will be the most affected by the climate change impact (Hashemi, 2019). In this sense, and due to its high demand in contemporary cities, housing is an instrument that allows satisfying comfort needs (Espinosa and Fuentes, 2015).

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A response thereto is Resilient Design, which in this case seeks adaptation and flexibility with the aim of guaranteeing comfort vis-a-vis a constantly changing climate. According to the Resilient Design Institute (2020), this concept embraces the intentional design of buildings, communities and regions to respond to natural and human-made disasters and disturbances, as well as to the resulting long-term changes. The buildings' performance depends on the climate to which they are exposed; so, their lifecycle (50 to 100 years) is the time scale expected for climate to show a substantial change. This means that currently built constructions need to be designed to operate in both the present and the future successfully (Coley, 2012).

The question guiding this research arises from that perspective: Which are the resilient design characteristics responding to the thermal comfort need in social housing? The objective of this study is to evaluate resilient design characteristics responding to the need for thermal comfort in social housing. In this context, climate change becomes an opportunity, since it allows reconsidering the negative view of the urbanization process in Latin American cities towards a sustainable and resilient one (Cubillos Gonzales, 2017); (GGGI, 2020).

According to the above, the study hypothesis proposes the following: if resilient design characteristics in social housing are assessed, then the need for thermal comfort of their dwellers is dealt with. Therefore, the methodological process consisted in a theoretical and an empirical stage with a case study in the cities of Passo Fundo and Tunja. The structure of the article is the following: first, the methodology is explained. Then, the results of the study are described. Subsequently, the discussion and conclusions are presented and, finally, the references are listed.

## 2. Methodology

In order to meet this objective, the methodological frame of the research was developed in two main stages: the theoretical stage and the empirical stage.

### 2.1 Theoretical Stage

This stage consisted in a systematic review of structured and non-structured data through the PRISMA approach (Moher et al., 2009). The purpose of the review was to establish the thermal comfort and resilient design constructs prior to the identification of the existing thermal comfort ranges and the design strategies.

#### 2.1.1 PRISMA Systemic Review

This method consists of a list of 27 items and a four-stage flow diagram that allows a rigorous review of a specific subject matter, thus reducing the risk of bias in the review (Moher et al., 2009). Therefore, the review considered three keywords: thermal comfort, resilient design and social housing, as shown in (Table 1), within a timespan of the last five years.

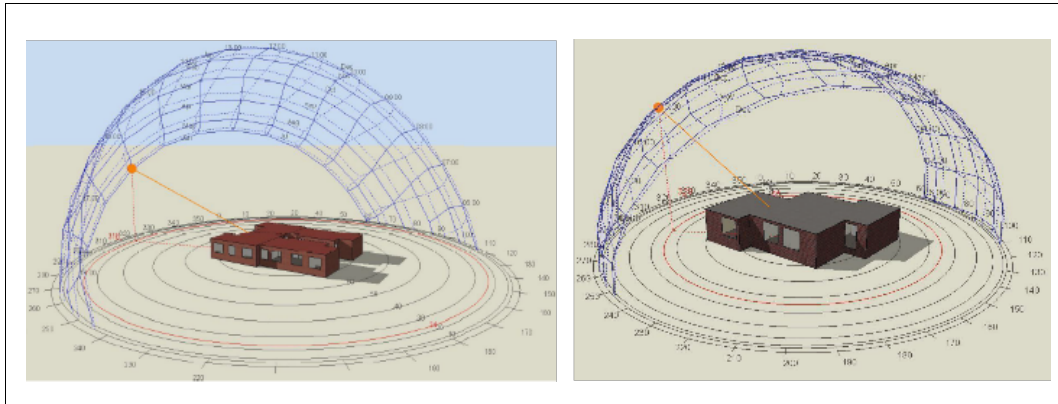
Table 1. Systemic Review

<b>Resilient Design, Thermal Comfort, Social Housing</b>
1. Identification: First, the records were identified through a database search (n = 133). Second, additional records were recognized through other sources (n = 40)
2. Screening: duplicate records were removed (n = 172). Then, the records were screened (n = 100). Finally, recognized records were excluded (n = 0).
3. Eligibility: Full-text articles carefully selected for their eligibility were assessed (n = 45). Then, certain full-text articles were excluded (n = 7).
4. Finally, the studies designated in the quantitative synthesis (n = 1), qualitative (n = 12) and mixed (n = 7) were included.



## 2.2 Empirical Stage

Two case studies were carried out, one in the city of Passo Fundo, in a standard apartment of 42.5 m<sup>2</sup>, and the other in the city of Tunja, in a standard apartment of 56.42 m<sup>2</sup>. (Figure 1) shows the models of the studied apartments, which correspond to social housing projects. The first project has 2 towers of 9 floors each, including 1 bedroom, 1 bathroom, living-dining room, kitchen and laundry area. The second project has four towers of 5 floors each, comprising 3 bedrooms, 2 bathrooms, living-dining room, kitchen and laundry area. This stage includes climate data collection and the identification of the characteristics of materials and construction systems in both cities.



**Figure 1.** Standard apartment models in Passo Fundo and Tunja, respectively.  
Source: Architect Luis Edgardo Fonseca

### 2.2.1 Data Collection

Temperature and relative humidity data from the studied cities were reviewed in a 30-year period (1988-2018) called *Climate Normal*. Therefore, the analysis was based on hydrometeorological information obtained from agencies such as the National Institute of Meteorology of Brazil (INMET) and the catalog of meteorological stations of the Institute of Hydrology and Meteorology and Environmental Studies (IDEAM) of the Colombian Government (Ideam, 2019). The meteorological stations used were N° 839140 located in Passo Fundo and N° 24035130 located in Tunja. Both contexts considered the Köppen climate classification. For Passo Fundo it is (A)Ca(fm) (e)w'', that is, mild temperate, not the Ganges-type of temperature oscillations. For Tunja, it is Cb (x')(w1)igw'', that is, temperate, isothermal, Ganges-type of temperature oscillations.

### 2.2.2 Simulations

**General Climate Analysis:** the first step included a review of bioclimatic strategies related to the weather of both Passo Fundo and Tunja, using the tool *Climate Consultant 6.0* (UCLA Energy Design Tools Group & California Energy Commission PIER Program, 2020), according to the Predicted Mean Vote (PMV) model, the Adaptive Model and the Design Guidelines proposed in the ASHRAE standard 55 (Turner et al., 2010). The Normal Climate of each case was used thereto. This process allowed identifying and selecting the type of strategy that best suits the needs of each city.

**Envelope Analysis:** Once the strategies were decided, the software *Open Studio 2.8* (National Renewable Energy Laboratory, 2019) was used to execute five simulation processes for each standard apartment. It should be highlighted that, in this case, the approach considered just the envelope to define improvements in the thermal transmittance conditions of the materials. In this sense, following a review of the materials, the CEB or Compressed Earth Block was chosen, which can be manufactured onsite or obtained in the surroundings of the studied cities (Andr et al., 2019), which implies a transportation cost reduction and, consequently, a lower environmental impact (Barrera Martínez, 2014). The simulation processes were as follows:

### *Current condition of the envelope materials (façade) in the face of climate*

- Improvement 1: Wall with CEB of 0.15 m
- Improvement 2: Wall with CEB of 0.20 m
- Improvement 3: Composite wall with solid brick
- Improvement 4: Composite wall with CEB

Subsequently, the software *Design Builder 6.1.0.006* was used for simulating the validation of previous results (*Design Builder Software Ltd., n.d.*). Additionally, the buildings' outdoor and indoor temperatures were assessed in this step.

#### **2.2.3. Evaluation**

The simulation results were evaluated and the most viable alternative for the studied context was proposed.

## **3. Results**

### **3.1 Results of the Theoretical Stage**

The results of the theoretical stage, where the constructs of resilient design and adaptive thermal comfort are defined, are presented below.

#### **3.1.1 Resilient Design**

The adaptation strategies take the current structure and its future evolution, thereby understanding how it yields and reacts to the opportunities (Courtney et al., 1997). In other words, resilient design makes the environment less uncertain, which implies a level of compliance for a longer period. Thus, regarding the thermal comfort from the resilience perspective, it is necessary to consider, besides the actual range, a scenario with extreme characteristics to which structures need to respond.

On the other hand, it was possible to observe that the envelope is a key aspect when talking about resilient design, because it has a high "U" value due to its heat gain from the exterior (Bhikhoo and Hashemi, 2017; Osman and Sevinc, 2019; Perez et al., 2018). Consequently, it is necessary to envisage its effects on the indoor environment of the apartments on higher floors, and to give special attention to its design so it can be adapted to the needs of the different levels.

Likewise, it is important to mention the bioclimatic design (Moore et al., 2017), because the optimization of the humans-climate relationship is given through the architectonic form (Rubio et al., 2015). Consequently, this can be a first step for a sensitive adaptation towards climate change. That said, a resilient design strategy implies taking bioclimatic actions to reduce a population's vulnerability in a specific place and, in this case, guarantee the thermal comfort in climate change scenarios.

#### **3.1.2 Adaptive Thermal Comfort**

First, it was possible to identify that most methodologies for evaluating thermal comfort are based on adaptive models (Bhikhoo et al., 2017); (Mahar et al., 2019); (Sánchez et al., 2019); (Silva et al., 2016); (Trebilcock et al., 2017); (Vellei, 2015), as indicated in the ASHRAE standard 55 (Turner et al., 2010). Thus, in the understanding that the adaptive comfort theory states that comfort depends on both the context and the behavior of the occupants and their perception, it is possible to predict scenarios that are more realistic and consider the changing climate conditions.

However, the adaptive model arises as a complement of the PMV model, which has a 34% effectiveness (Abushakra et al., 2017). The PMV model is developed under static conditions, while the adaptive one operates under dynamic conditions. Therefore, it is necessary to apply both models to evaluate the thermal comfort in terms of resilience, in order to reduce the degree of uncertainty in their evaluation.

Furthermore, regarding buildings such as housing, where occupants have the possibility of adjusting their conditions by modifying the levels or layers of clothing and opening or closing the windows, the preferred temperature is best represented by the theory of the adaptive thermal comfort (Coley et al., 2017). This does not mean that it fully and effectively meets the comfort needs of the occupants, in view of the climate change phenomenon and its progressive increase over time.



### 3.2 Results of the Empirical Stage

#### 3.2.1 General Climate Analysis

**Simulation with the Static Model:** (Figure 2) corresponds to the simulation using the psychrometric chart that the Climate Consultant software establishes by default when introducing the climate data of each city, using the static model of the ASHRAE standard 55. This chart indicates that the thermal comfort zone is located between 22°C and 28°C. Regarding Passo Fundo, it corresponds to 20% of comfort per year, meaning 1757 hours out of 8760 per year within that range. Likewise, the chart reveals that the sole fact of using passive strategies would considerably increase the comfort levels in this city.

On the other hand, and unlike Passo Fundo, Tunja is in that zone only 3% of the year see (Figure 3). This means that, out of 8760 hours per year, this city is comfortable only 26 hours, according to the software criteria. Moreover, in order to counteract this situation in terms of comfort, the software proposes the use of active and passive strategies and their respective improvement percentage during the year.

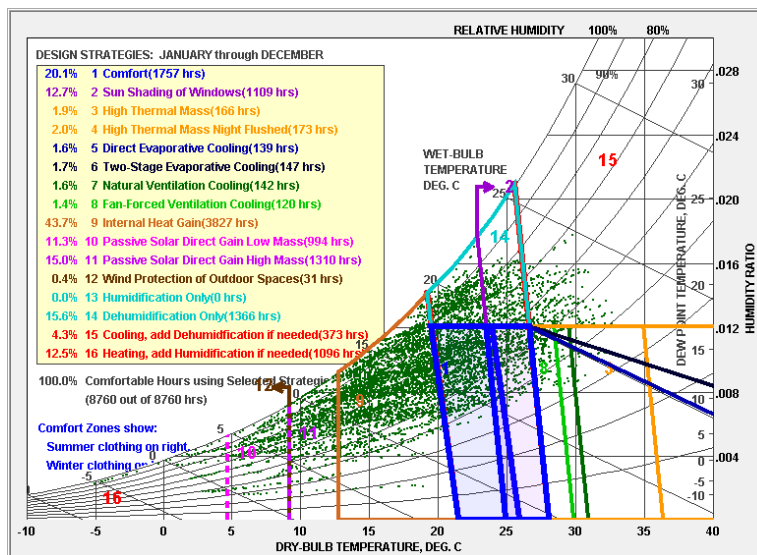


Figure 2. Psychrometric chart for Passo Fundo using the Static Comfort Model  
 Source: Climate Consultant version 6.0

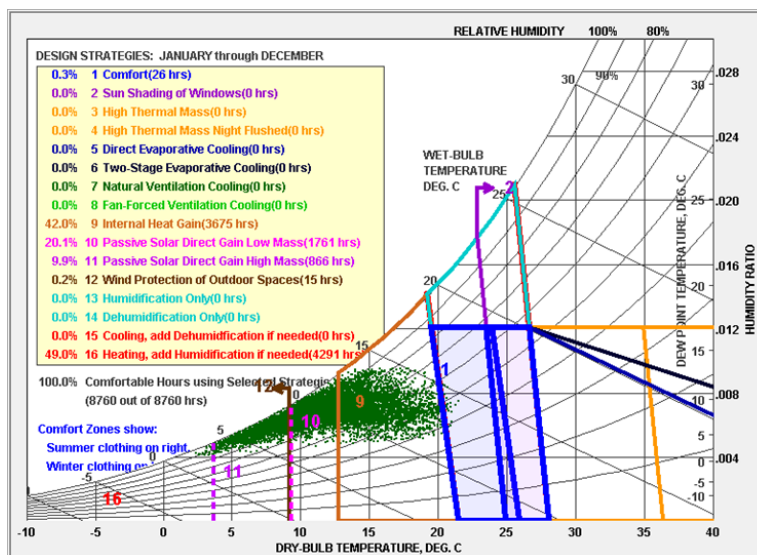


Figure 3. Psychrometric chart for Tunja using the Static Comfort Model  
 Source: Climate Consultant 6.0



The analysis of the strategies proposed by the software allowed establishing which can or cannot apply in the local context of each city and can be resilient therein. With regard to the first studied city, from all the strategies presented by Climate Consultant, those that fulfill the mentioned characteristics are:

- ✓ Heat gain from lights, people and appliances.
- ✓ Lightweight construction and operable walls, shaded outdoor spaces.
- ✓ Low sloping roofs with wide cantilevers.
- ✓ Chimney providing surface thermal mass to store daytime winter and nighttime summer solar gains.
- ✓ Orientation enabling winter sunlight to enter daytime-use spaces.
- ✓ Envelope material that accumulates energy.
- ✓ Nearby east-west vegetation.

Regarding the second city, the selected strategies were:

- ✓ Heat gain from lights, people and appliances.
- ✓ Chimney providing surface thermal mass to store daytime winter and nighttime summer solar gains.
- ✓ Orientation enabling winter sunlight to enter daytime-use spaces.
- ✓ Envelope material that accumulates energy.
- ✓ Nearby east-west vegetation.
- ✓ Additional insulation in the roof.
- ✓ Windows without shading.
- ✓ Use of operable elements (operable windows) (blackout blinds, curtains).
- ✓ Basement insulation.

Therefore, given that the common strategies for both cities are: 1. Heat gain from lights, people and appliances; 2. Chimney providing surface thermal mass to store daytime winter and nighttime summer solar gains; 3. Orientation enabling winter sunlight to enter daytime-use spaces; 4. Envelope material that accumulates energy and 5. Vegetation, the solutions in the static model are aimed mostly at passive solar use and heat gain.

Likewise, the strategies' relation with the 2030 Palette was verified. This Palette is a resource for the design of built environments that are zero-carbon, adaptable and resilient (Architecture 2030, n.d.). It is also integrated into other software such as Sefaira, Insight 360 and Climate Consultant, and includes design tools from EDGE and examples of projects certified by EDGE.

Consequently, the strategies identified in this model for both cities, which in turn respond to the project of 2030 Palette, are the following: 1. Orientation enabling winter sunlight to enter daytime-use spaces; 2. Chimney providing surface thermal mass to store daytime winter and nighttime summer solar gains and 3. Windows without shading.

**Simulation with the Adaptive Model:** in the simulation with the adaptive model, the psychrometric chart shows that the comfort zone lies within the range of 19°C to 24°C approximately. Therefore, the software proposed using ventilation strategies for controlling the temperature. According to the above, the application of these strategies constitute a comfort percentage of 21% for Passo Fundo, which means 1849 hours of comfort per year see (Figure 4). For Tunja it indicates a percentage of 1.8%, that is, the occupants would be under adaptive comfort conditions 162 hours, out of 8760 hours per year see (Figure 5).



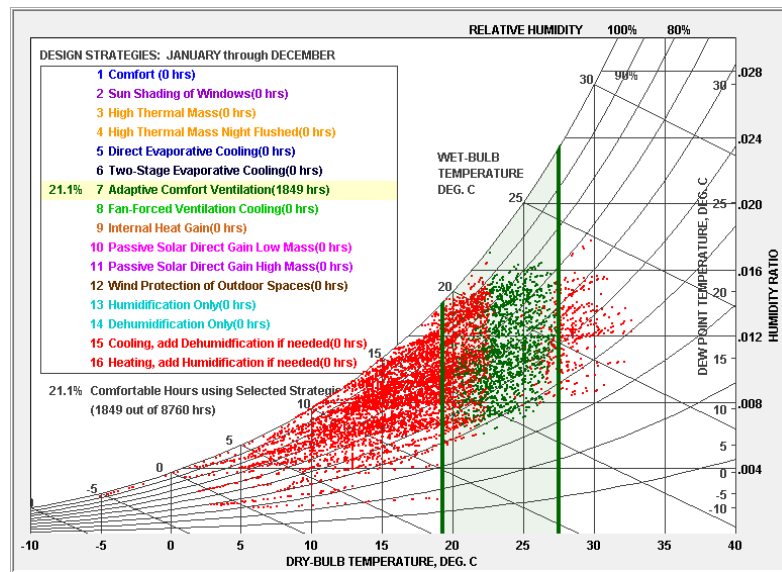


Figure 4. Psychrometric chart for Passo Fundo using the Adaptive Comfort Model  
Source: Climate Consultant 6.0

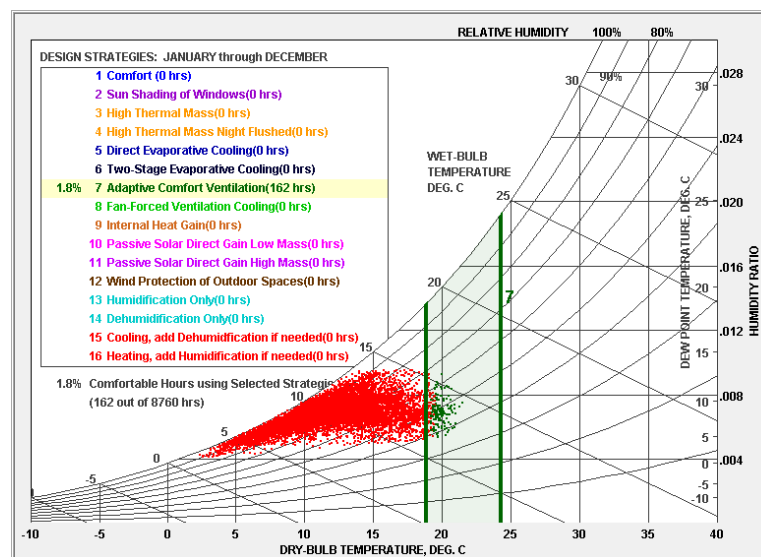


Figure 5. Psychrometric chart for Tunja using the Adaptive Comfort Model  
Source: Climate Consultant 6.0

As in the previous model, the strategies proposed by the software were analyzed to see which ones apply or do not apply and can be resilient in each city. In this case, the same strategies work for both Passo Fundo and Tunja. These are:

- ✓ Natural ventilation, with wind direction up to 45° towards the building through exterior walls and natural barriers.
- ✓ Roof vents.



- ✓ Shading preventing summer breezes and passive solar gain in the winter.
- ✓ Lightweight constructions with operable walls.
- ✓ Traditional passive houses in humid and warm climates with high ceilings and windows.
- ✓ Outdoor-indoor transition area (porch, patio, shaded pergola, etc.).
- ✓ Glazing on the north face for crossed ventilation.
- ✓ Low sloping roofs in mild climates (eaves).
- ✓ Plants on the east side for heat gain.
- ✓ Well-ventilated attics to protect porches and work areas.
- ✓ Elevate the building to minimize the humidity and maximize the natural ventilation.
- ✓ Indirect sunlight with cantilevers, eaves, operable walls, etc.

As in the strategies indicated in the adaptive model, which are also part of the 2030 Palette, the following common strategies were detected: 1. Shading preventing summer breezes and passive solar gain in the winter; 2. Plants on the east side for heat gain; 3. Well-ventilated attics to protect porches and work areas; and 4. Indirect sunlight with cantilevers and eaves.

**Simulation with the Comfort Model Design Guidelines (ASHRAE 2005):** Finally, the same simulation procedure was carried out, but this time using the Design Guidelines of the Comfort Model. These guidelines gather characteristics from both models and set the winter comfort zone between 20°C and 25°C, and the summer comfort zone between 24°C and 28°C. In this model, and as shown in (Figure 6), Passo Fundo would be 2133 hours per year in the comfort zone (24% annual), and the software suggests using mainly passive strategies. On the other hand, Tunja would be 44 hours per year in the comfort zone, that is, 5% annual and, in order to achieve 100%, the software recommends using mixed strategies see (Figure 7).

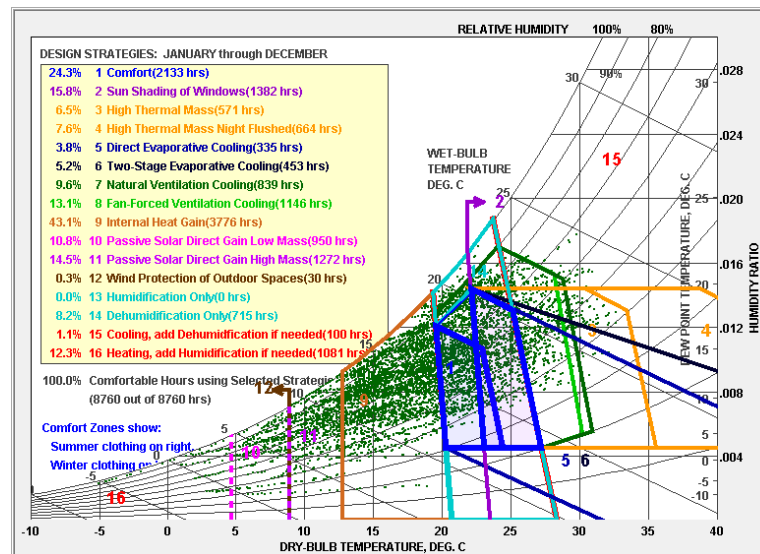


Figure 6. Psychrometric chart for Passo Fundo using the Comfort Model Design Guidelines  
Source: Climate Consultant 6.0





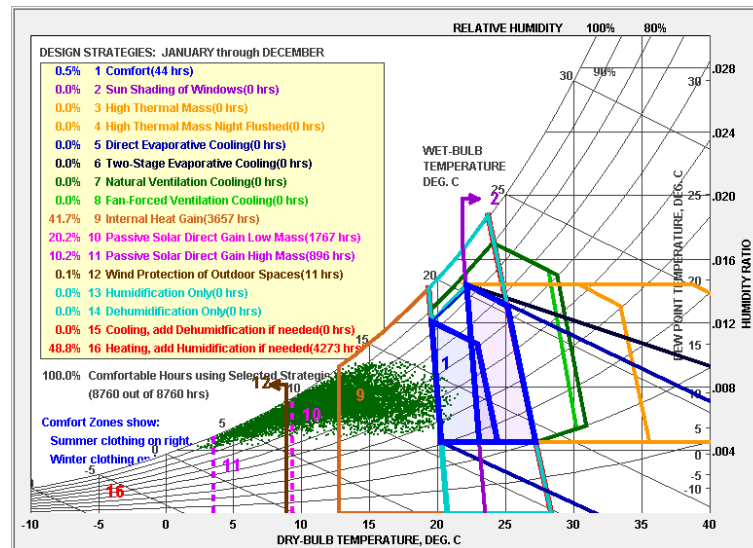


Figure 7. Psychrometric chart for Tunja using the Comfort Model Design Guidelines  
Source: Climate Consultant 6.0

When analyzing the strategies for Passo Fundo, those that apply and have a resilience potential are:

- ✓ Lightweight construction and operable windows; shaded outdoor spaces.
- ✓ Cantilevered windows or operable sunshields.
- ✓ Enabling crossed ventilation by locating doors and windows on the opposite side of the building.
- ✓ Solar gains by orientation. Maximizing exposure in the summer.
- ✓ Heat gain from lights, people and appliances.
- ✓ Orientation enabling winter sunlight to enter daytime-use spaces.

For Tunja, the selected strategies are:

- ✓ Solar gains by orientation. Maximizing exposure in the summer.
- ✓ Heat gain from lights, people and appliances.
- ✓ Orientation enabling winter sunlight to enter daytime-use spaces.
- ✓ Nearby east-west vegetation (at 45°).
- ✓ Windows without shading.
- ✓ Basement insulation.
- ✓ Use of operable elements (operable windows) (blackout blinds, curtains).
- ✓ Garages or storage areas on the side of the building facing the coldest wind to improve insulation.

With regard to their relation to the 2030 Palette, the associated strategies are: 1. Cantilevered windows or operable sunshields; 2. Enabling crossed ventilation by locating doors and windows on the opposite side of the building; 3. Solar gains by orientation; 4. Heat gain from lights, people and appliances; 5. Orientation enabling winter sunlight to enter daytime-use spaces; 6. Vegetation; 7. Windows without shading; 8. Basement insulation; 9. Use of operable elements, and 10. Garages or storage areas on the side of the building facing the coldest wind to improve insulation.

### 3.2.2 Envelope Analysis

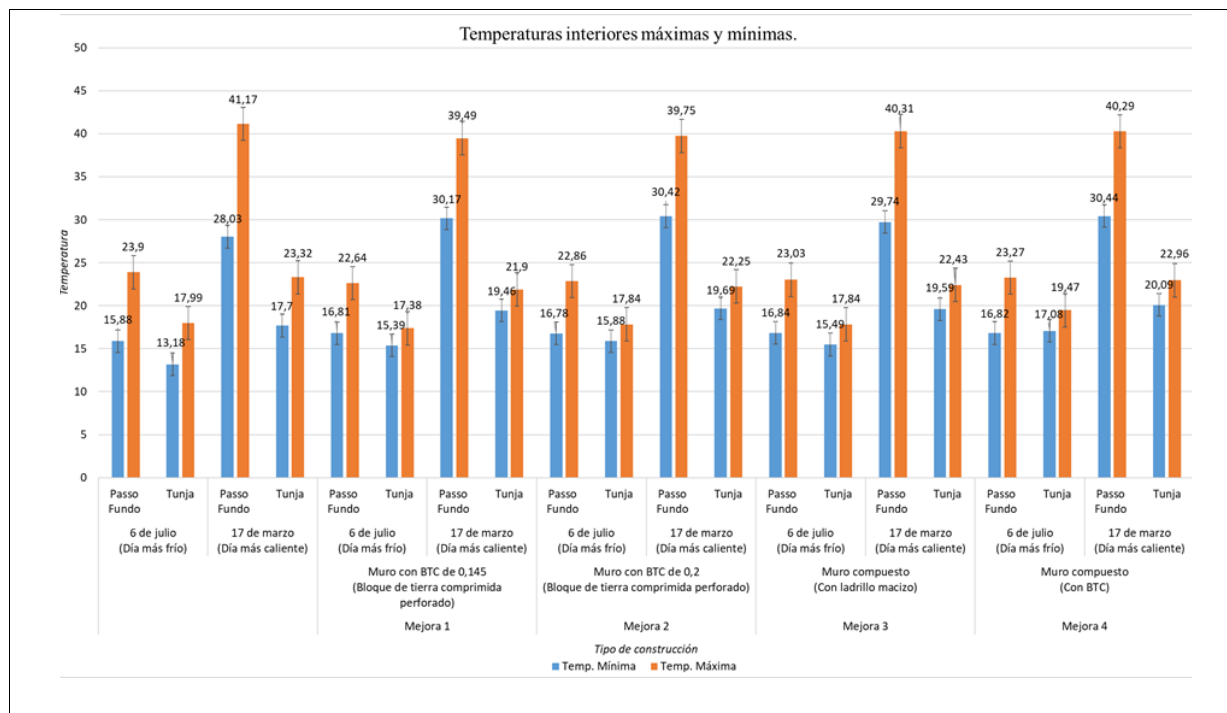
Considering the aforementioned results, the type of strategies that best fit both case studies are those concerning indoor heat gain, rather than those related to the architectural form. Consequently, an improvement of the envelope materials was evaluated, specifically in the façade. An average was defined see (Table 2) to analyze the thermal variability in extreme days, considering the maximum and minimum outdoor temperatures in both cities, and thus compare the data observed in the Climate Normal (1989-2019) in each case. The purpose was to evidence the climate change situation and establish the outdoor temperatures to which the envelope must respond.

**Table 2.** Maximum and minimum outdoor temperatures during the standard climate year

Season of the Year	City	Dry-bulb Temperature °C	
		Minimum Temp.	Maximum Temp.
July 6 (Coldest day)	Passo Fundo	6.46	20.20
	Tunja	6.30	14.92
March 17 (Hottest day)	Passo Fundo	22.68	36.6
	Tunja	10.04	17.86

Therefore, in view of the fact that social housing in Brazil and Colombia have problems associated to the choice and use of materials that are climate-change consistent in terms of thermal comfort conditions (Medina and Escobar, 2019), the compressed earth block or CEB seems a viable option due to both its thermal and environmental characteristics, (Barrera, 2014; Gutiérrez, 2015).

Consequently, (Figure 8) records the indoor temperature variations of the apartments in Passo Fundo and Tunja respectively, with all the improvements made to the current condition. Improvement 1 uses simple walls with CEB of 0.145 m thick, while improvement 2 proposes a 0.2 m increase of the CEB wall section. Moreover, improvement 3 uses composite walls with solid brick, while improvement 4 uses composite walls with CEB.



**Figure 8.** Maximum and minimum indoor temperatures



Accordingly, the current minimum temperature inside the apartment in Passo Fundo increases 12.18°C in relation to the outdoor temperature, while the maximum temperature increases 11.47°C. In Tunja, the minimum indoor temperature increases 6.88°C and the maximum increases 5.46°C in relation to the outdoor temperature. Following improvement 1, the minimum indoor temperature of the Brazilian city increased 13.11°C, while the maximum increased 9.79°C. In the Colombian city, the minimum indoor temperature increased 9.09°C and the maximum, 4.04°C. As for improvement 2, in the former the minimum temperature increased 13.08°C, and the maximum, 10.05°C. While in the latter, the minimum temperature increased 9.58°C and the maximum, 4.39°C.

Furthermore, after improvement 3 in Passo Fundo, the values were 13.14°C and 10.61°C, respectively. Likewise, in Tunja these values were 9.19°C and 4.57°C. Finally, with improvement 4, in Passo Fundo the minimum and maximum indoor temperatures increased 13.15°C and 10.59°C. Regarding the Colombian city, these temperatures were 10.78°C and 5.10°C, where the latter is the best option for Tunja in terms of thermal insulation towards the interior. Finally, an estimated cost was calculated for the proposed improvements. The values are expressed in US dollars to make the understanding easier at global level. These costs refer to local values for 2019, as indicated in (Table 3).

**Table 3.** Estimated costs of materials per m<sup>2</sup>

<b>Condition</b>	<b>Materials</b>	<b>Cost in USD per m<sup>2</sup></b>
Current condition	Solid brick	15.01
Improvement 1	CEB	17.55
Improvement 2	CEB -0.20	22.78
Improvement 3	Composite wall with solid brick	30.03
Improvement 4	Composite Wall with CEB	35.09

#### 4. Discussion

Several authors (Andr et al., 2019); (Barrera, 2014); (Gutiérrez, 2015) agree that CEB is a sustainable material for social housing in Latin American contexts, because they have a low environmental impact and, additionally, they are natural temperature regulator. Nevertheless, considering the results obtained in the simulations, this material causes overheating inside the housing in Passo Fundo, Brazil, where the indoor temperature escapes the established comfort ranges.

On the contrary, in Tunja the proposed material shows a better thermal behavior, thus allowing maintaining the comfort zone inside the housing for a longer time. In this sense, the costs per m<sup>2</sup> were analyzed for all the materials proposed. From the thermal point of view, the composite wall with CEB is the best option for Tunja, but it is 2.3 times more expensive than the solid brick currently used for this type of construction.

However, if Tunja just changes the currently used solid brick for a CEB of 0.15 m (improvement 1), there is already a thermal benefit and the costs would increase only 0.16 times in relation to the current value. This benefit is explained by the fact that the wall with CEB of 0.15 m significantly increases the thermal insulation towards the interior (2°C), in relation to solid brick, and it also guarantees 6144 hours of comfort per year (70% annual). When implementing improvements 2, 3 and 4, indoor temperatures do not change significantly with regard to improvement 1, but they imply a higher cost.



## 5. Conclusions

Considering the above, the envelope plays a key role in the resilient design associated to thermal comfort, through which the heat gain or loss towards the interior is produced. It should be highlighted that, in the Colombian case, the change of materials represents a significant improvement in the thermal comfort ranges; however, in the Brazilian city, this change tends to worsen the comfort conditions in the hot seasons of the year. This means that the resilience has certain limits and there is the risk that, at some point, some active strategy will be needed to guarantee more comfort hours per year.

Likewise, it can be concluded that the chosen material behaves better in climates that do not have significant seasonal changes. This implies that the assessment studies addressing the impact of the climate change must adapt to the specific needs of each place. Additionally, it is possible to observe that, sometimes, the standards and regulations dealing with thermal comfort issues are not implemented correctly in local contexts. For example, in Colombia, the sustainable construction regulation 0549 (which is not mandatory) uses PMV in terms of comfort only (Giraldo et al., 2021). However, the results show that it is necessary to take into account both models: the PMV or static model and the adaptive model, which considers the thermal adaptation as a process integrating the thermal expectations of the occupants and their adaptive actions.

In this sense, the role of the occupants is also a challenge in the resilience design. The models used for simulating the climate conditions already consider the residents' activity. Nevertheless, it would be useful to evaluate their perception in order to corroborate the effects of their decisions and better understand the relationship with their space. To that effect, and as a complement of the simulation processes, the application of the survey proposed in the ASHRAE standard 55 is suggested (Turner et al., 2010).

On the other hand, there is also evidence that the design envisaging climate change conditions undergoes a constant limitation concerning data collection and access to climate data in each place. Specifically for this research, it would be advisable to confirm the data on temperature and relative humidity with onsite measurements and in real time, with the help of specialized instruments, in order to reduce the risk of uncertainty. Finally, the next step is to reflect upon how this kind of improvements affects the local production field and their viability from the industrial perspective. Because this approach allows us to approximate it, from the design and construction point of view, to transitional exercises in the cities, with the purpose of dealing with the environmental, economic and social impacts of climate change.

## 6. Acknowledgements

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