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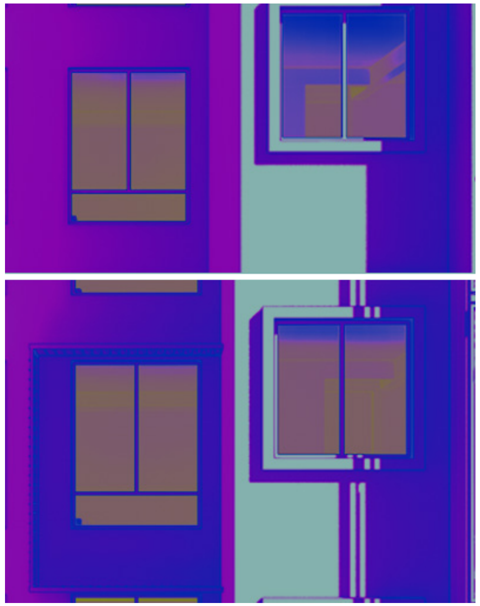
Case study "Perdiz"
Envelope renovation in Barranquilla, Colombia



Lina María García Niño
February, 2023

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Envelope renovation in Barranquilla, Colombia

Department of Architecture and Design
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uniandes

Esto es dedicado a la ciudad.
A la dimensión compleja e incontenible de la que somos parte, al espacio que nos permite habitar. Al espacio que nos da calidad de vida. Al espacio que nos permite vivirlo.

It is dedicated to the city.
To the complex and uncontainable dimension of which we are part, to the space that allows us to inhabit. To the space that gives us a quality of life. To the space that allows us to live it.

Lina María García Niño

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Content

Abstract

The global concern regarding climate change and city population increases are constantly growing. As reported by the UN, the urban population will be more than 70% of the world population by 2050. Therefore, this thesis proposal understands sustainable architecture as the design and construction of buildings with respect for the environment and people (McLennan, 2004). It implies improving the relationship between the environment, the social and the economic files to mitigate the environmental impact of the construction industry and satisfy human needs. In Which, **Habitability is the social function of sustainability,** and its objective is the satisfaction of human needs (Tarchópulos Sierra & Ceballos Ramos, 2003).

Hence, this study focuses on social housing (VIS) in Colombia. It recognises that Interior **thermal comfort** is an essential variable in a building design due to its impact on **housing habitability conditions, the inhabitants' well-being, and the building energy efficiency by decreasing CO2 emissions.** Nevertheless, due to its scarce approach to hot tropical climates, **the thesis investigates which thermal comfort criteria could be involved in an existing high-rise VIS building in Barranquilla, Colombia, by Improving the dweller's living conditions in the current and future climate change scenario**. The methodology combines dynamic thermal simulations and file work. Data will be collected by measures, observation, surveys, and interviews; After this, some criteria to optimize habitability through the **building envelope renovation** will be defined.

Keywords: Bioclimatic, climate change scenarios, passive cooling, social housing, thermal Comfort.

Resumen

La preocupación mundial por el cambio climático y el aumento de la población de las ciudades crece constantemente. Según lo informado por la ONU, la población urbana será más del 70% de la población mundial para el año 2050. Por lo tanto, esta propuesta de tesis entiende la arquitectura sostenible como el diseño y construcción de edificios con respeto por el medio ambiente y las personas (McLennan, 2004). Esto Implica mejorar la relación entre el medio ambiente, lo social y lo económico para mitigar el impacto ambiental de la industria de la construcción y satisfacer las necesidades humanas. En el cual, **la Habitabilidad es la función social de la sustentabilidad,** y su objetivo es la satisfacción de las necesidades humanas (Tarchópulos Sierra & Ceballos Ramos, 2003).

Por lo tanto, este estudio se centra en la vivienda social (VIS) en Colombia. Reconoce que el **confort térmico interior** es una variable esencial por su impacto en las **condiciones de habitabilidad, el bienestar de los habitantes y la eficiencia energética del edificio al disminuir las emisiones de CO2**. Sin embargo, debido a su escasa aproximación a los climas cálidos tropicales, **la tesis investiga qué criterios de confort térmico podrían estar involucrados en un edificio VIS de altura existente en Barranquilla, Colombia, para mejorar las condiciones de vida de los habitantes en el escenario actual y futuro de cambio climático.** La metodología combina simulaciones térmicas y trabajo de campo. Posteriormente, se definirán algunos criterios para optimizar la habitabilidad a través de la **renovación de la envolvente del edificio.**

Palabras clave: Bioclimática, escenarios de cambio climático, refrigeración pasiva, vivienda social, Confort térmico.

Introduction

United Nations stated that Sustainable Development Goals (SDGs) would be impossible if local action is not contemplated in a predominantly urban region like Latin America and the Caribbean. To guide Latin America in the sustainable developed path is necessary to overcome its problems of inequity, high rate of population increase, housing deficit and low technology development. In addition, due to climate change, new approaches and policies are needed.

Alicia Bárcena stated that cities and housing provide an opportunity to transform the region's development model. Given this, the object of the investigation will be the **social housing (VIS) in Colombia**; this is the most dynamic housing segment; between January and September 2021, the family's investment in this type of housing reached 15 billion. Unfortunately, Colombia has a representative housing deficit; in the quantitative spectrum, it equals 7.5% of households; in the qualitative spectrum, it equals 23.5%.

As can be seen, the more significant deficit is qualitative due to the lack of construction codes that specify the minimum quality requirements in dwelling units. However, some quality guides were created by private entities, like *El Observatorio de Vivienda de La Universidad de Los Andes*; the guides propose some criteria related to the building scale and consider quality parameters related to anthropometric adaptation, sanitary facilities and services, climatic conditioning, and energy and water efficiency. However, **allowing people to supply the physiological need of thermal equilibrium is neglected in the minimum habitability conditions of social housing**.

Providing thermal equilibrium to the dwellers is directly related to granting buildings thermal comfort; In the architecture file, it is strongly related to bioclimatic design and energy saving. Understanding hygrothermal comfort as a habitability criterion will create well-being houses and less CO2 emissions in Colombia.

By understanding the impact of thermal comfort on the population's quality of life and the environment, **the thesis research project looks to evaluate the social housing habitability from the building scale. Identify the user satisfaction concerning the physical and non-physical relationship between the dweller and the house's interior environment, proposing some optimization criteria for existing social housing buildings (VIS)**.

This thesis has Four sections; the first are conceptual and argumentative, while the last are experimental. In **The conceptual sections**, the VIS in Colombia is contextualized regarding political, urban, technological, legal, economic, and social issues; the state of the art of Thermal comfort is described; the case study recognition of the climate change exposure is illustrated, and the possible adaptation capacity is review through traditional construction techniques and bioclimatic strategies in hot-humid climate. **The experimental section** describes and identifies the project sensitive to climate change exposure through thermal comfort measurements, proposes and evaluates the best renovation criteria, and sets a possible design implementation.

Chapter 1

Research Project

Problem definition

In 2015 all member countries of the United Nations (UN) approved the 2030 agenda for sustainable development, a plan that seeks to achieve prosperity that respects the planet and its inhabitants. This plan looks to address climate change and its negative impacts helping the nations to accomplish the Paris agreement, which aims to decrease greenhouse gas emissions (GHG) to limit global temperature rise to 1.5°C.

As stated by United Nations (UN), n.d.:

The 2030 Agenda presents a historic opportunity for Latin America and the Caribbean since it includes high-priority issues for the region, such as the eradication of extreme poverty, the reduction of inequality in all its dimensions, inclusive economic growth with decent work for all, sustainable cities, and climate change, among others.

Relative to sustainable cities the World Green Building Council highlight that buildings are one of the main factors of climate change, globally they are responsible for 38% of carbon emissions related to energy consumption and 50% of the consumption of all extracted materials. **In Colombia, emissions from buildings represent around 7% of the national emissions, and GHG emissions associated with buildings are expected to increase from 18,9 Mt-CO2eq to 32,6 Mt-C02eq in 2050. These emissions will be generated mainly in the operation stage of buildings, particularly residential ones**. (Consejo Colombiano de Construcción Sostenible (CCCS), 2022, p. 11).

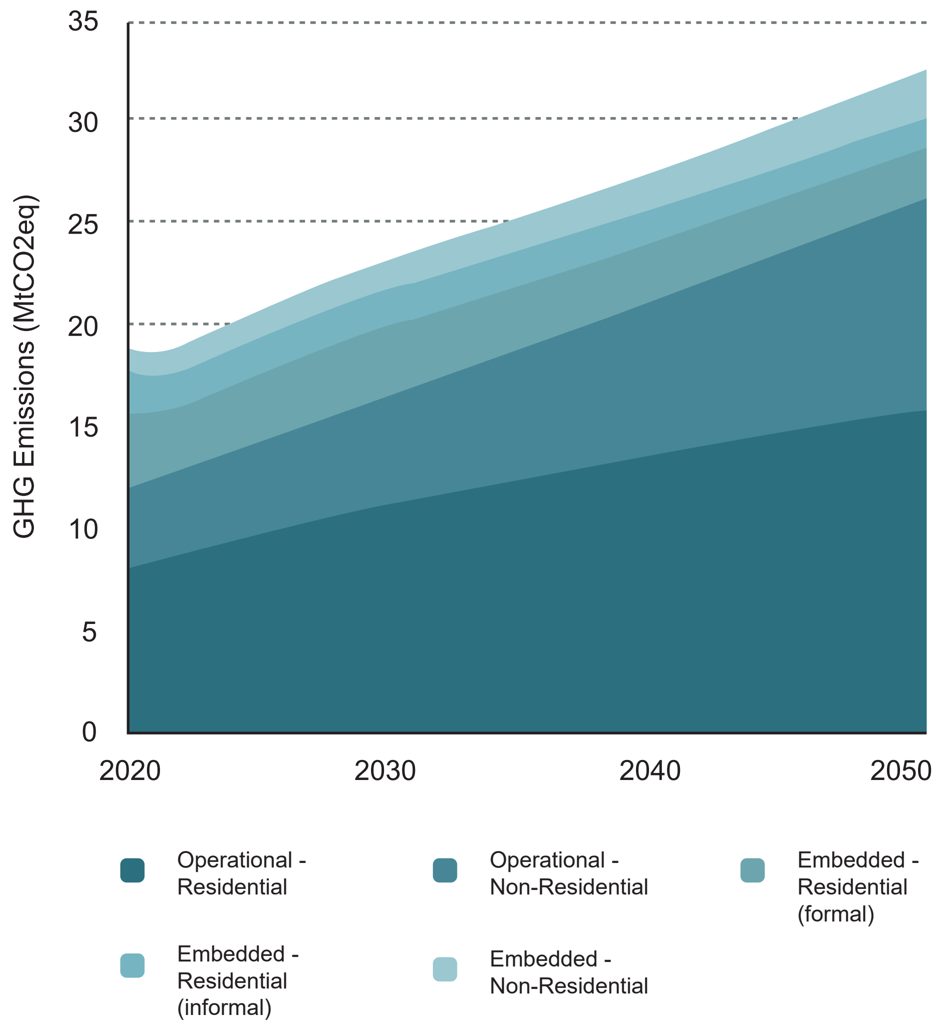


Figure 1. Projection of GHG emissions in Colombia according to type of source and typology under the midpoint scenario (2020-2050). Source: Línea base de emisiones GEI de las edificaciones. By la Universidad de Los Andes y Hill consulting.

As claimed by the national census of population and housing the residential stock in Colombia comprises 13.480.729 houses, of which 11.451.882 are urban and 2.028.847 are rural (DANE, 2018). On the other hand, the total of households living in these dwellings is 16.908.000, corresponding to 99.1% of the country's households. The National Survey of Quality of Life (ECV) reports that 5.240.000 of these households are in a housing deficit, representing 31% of households nationwide (DANE, 2022a).

In Colombia, the housing deficit is measured in two attributes: The first is the quantitative deficit defined by the households living in dwellings with structural and space deficiencies that need new houses, and the second is the qualitative deficit represented by households living in dwellings with non-structural deficiencies in which it is possible to make improvements or adjustments to achieve adequate habitability conditions. Regarding these, by type of deficit in Colombia 7,5% of households are in quantitative deficit and 23.5% are in qualitative deficit (DANE, 2022a).

As can be seen, Colombia's sustainable social housing sector has one of the leading roles in the reduction of CO2 emissions and in the capability of providing better habitability conditions to the population, due to its impact on CO2 emissions and the need to fulfil the dwellings deficit. Although the country is already developing policies around climate change and established ambitions and goals that generate a favourable policy framework for decarbonization, the main regulatory advances and incentives are focused on energy efficiency measures, the use of clean energy and the decarbonization of the energy matrix (Consejo Colombiano de Construcción Sostenible (CCCS), 2022, p. 34).

The most recent and mandatory national regulation is the Resolution 0549 of 2015, its objective is to improve the building's energy and water efficiency performance. The main strategies required for the residential building stock are related to equipment efficiency. **The policy neglects the bioclimatic strategies that could provide energy efficiency and interior thermal equilibrium.** In addition, no effective monitoring system guarantees their application in the national territory (Consejo Colombiano de Construcción Sostenible (CCCS), 2022, p. 12)

Other regional legislations were developed for the more relevant cities of the country: the sustainable construction public policy of El Valle de Aburra (2015), the building energy accelerator project (BEA) in Bogotá (2016), and the Manual of Sustainable Construction of the District of Santiago de Cali (2022). Who gives general parameters to guide the construction of sustainable cities and communities.

Despite the progress that has been made, some barriers still exist to affordable sustainable housing legislation. First the lack of a construction code related to house quality and building physics parameters that bring forth minimum acceptable indoor environmental conditions with thermal equilibrium, energy efficiency and people's well-being. Second, is the need for building retrofit policies. Third, the centralization of studies and policies in the main cities (Bogotá, Cali, Medellin) doesn't allow the establishment of preventive measures and regulations in time in the rest of the country.

Given the previous context and problems the following research question arises:

Considering the future climate change scenarios, which criteria will improve hygrothermal conditions of the multi-family social housing Perdiz project in Barranquilla, Colombia, to provide dwellers quality of life?

To answer the central question of this work, supporting inquiries were setted:

1. What are the hygrothermal conditions regarding the PMV and the ASHRAE 55 standard of 2010 in the multi-family social housing Perdiz project in Barranquilla, Colombia?

2. What is the hygrothermal sensation of the head of the household in the multi-family social housing Perdiz project in Barranquilla, Colombia?

3. What factors affect hygrothermal comfort in the multi-family social housing Perdiz project in Barranquilla, Colombia?

4. What is the approximate impact on the future climate change scenario of households' comfort conditions when the hygrothermal environment is improved in the multi-family social housing Perdiz project in Barranquilla, Colombia?

Research Objectives

General Objective

Formulate criteria that improve hygrothermal conditions for the current and future climate change scenario—providing users with quality life and energy security in the multi-family social housing Perdiz project in Barranquilla, Colombia.

Specific objectives

1. Measure and analyse the hygrothermal conditions regarding the PMV and the ASHRAE 55 standard of 2010 in the multi-family social housing Perdiz project in Barranquilla, Colombia.

2. Describe the hygrothermal sensation of the head of the household in the multi-family social housing Perdiz project in Barranquilla, Colombia.

3. Identify the main variables that affect hygrothermal comfort and energy efficiency in the multi-family social housing Perdiz project in Barranquilla, Colombia.

4. Estimate the impact on future climate change conditions when the hygrothermal environment is improved in the multi-family social housing Perdiz project in Barranquilla, Colombia.

Justification

The new multi-family social housing in hot-humid climates does not provide thermal comfort to its occupants. Due to the global temperature increase, the repetitive architectural prototype configuration of the residential buildings that do not respond to the climate conditions, the few hydrothermal studies and the lack of regulations related to hygrothermal parameters—bringing on bad habitability conditions and increasing the phenomenon of energy poverty.

In developing countries such as Colombia, the quality of social housing takes second place, and it is assumed as a commercial good whose main objective is to supply the quantitative housing deficit (Escallón & Rodríguez, 2010). In making decisions related to VIS, there are motivations other than the achievement of this kind of approach, which has transformed sustainability design into a process of technological equipment that only seeks energy efficiency, and that cannot be implemented in affordable housing because of the limited budget. Forgetting that "habitability arises as a determining factor in the construction of adequate sustainability" and defines it "as the capacity of a building to ensure minimum conditions of comfort and health for its inhabitants" (Cubillos et al., 2014, p. 114)

This diagnostic looks to improve the hygrothermal performance of social housing in Barranquilla, Colombia, concerning the international standards PMV and ASHRAE 55 of 2010. With the understanding of the current thermal performance of the VIS in a hot-humid climate, determining the adaptative comfort range of the Barranquilla people, and decreasing the energy consumption due to the cooling system. Through the proposal of strategic design modifications to improve the dwelling's habitability conditions.

The methodology approach of this study could be considered to develop similar research that can help construct baselines that will be used to determine technical parameters of thermal comfort at the national level.

Hypothesis

The hygrothermal conditions of the multifamily social housing Perdiz project in Barranquilla, Colombia, could be improved through optimization criteria based on three fundamental aspects: Prevention of heat gains, management, and dissipation. Bearing that the project currently has a thermosiphon system, the main renovation criteria will be those focused on preventing gains from solar radiation, which will positively influence the thermal performance of the building under a climate change scenario, providing acceptable interior temperature conditions. Hence, suitable habitability environments.

Methodology

Study Area

The proposed case study's analysis unit is the Perdiz project; it will have 6 towers of 12 stories with 600 housing units. At the time of the analysis, only 3 towers had been built, and the occupation of each was 30%, 94 housing units approx. **Moreover, due to the Covid situation, only 30 heads of households were solicited to make the study, with a response of 16 dwellings**. Following the ASHRAE 55 standard requirements "if solicited occupants' number between 20 and 40, at least 15 must respond" (ANSI/ ASHRAE STANDARD 55, 2017).

Thermal comfort survey

The development of the survey has the following components:

1. Thermal comfort measurements.
2. Residential satisfaction user survey (thermal rating scale).
3. Natural ventilation system survey.

According to Rodríguez et al. (2019), assessing thermal comfort is a complex task that involves the study of multiple interrelated physiological, psychological, and social factors. The common methodological approach to assess buildings' comfort is performed with two international standards: **(1)** the static model or PMV and **(2)** the adaptive comfort model. This research will use both paths to determine the current dwellings' thermal performance, the dwellers' perception, and the socio-physical modifications to reach thermal comfort.

The building survey used a **cross-sectional study**, in which the data collection was taken in the year's hottest week every 5 minutes with the measurement tools described in the following table. By the ANSI/ASHRAE standard 55-2017, the measurements were taken: **(1)** in places where the most extreme values are observed or estimated to occur, e.g., occupied areas near windows, corners, or doorways; and **(2)** where occupants are expected to spend most of their time. It was also considered not to place the measuring instruments near lamps, televisions, computers, etc.

As regulated by the ASHRAE (2017), the equipment was placed 1.1m above the floor for seated and standing occupants. Besides, a seven-point satisfaction survey was applied to the heads of households simultaneously with the data collection, which was filled out at 9:00, 15:00, and 21:00.

The data processing was carried out using Excel sheets. A cross-data analysis allows setting if the comfort range established by the PMV or ANSI/ASHRAE standard 55 correlates to the thermal sensations of the users at the time of the survey and measurement.

Scope	Description
Spaces to measure	Living room and main room (32 spaces)
Study population	Head of the household for the 16 dwellings of the Perdiz project in Barranquilla.
Dwellings position	At least one dwelling in each orientation and on the first, sixth and twelfth floors.
Measurement tools	Indoor temperature and relative humidity: globe thermometer and data logger. Outdoor temperature: Data l ogger and data f rom the nearest weather station. Satisfaction and social context: Semi-structured interview

Table 1. Measurement data. Source: Author's Elavoration.

The residential satisfaction analysis "is determined by the evaluation of its physical attributes and by the social and personal characteristics of the users" (Pasquali, 2005, p. 82). In the previous section, the physical attributes of the dwelling are evaluated concerning thermal comfort, therefore, in this stage will inquire about the social and personal characteristics of the users through a semi-structured survey.

The surveys will have as a sample the same 16 heads of households The survey is built on three main themes: general information, habits, and thermal comfort satisfaction.

Finally, by performing the physical and user perception analyses, it will be possible to determine the thermal comfort conditions for the family groups.

Definition of optimization criteria

After in-situ measurements and data processing, dynamic simulations are carried out. The dynamic model will be calibrated with the data collected and used to establish the most appropriate strategies to implement. The methodology consists of a base model, which contains the parameters of internal loads (occupancy, equipment, and lighting), and the envelope of the built project. Subsequently, based on the analysis of the heat balance in the warmest week of the year, it is determined which elements of the envelope or natural ventilation strategies are the most relevant to optimize the thermal performance of the dwellings.

Next, several annual optimization iterations (proposed models) are performed. According to the annual temperature distribution, the most pertinent strategy to implement in the post-construction process is selected. In addition to this, the ranges that each measurement must-have in hot humid weather are established. The processing of the data will be carried out in Excel through the crossing of information.

Chapter 2

Social housing and its relationship with indoor thermal comfort

Evolution of Social housing

Social housing in Latin America

The global population that occupies cities has constantly been increasing. In 1990 less than 40% of the world's population lived in cities; in 2010, it was more than 50%, estimated to be 70% by the year 2050 (Mejía Lalinde, 2020). Furthermore, as Alicia Bárcena emphasised, "Latin America is one of the planet's most urbanised regions, with 82% of its population living in cities and 17% of its urban population concentrated in 6 megacities that have more than 10 million inhabitants apiece" (United Nations - ECLAC, 2021, para. 5).

In 2010 the population of Latin America was 590 million people; 252 million were in a state of poverty, of which 72 million correspond to a state of extreme poverty. In 2016 the population increased by 39 million (629 million people), but the number of people in poverty decreased to 188 million and 61 million in extreme poverty. Currently, the Latin American population is 660 million. According to the CEPAL estimates for 2050, Latin America will reach a population of 749 million (CEPAL, 2022).

These trends and the situation of poverty have created enormous housing demand in Latin American cities, and the house has become a fundamental element in guaranteeing human dignity. However, as in most parts of the world, in Latin America, "the housing deficit has not been reduced over the years and in many countries has been getting larger" (Gilbert, 2012, p. 79). As reported by the Economic Commission on Latin America and the Caribbean (ECLAC) in 1990, the housing deficit was approx. 38 million homes, in 2000, the deficit was 52 million, and in 2007, the deficit was around 60 million homes, of which 22% of dwellings have a qualitative deficit and 18% a quantitative deficit (McBride & French, 2011).

The last data reported show that in 2012 the housing deficit in Latin America affected almost 45% of households (Wainer, 2022), and as shown in the Inter American Development Bank (2012) report:

> of the 130 million urban families in the region, 5 million rely on another family for shelter, 3 million live in houses that are beyond repair, and another 34 million live in houses that lack either title, water, sewerage, adequate flooring, or sufficient space.

The concept of social housing in Latin America in the mid-twentieth century was determined by: (I) the intervention of the USA in the political and economic panorama of Latin American countries, (II) the urbanization of the population, and (III) The institutionalization of housing (Corporación Universitaria del Caribe [CECAR], 2022).

Social housing arose in the middle 20th century because of the accelerated and uncontrolled growth of cities. From the 1920s every Latin American government established housing agencies to decrease the housing deficit. Hence, the governments presumed the role of promoters and direct executors of housing policies, looking to solve the poverty issue. In 1951 the organization of American States – OEA - created the Centro Interamericano de Vivienda y Planeamiento – CINVA – Its purpose was the training of professionals and communities in economic, social, cultural, and regulatory aspects of social housing and urban planning. The experimental proposal was based on integrating four variables community development, community action, urban renovation, and social housing (CECAR, 2022).

In 1975 the United Nations Foundation for Habitat and Human Settlements (FNUHAH) was founded. As the first official UN entity dedicated to urbanization, its main task was to support national human settlements programs by providing capital and technical assistance, mainly in developing countries (Flórez, 2017). Subsequently, in 1976 in Vancouver, the Habitat I conference was held, in which the governments recognised that human settlements affect human, social and economic development; and that uncontrolled urban growth had severe environmental and ecological impacts. The UN gave some recommendations about land use and tenure, population growth, infrastructure, essential services, and adequate housing and employment (UN-HABITAT, n.d.).

From the 1960s to the 1980s, public housing projects in Latin America were "small in scale, largely unaffordable by the poor, poorly targeted, and largely inefficient" (Gilbert, 2012, p. 83). Due to the inability of state institutions to overcome the growing deficit and the lack of public resources, from the middle 1980s, most Latin American governments abandoned their role as housing producers, regulators, and facilitators, encouraging the private construction sector and housing the poor. They started to use the up-front capital subsidy, focused on demand setting up an ABC package of savings (ahorro), subsidy (bono), and credit (credito). It began in Chile and spread to Colombia, Costa Rica, Ecuador, Mexico, Panama, and Peru (Gilbert, 2012).

Finally, in 1996 at the Habitat II conference, the governments recognised a worldwide deterioration in settlements and living conditions, with critical proportions in several developing counties. The Habitat Agenda was proclaimed, in which they stand out four action areas for efficient urban development: (1) Adequate urban planning, (2) access to basic services, (3) infrastructure, and (4) **adequate housing**. In addition, the agenda defended decentralised systems with the active participation of the private sector, which should assume greater responsibility for facing the housing deficit with governments and local authorities (UN-HABITAT, n.d.).

For the past two centuries, Latin America's social housing sector has struggled with low-quality residential projects. Because the governments and private sector have been focused on decreasing the quantitative housing deficit faster, the house stopped being considered a space to inhabit, which enables human development and implies a relationship with the environment and a qualification of it. Denying its ties with the cultural, social, and biophysical context (Valencia, 2018b).

Social housing in Colombia

The stages of the social housing evolution in Colombia are: (1) the hygienist, (2) the institutional, (3) the transitional, (4) the corporation creators, and (5) the subsides (Ceballos et al., 2008). In the hygienist stage (1919 – 1942), the housing policy was seated in public health; the state developed the water and sewage networks in the main cities of the country and focused its attention on the issue of working-class's housing with the establishment of some institutions like the Banco Central Hipotecario, the Caja de Vivivenda popular and the Instituto de Crédito Territorial.

The Instituto de Crédito Territorial (ICT) established in 1939 had as initial responsibility to support functional, hygienic, and aesthetic improvements to traditional rural housing. Eventually, in 1942 the urban housing department was born, and Its duty was to create statal programs that supply the qualitative and quantitative urban deficit (Ramírez Nieto, 2019).

Giving rise to the institutional stage (1942 – 1965), in which The ICT published the book “Una política de vivienda para Colombia” on June 13, 1956, which contained information, material and presentations produced within the framework of the “First National Housing Seminar” held between April 25 and May 1, 1955. One of the fundamental aspects to discuss was defining the house type and its construction components, stating that tradition and experience accumulated over time are valid arguments for building affordable architecture. In this sense, the proposals of the ICT could be modern without ruling out the local tradition (Ramírez Nieto, 2019). The institution was recognized for building and designing good-quality residential projects; the problem was that it could never keep up with the demand. The combination of too many low-income families, too few resources and poor administration killed it in 1991.

Likewise, in this stage, the state promoted credit and granted subsidies to cooperatives and working families. Above all, the construction of affordable housing not large than 150m² is encouraged, and there is a concern about avoiding speculation in the price of land (Ceballos et al., 2008).

Then, in the transitional phase (1965 – 1972), the Colombian State began a period of change, delegating some responsibilities and setting up the residential construction sector as a mechanism to encourage economic development, involving private builders and banks in the design and construction of social housing. It helps to face migration and the construction of slums with residential high-rise projects (Ceballos et al., 2008).

Later, between 1972 and 1990, a policy of creating corporations is implemented. Their priority was to develop residential projects for the middle and upper classes, increasing the deficit of low-cost housing and strengthening urbanization through slums. The consequences of this period were a setback in the social housing quality and a speculative price of the houses and land (Giraldo, 2018).

In the last stage, the subsidies (1990 – to the present), born the Political Constitution of Colombia of 1991 that establishes in article 51 that the state is responsible for guaranteeing the right of all Colombians to access affordable housing with the promotion of housing plans and adequate financing (Mejía Lalinde, 2020). From now on the state cut back its role as an executor to boost the economy, believing in the financing mechanism as the leading solution. Some public institutions, such as the Fondo Nacional del Ahorro and the Caja de Vivienda military, survived and adapted their policies and processes to the new model. The Cajas de Compensación were established for the aid administration and social housing projects development (Giraldo, 2018). Nonetheless, this policy and programs have not been able to supply the qualitative and quantitative housing deficit.

At first, the financial aid just applied to new residential buildings; later, it applied to the auto-construction in lots and terraces, used home purchases, and improvement of housing and surroundings.

Unfortunately, these options other than new housing only apply in exceptional cases; and new residential projects are characterized by a lack of variety, low quality, and high cost.

Like other counties in the region, Colombia's housing policy between 2010 and 2022 has been directed towards consolidating the demand model through subsidy programs and the promotion of financing and saving schemes (Mejía Lalinde, 2020). However, as Gilbert (2012) remarks:

> subsided accommodation is often built to very poor standards or is very small in size. In Colombia, some VIP housing has had a floor area of only 36m² and has been six floors up in a building with no lift. Generally, highly subsidised housing is located in inconvenient locations built where land is cheap.

Until now, the housing policy has focused on financing programs, disclaiming the need for quality requirements, retrofit and regional development regulations. Housing quality criteria should not be subject to market dynamics; they should be regulated by more demanding regulations than currently.

Typology of social housing in Colombia

Article 91 of LEY 388 (1997) states that social interest housing is a dwelling unit developed to guarantee the right to housing for lower-income households. In each National Development Plan, the Government will establish the type and maximum price of the solutions intended for these households. In Colombia, two types of affordable houses have been defined to solve the deficit problem of the most vulnerable population: vivienda de interes social (VIS) and vivienda de interes prioritario (VIP). As stated by the Ministerio de Vivienda Ciudad y Territorio [Minvivienda] (2020), VIS is a dwelling unit whose price cannot exceed 150 SMLM (equivalent to COP 150.000.000 or about USD 31.100,48 – TMR October 29th, 2022).

While the VIP must not exceed 90 SMLM[1] (equivalent to COP 90.000.000 or about USD 18.660,29 - TMR October 29th, 2022). Both are destinated for citizens who earn less than 4SMLM (about USD 829,34 – TMR October 29th, 2022).

Further, in Colombia, residential property is classified into six socioeconomic strata: low-low (1), low (2), medium-low (3), medium (4), medium-high (5) and high (6). The VIS and VIP are primarily in strata 1, 2, and 3. As reported by the "Departamento Nacional de Estadistica" (DANE, 2022b), in the second quarter of 2022, the construction of 40.505 homes in Colombia was completed; of these, 21.634 were VIS.

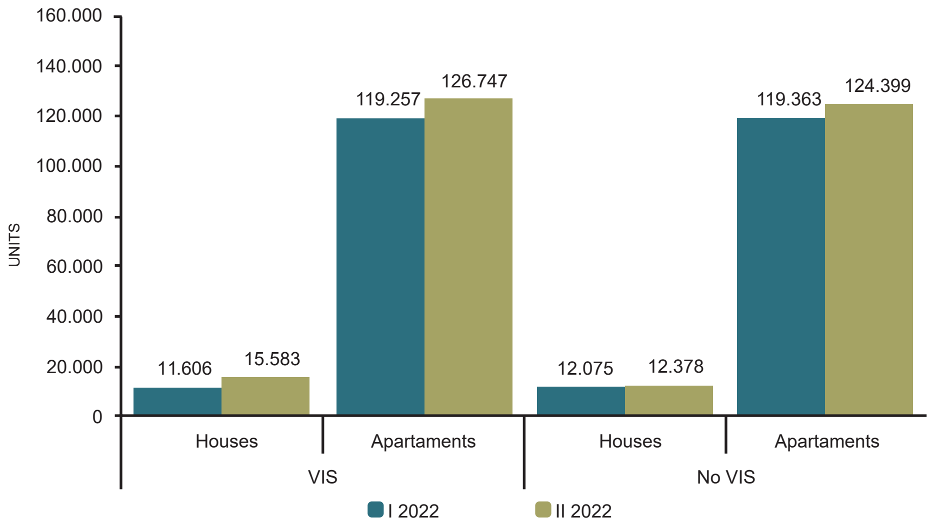


Figure 2. Total of dwelling units in construction stage, by type of home and destination – I & II quarter 2022. Source: Boletín Técnico Vivienda VIS y no VIS II trimestre de 2022. By DANE, 2022b, p. 13.

1 SMLM: Spanish acronym for the legal monthly minimum wage in Colombia. In 2022 the Legal monthly minimum is COP 1.000.000 or USD 207,33 – TMR October 29th, 2022.

II Quarter 2022			Percentage (%)
Areas of influence	TotalV	IS	NO VIS
Bogotá D.C.	18,7	16,7	19,8
Cundinamarca	10,5	12,2	9,5
Medellín y Oriente AM	20,3	11,7	25,4
Cali AU1	1,9	18,7	7,8
Barranquilla AU7	,7	10,1	6,3
Bucaramanga AM4	,8	3,6	5,6
Pereira AU	2,0	2,2	1,9
Armenia AU	1,8	1,4	2,1
Cartagena AU4	,5	3,7	4,9
Ibaguè AU3	,7	3,1	2,2
Cúcuta AM	1,5	2,0	1,3
Manizales AU1	,7	1,4	1,9
Villavicencio AU	1,1	1,0	1,2
Neiva AU	1,1	1,6	0,8
Pasto AU	1,4	1,0	1,6
Popayán AU0	,9	0,7	1,0
Tunja AU	2,0	1,4	2,5
Valledupar AU0	,8	1,4	0,5
Montería AU0	,6	0,7	0,5
Santa Marta AU2	,3	1,7	2,6
Sincelejo AU	0,3	0,1	0,3
Yopal AU	0,3	0,6	0,1
Florencia AU	0,2	0,2	0,2
Total	100,0	100,0	100,0

Figure 3. Percentage distribution of the total area in construction stage by type of housing, according to area of influence (Urban / Metropolitan) – II quarter 2022. Source: Boletín Técnico Vivienda VIS y no VIS II trimestre de 2022. By DANE, 2022b, p. 16.

Also, the country has 279.107 homes in the construction stage[1], and VIS constitute a significant percentage equivalent to 51% of the total stock (142.330 dwelling units), of which 126.747 are high-rise buildings and 15.583 low-rise buildings. The cities with the most significant VIS stock in the construction stage are Bogotá D.C. (16,7%), Cali (18,7%), Cundinamarca (12,2%), Medellín y Oriente (11,7%) and Barranquilla (10,1%), adding an equivalent to 98.777 dwelling units (Figure 3).

1 Construction stage: All the projects at the census time have been doing some construction process (DANE, 2022b).

Furthermore, Colombia has 56.016 homes in the proposal stage3 with 32.519 VIS dwellings (25.949 high-rise buildings and 6.570 low-rise buildings). Cali, Medellín y Oriente, Bogotá, and Cundinamarca have the largest share of the new residential projects. However, by type of housing, Cali, Barranquilla, and Bogotá register the highest VIS participation, adding 51.4% (DANE, 2022b).

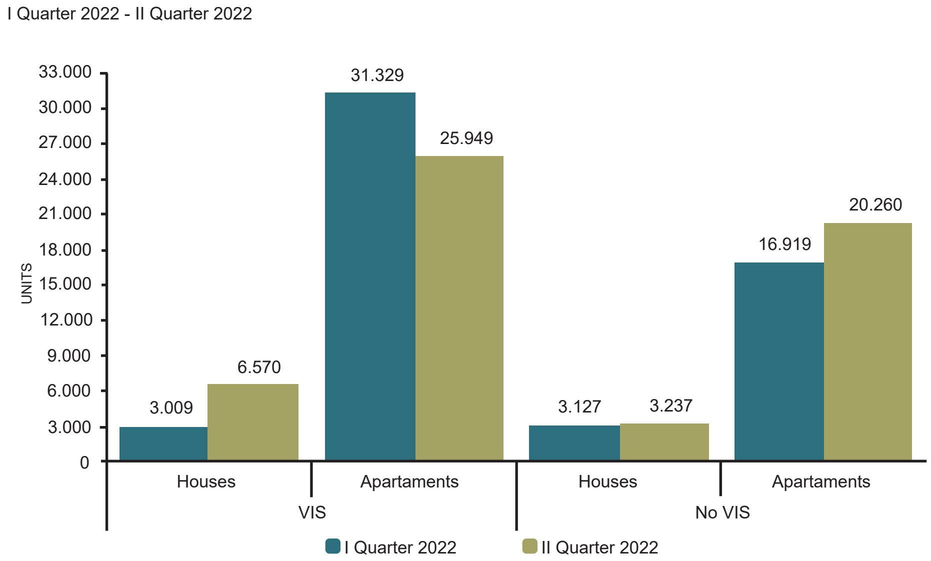


Figure 4. Total of new dwelling units, by type of home and destination – I & II quarter 2022. Source: Boletín Técnico Vivienda VIS y no VIS II trimestre de 2022. By DANE, 2022b, p. 22

As Giraldo (2018) remarked is challenging to estimate the actual quantity of social housing (VIS) in Colombia because the illegal construction phenomena imply an unknown number of VIS that could increase the amount reported for the statistics.

However, in the second quarter of 2022 can be inferred that Colombia developed 196.483 VIS dwellings. The cities with more amount of VIS are Cali (35.396), Bogotá (27.379), Cundinamarca (20.584), Medellín y Oriente (19.644), and Barranquilla (18.733). Moreover, among the main cities, the average area for high-rise VIS projects ranges between 44m² and 67m², while the size for low-rise VIS projects varies between 58m² and 83m². which depends on cultural and economic factors such as the price of land and construction materials in each city (Giraldo, 2018).

Materials and Systems of social housing in Colombia

The materials used in the social housing system (VIS) are 99% of them high-density materials like concrete masonry, clay masonry (bricks), and industrialized systems like outinord or contech that are reinforced concrete walls with a thickness between 8cm to 12cm (Giraldo Castañeda et al., 2021).

As reported by the Cámara Colombiana de la Construcción (CAMACOL) (2016), between 2012 and 2015, the VIS construction was led by three systems: industrialized systems [40,37%], confined masonry [30,99%], structural masonry [27,58%], other systems [1,01%] (García López et al., 2020).

The industrialized systems are structural systems with concrete walls and slabs either cast in situ or prefabricated. Confined masonry are systems with horizontal and vertical elements called beams and columns; these are complemented with masonry walls (bricks or clay and concrete blocks) that work as confinement units.

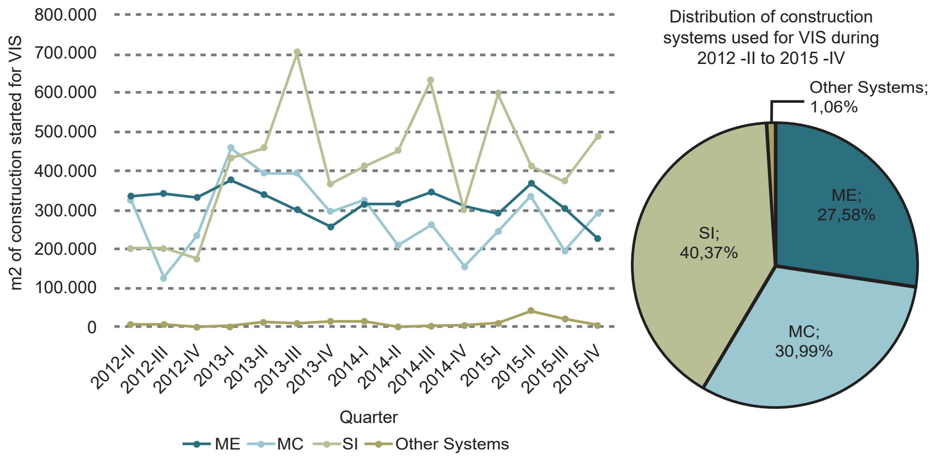


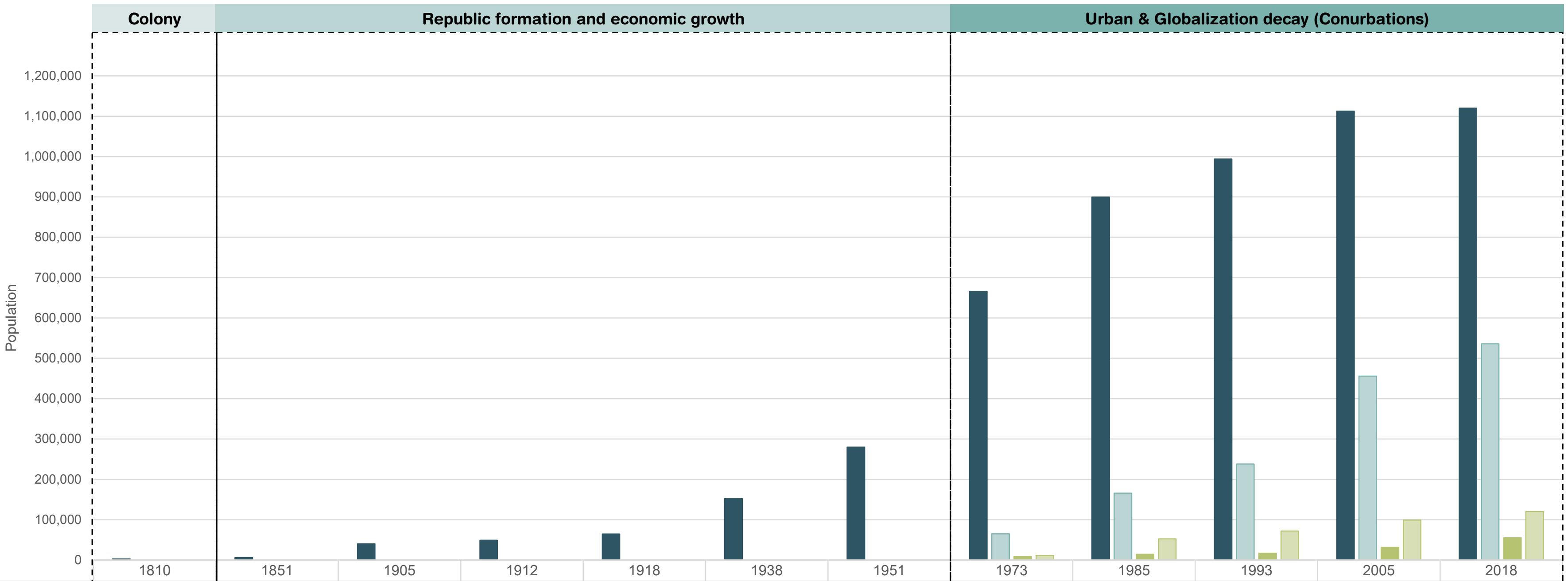
Figure 5. Distribution of construction systems used for VIS from the second quarter of 2012 to the fourth quarter of 2015, according to figures from CAMACOL (2016). Source: Comparación de los principales sistemas constructivos de VIS en Colombia, desde una perspectiva de sostenibilidad, empleando BIM: caso estudio en Soacha. By García López et al. (2020)

Population growth, economic development and social housing in Barranquilla.

As Llanos Henriquez (2016) remarks, **Barranquilla has structured according to the needs and interests of the local elites and in line with the development and the demands that the capitalist system presented**. The economic dynamics of the city at the end of the 19th century led to the fast growth, mainly through rural-urban migration and international migration (especially Germans, Americans, Italians, Spanish, Lebanese, and Jews, among others) caused by the first and second world Wars. Indeed, the foreign immigrants' business initiatives turned Barranquilla into the most important country, river, sea, and airport port. (M. Hernández et al., 2016; Martínez González et al., 2021).

The city experienced an economic decline at the beginning of the 1930s because of: (1) the world economic crisis of 1929, (2) the construction of the Panama Canal between 1904 to 1914, which lowered the importance of Barranquilla as a riverport, allowing Buenaventura to host the most significant percentage of exports, and (3) The construction of the Barrancabermeja – Cartagena oil pipeline at the end of the 1920s allowed the Cartagena port's recovery and weakened the Barranquilla port. Nonetheless, Barranquilla had an investment diversification that strengthened the city industry, Due to the capital port accumulation and the 29 crisis that strengthened the national economy (Llanos Henriquez, 2016).

Eventually, at the end of the 1950s, the Barranquilla development stagnation because, added to the loss of leadership of the port, came the navigability crisis of the Magdalena River, the narrowness of the regional coastal market, and competition from national and foreign industries. This crisis lasted until the 1990s when Barranquilla began its economic and urban recovery (Aldana Domínguez et al., 2018; M. Hernández et al., 2016; Llanos Henriquez, 2016).



	1810	1851	1905	1912	1918	1938	1951	1973	1985	1993	2005	2018
Barranquilla Population (million)	2,633	6,114	40,115	48,907	64,543	152,348	279,627	665,917	899,781	993,759	1,112,889	1,120,103
Soledad Population (million)								65,127	165,791	238,153	455,796	535,984
Galapa Population (million)								9,165	14,046	16,873	31,596	55,123
Malambo Population (million)								11,265	52,584	71,925	99,058	119,920

Figure 6. Barranquilla Population. Source: Compilation based on (DANE, 1985, 1993, 2005, 2018; Llanos Henriquez, 2016).

Barranquilla's economic development in the first half of the 20th century will be reflected in its social and physical dynamics. The rapid urban growth of Barranquilla began in the mid-nineteenth century due to its economic growth and migration dynamics. Its population went from 2.633 inhabitants in the colonial period to 6.114 Inhabitants in 1851 and 40.115 in 1905, for an average annual population growth of 3.48%, six-folding its population in a little over 50 years. At the end of the republic formation and economic growth period, Barranquilla raised its population to 993.759 in 1993 and 1.112.889 inhabitants in 2005, showing an increase of more than 100.000 people per year in 7 years. This accelerated growth remains until now; in the last census of 2018, the city had 1.120.103 inhabitants, becoming the fourth most populated city after Bogotá, Medellín and Cali. (DANE, 2018; Llanos Henriquez, 2016).

Simultaneously, the demographic pressure implied the need to create new urbanizations to satisfy the housing demand of the new settlers attracted by the city's economic growth. Boosting an increase in the urbanized area of the city from 400 ha at the beginning of the XX century to approximately 2,400 ha at the beginning of the 1950s. **The city's physical expansion was made in two directions, led by a two-pronged that followed two distinct socio-economic patterns: (1)** the business elite to the northwest and **(2)** The working-class neighbourhoods consolidated to the city's south, with an uncontrolled growth that gave rise to slums and began a process of socio-spatial segregation that became even stronger with the advancement of the 20th century (Llanos Henriquez, 2016; Martínez González et al., 2021).

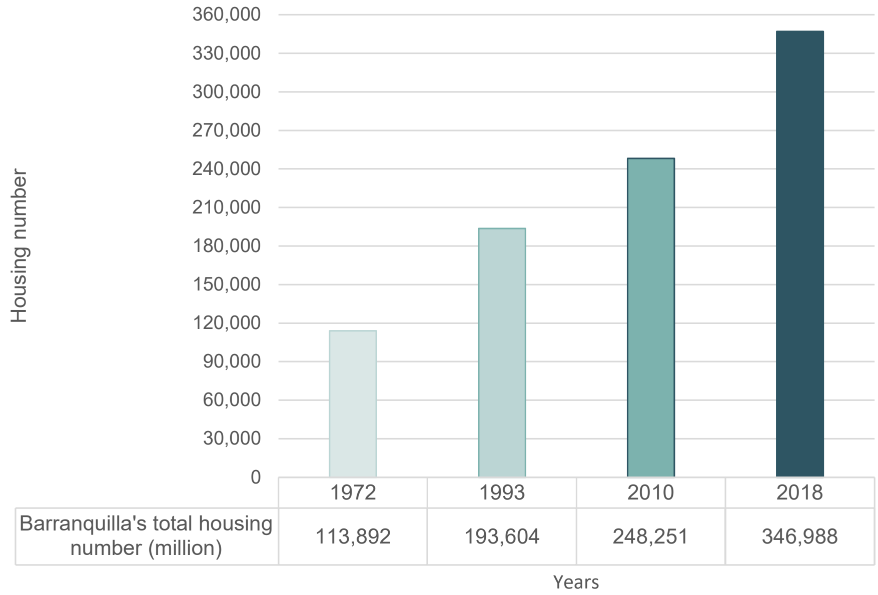


Figure 7. Barranquilla's total housing number in the urban and globalization decay. Source: Compilation based on (DANE, 2018; Llanos Henriquez, 2016).

At the beginning of the Urban decay in Barranquilla (1970 -1990), residential project construction was privatised for medium and high-strata developments. However, the Instituto de Crédito Territorial (ICT) was responsible for social housing projects, with difficulties that did not allow them to embrace the country's total housing demand. Both circumstances sped up the construction of high-cost housing, the informality, and the inability of the administrations to generate development policies for the entire population in Barranquilla. In this stage, the expansion of the urban area in Barranquilla corresponded to an increase of 44.8%, going from 5,525 hectares in 1972 to 8,200 in 1992. Likewise, the number of houses built increased from 113,892 in 1972 to 193,604 in 1993, an increase of 69.98% (Llanos Henriquez, 2016).

In the Globalization stage (1990 -2022), when housing construction was privatized, the territorial expansion of Barranquilla produced conurbations with Galapa, Soledad and Malambo, showing a high population increase rate in these municipalities and low increase rates in Barranquilla. At this point, the city's growth was consolidated through the construction of new neighbourhoods; the number of neighbourhoods went from 133 in 1993 to 166 in 2010, most of them being the product of invasions located in the south of the city. The homes in Barranquilla increment from 193,604 in 1993 to 248,251 in 2010, and its urbanized area changed from 8,200 hectares in 1993 to 11,152 in 2010 (Llanos Henriquez, 2016).

As DANE (2018) reported in the last national census, Barranquilla has total residential units of 346.988, of which 142.090 are houses and 188.014 apartments, the remaining 16.884 correspond to rooms, traditional indigenous housing, traditional ethnic housing, and others; the stock shows an increase of 39.77% respect to 2010. Besides, 98.97% of the residential units have aqueduct networks, 97.84% have sewer systems, 94.36% have natural gas, and 99.57% have electricity service. However, 26.04% of the residential units have a housing deficit, 5.13% quantitative and 20.90% qualitative.

An increase in the social housing market happens due to the Plan de Ordenamiento Territorial Del Distrito Especial, Industrial y Portuario de Barranquilla 2012-2032 [POT] (2014)[1] that set a transformation call for a fair and inclusive city, which aims to promote social, economic, cultural, and environmental conditions that improve the quality of life of Barranquilla's inhabitants, with optimal primary conditions for education, health care, mobility, and housing, among others. Regarding housing was proposed a housing improvement of informal settlements and a new offer of VIS and VIP housing for the migrant population, setting up expansion zones in the city. As reported by DANE (2022b), in the third quarter of 2022, Barranquilla began the construction of 4,563 homes, increasing the stock with 3,852 VIS dwellings and 711 NON-VIS dwellings. On the other hand, the construction of 3.723 residential units culminated in the same period with 3.354 VIS and 369 NON-VIS.

1 Plan de Ordenamiento Territorial (POT): It is the primary instrument to develop the land use planning process, comprised of a set of objectives, guidelines, policies, strategies, goals, programs, actions, and regulations adopted to guide the physical development of the territory and land use (POT, 2014).

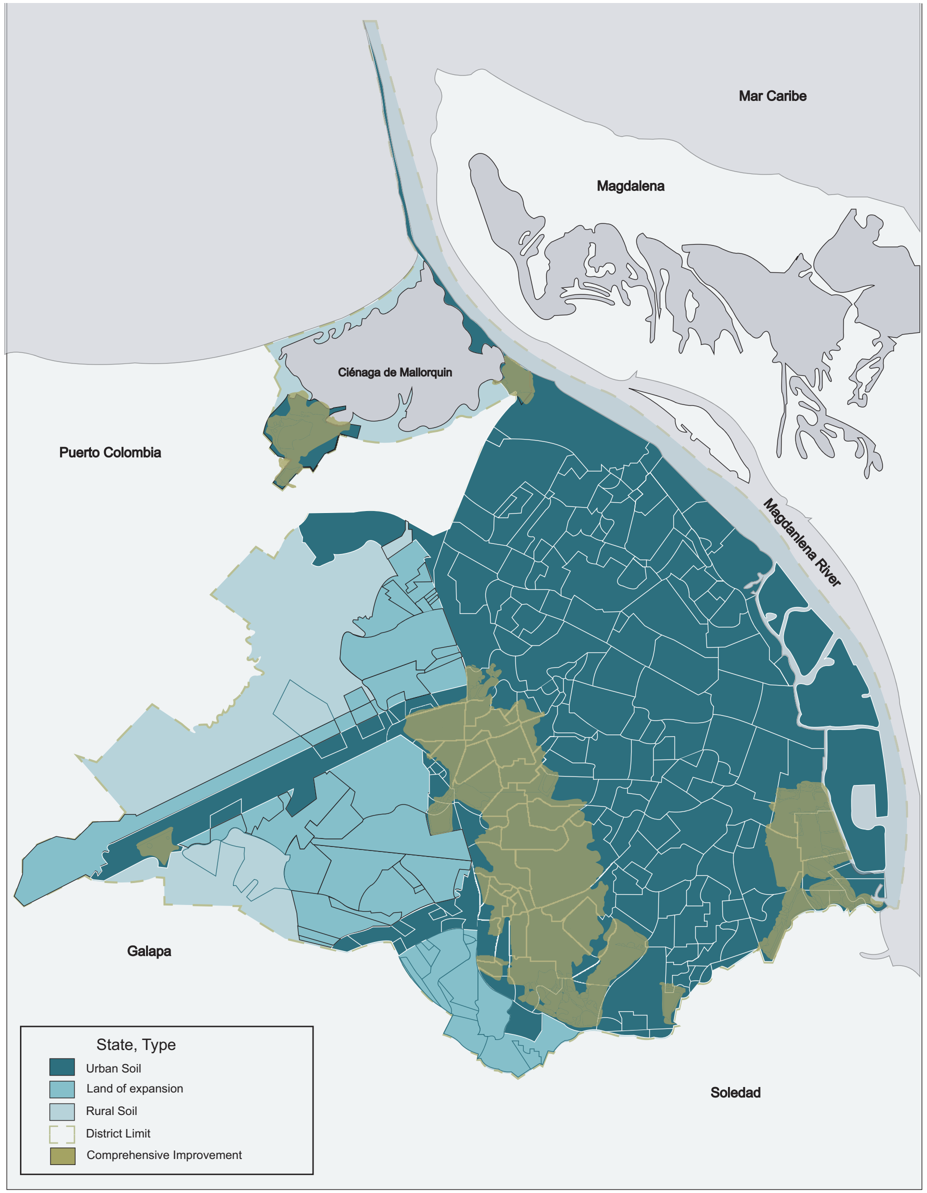


Illustration 1. Barranquilla - General Land Classification. Source: Compilation based on (POT, 2014).

Habitability & Thermal comfort as a concept for social sustainable housing

Habitability in social housing

In 1987, the United Nations Brundtland Commission defined sustainability as “meeting the needs of the present without compromising the ability of future generations to meet their own needs”. That means sustainability **implies guaranteeing human beings’ quality of life concerning the environment and its limitations.** Winston & Pareja (2007) describe **the role of housing in the sustainability of cities**, classifying their indicators into three categories: **quality of life, human well-being**, and freedom. **Habitability is related to the quality of life** and is susceptible to quantification and, even more, to control by the architectural design; **it refers in housing to the conditions in which the family inhabits it**. Therefore, **A properly designed home** based on the characteristics, needs and expectations of users, their environment, and the relationship with the city, is essential for **psychological and social development, favours urban sustainability and contributes to raising well-being, while reducing the environmental impact** (Mejía Lalinde, 2020).

The concept of habitability dates to the 19th century when Lord Shaftesbury defined for the first time the minimum standards of healthiness for dwelling units and the urban environment. Due to the health crisis that Europe was going through. He established the minimum spaces, lighting, and ventilation; the mandatory provision of water and one bathroom per family within the dwellings. As well as the provision of infrastructure networks for water and sewerage at the urban level (Naredo, 2000).

Later, in 1981 Alberto Saldarriaga Roa defined **habitability as the set of physical[1] and non-physical[2] conditions of space which allow human permanence, survival, and the gratification of their existence (**Aguillón Robles et al., 2013). In 2019 due to the social inequality, air contamination, and environmental problems caused by cities expansion and the evolution of the metropolis, the United Nations [UN] stated that adequate housing must comply with seven characteristics: security of tenure, availability of services, affordability translated into costs, physical accessibility for people with disabilities, location, cultural suitability, **and habitability. Regards the last one was described as the capacity of built spaces to meet the needs of individuals in close relationships with socio-cultural and natural environments** (Rodríguez Hidalgo, 2022).

Then as Saldarriaga Roa (2006) suggested, **architecture, as a need satisfier,** is the discipline of habitat, and its obligation must be well-being and not human life degradation; **the object of architecture must be the habitat of well-being by recognising and treating the problems that can affect it.** Thus, the objective of architecture in social housing should be, at least in theory, to increase the number of people in good living conditions, not the number of inhabitants with housing problems.

Remarkably the entire population has the right to decent and adequate housing. Therefore, its achievement is crucial in the vital development of every person and every human community (Arcas et al., 2011). Well design spaces improve the life quality of those who inhabit them; they reduce poverty, improve coexistence, and contribute to citizen inclusion (Carrizosa Bermúdez, 2010). As well as it could affect negatively or positively the health of the occupants.

The Habitability in social housing has two interrelated variables, the users, and the habitat, that interact under three scales: (1) the building, (2) the neighbourhood, and (3) the city (G. Hernández & Velásquez, 2014). It comprises the anthropometric adaptation, the sanitary facilities and services, the climatic conditioning (thermal, acoustic, lighting), and the organization of the rooms within the house as a whole (Aguillón Robles et al., 2013).

This interaction between the variables and the scales implies a notion of satisfaction that is established from each person's ideas or suggestions about what is habitable or comfortable. Namely, **the habitat conditions arise from the people's cultural reality that cannot be separated from their physical, bodily (sensory) and social environment** (Vale & Salomão, 2018). Added to the alteration of the dweller's perception due to the temporality associated with the events that take place before purchasing the housing (the past), the situations that occur once it is acquired (the present) and the events that will appear in time (the future) (Aguillón Robles et al., 2013).

1 Physical / Physical-spatial: The objective variable relates to the building and its shape, dimensions, and materials.

2 Non-physical / Psychosocial: The subjective variable is the mental state that the environment generates in the occupants, that is, sensations such as security, privacy, or comfort.

Quality of life standards

Given the need to evaluate habitability in architectural proposals, different evaluation methodologies have emerged and seek to objectify habitability parameters to measure the capacity of a building to provide quality of life. Some of the methodologies' indicators are established based on satisfy the needs contemplated in the hierarchic theory of needs proposed by Abraham Maslow, which influenced several fields, including architecture.

When speaking of needs, five categories are established (Figure 6). These follow one another on an ascending scale and are organized into two large blocks that establish a growing and cumulative sequence from the most objective to the most subjective. In such an order, the subject must address the needs located at the lowest levels (objective) to be motivated or driven to satisfy the needs of a higher order (subjective) (Moreno Olmos, 2008).

In the first block, four types of needs are established, of which the fourth –esteem needs– and in the second block –meta-needs (virtues, desires, aspirations, potentialities, among others)– suggest psychological aspects, individualistic and subjective. The three lower levels of needs are the most important to study. because they impact habitability methodologies' indicators when understanding architecture as a satisfier:

1. Physiological needs: They are the most basic needs, and their absence threatens human survival. From the architectural point of view, the dwelling unit must provide the infrastructure for hydrating, feeding, sleeping, removing bodily waste, having sex, and keeping body temperature.

2. Health and safety needs: It refers to a safe, orderly, and confident life without dangers and risks to personal and family integrity. The housing must give the dweller health and safety; and facilitate access to resources such as transportation, education, health, etc., to survive with dignity.

3. Social needs: It alludes to feeling rooted in places and integrated into groups and social networks, promoting relationships, participation, and social acceptance. It means that architecture must supply spaces that enable contact, social relations, friendship, association, sports, and cultural and recreational activities.

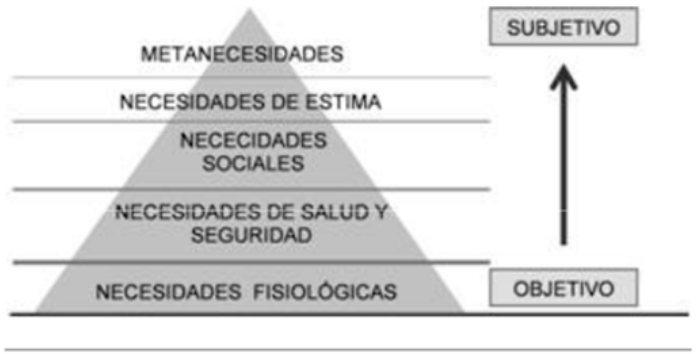


Illustration 2. Maslow's pyramid. Source: Moreno Olmos (2008).

As shown, the **body's thermal equilibrium is one of the primary physiological needs** to be guaranteed, and it is **directly related to the house's thermal comfort**, the main variable of this study. Hence, the indicators analysis of some quality-of-life standards allowed for identifying in the building scale if a thermal equilibrium is assessed, how it is evaluated, and if climatic differentiation is considered in the criteria used (Table 2).

ASSESSMENT CRITERIA IN THE BUILDING SCALE

		Anthropometric adaptation & organization of the rooms					**Sanitary facilities and services**				
		Overcrowding	Spaces distribution	Storage spaces	Furniture	flexibility	Drinking water	Swage	Energy	Gas	Others (TV, DATA, ect)
	Physiological needs / **Health and safety needs**	Physiological needs	Physiological needs	Health and safety needs	Physiological needs	Health and safety needs	Physiological needs	Physiological needs	Physiological needs	Physiological needs	Health and safety needs
1	Indicadores de necesidades básicas insatisfechas [NBI] (CEPAL, 1987)	(1) Number of people in the household (2) Number of rooms in the house					(1) Availability (Yes / No) (2) Water supply source	(1) Availability (Yes / No) (2) disposal system			
2	Document of Calidad de la Vivienda dirigida a los Sectores de Bajos Ingresos (2003, Bogotá)	(1) The ratio between the number of spaces and the number of inhabitants	(1) essential spaces		(1) Availability of essential appliances (Yes/No)		(1) Availability (Yes / No)	(1) Availability (Yes / No)	(1) Availability (Yes / No)	(1) Availability (Yes / No)	(1) Availability (Yes / No)
3	La metodología de evaluación de calidad del Observatorio de Vivienda de La Universidad de Los Andes (2006, Colombia)	(1) The ratio between the number of spaces and the number of inhabitants	(1) essential spaces (2) spaces dimension - minimum side & area (3) Productive space	(1) Availability (Yes / No)	(1) flexible furniture (Yes/No)	(1) Flesible interior walls (Si/No)	(1) Availability (Yes / No)			(1) Availability (Yes / No)	(1) Availability (Yes / No)
4	The study of habitat needs and the application of the pilot test carried out in the Bosa neighbourhood of Bogotá by UN-Habitat in 2007		(1) essential spaces (2) spaces dimension - minimum area				(1) Availability (Yes / No)	(1) Availability (Yes / No)	(1) Availability (Yes / No)	(1) Availability (Yes / No)	(1) Availability (Yes / No)
5	The HQI – Housing Quality Indicators in England	(1) The ratio between the number of spaces and the number of inhabitants	(1) essential spaces (2) spaces dimension - minimum area	(1) Availability (Yes / No) (2) Minimum size	(1) Availability of essential appliances (Yes/No) (2) Minimum size		(3) Water metering				

Physiological needs
Health and safety needs

Table 2. Criteria of habitability assessment models in the building scale. Source: Compilation based on some Quality-of-life standards.

		Climatic conditioning								Energy and water efficiency			
Networks quality	Materials & construction quality	Natural Light	Acustic comfort	Conditioning system	Ventilation System	Building orientation	Envelope energy & comfort performance	Draught-proofing	Room temperature control	Low energy fittings	Renewable energy source	Efficient water fittings	Recycling and reusing water
	(1) Construction materials used in flooring, walls and ceiling												
	(1) Construction materials used in flooring, walls and ceiling	(1) Windows Availability (Yes / No)	(1) Availability of acoustic walls (Yes / No)		(1) Availability of natural system (Yes / No)								
(1) Networks share a shaft (2) easily inspectect shaft	(1) Construction materials used in flooring, walls and ceiling	(1) Windows Availability (Yes / No)	(1) Availability of acoustic walls (Yes / No)		(1) Availability of natural system (Yes / No)	(1) adequate orientation according to the climate (Cold & hot)				(1) Efficient light (Yes/ No)	(1) System Availability (Yes / No)	(1) Efficient equipment (Yes/No) (2) flow at 3 bar	(1) System Availability (Yes / No)
	(2) Structure type & condition												
	(3) Sustainable timber use	(1) Windows Availability (Yes / No)	(1) Availability of acoustic strategies (acoustic walls, rooms location, etc) (Yes / No)	(1) Efficiency and type of the mechanical system	(2) Type of systrem		(1) Availability (Yes / No)	(1) Availability (Yes / No)	(1) Availability (Yes / No)	(1) Efficient light (Yes/ No)	(1) System Availability (Yes / No)	(1) Efficient equipment (Yes/No) (2) flow at 3 bar	(1) System Availability (Si / No)

THERMAL COMFORT & ENERGY EFFICIENCY

All the assessment standards include the anthropometric adaptation & organization of the rooms and sanitary facilities. On the other hand, the documents (2) Calidad de la Vivienda dirigida a los Sectores de Bajos Ingresos, (3) Metodología de Evaluación de Calidad del Observatorio de Vivienda de La Universidad de Los Andes, and (5) the HQI – Housing Quality Indicators in England examine natural light, acoustic comfort and ventilation system efficiency and quality. The last two also check out strategies related to efficiency, like low energy fittings, efficient water fittings, water recycling and reusing, and renewable energy sources.

Even if it suggests some measures related to thermal comforts, such as **the absence of overcrowding, the orientation, the ventilation system, and the envelope performance.** These criteria do not consider a systematic climate differentiation, nor their primary goal is the thermal comfort evaluation. Although in the Observatorio de Vivienda standard, the orientation criteria have a climate differentiation between cold and hot, the ventilation system does not, and the existence of windows only verifies it without considering minimum aperture or airflow.

Besides, the envelope performance is only assessed in the HQI standard, focusing on energy efficiency due to the culture, climate and HVAC equipment used in these countries.

Social housing sustainability certifications and policies

As mentioned, construction is a productive activity that generates the most significant environmental impact. This is why within the framework of the congress held by the International Union of Architects in 1993, the architects' labor union established co-responsibility in the environmental crisis setting that: sustainable design integrates considerations of efficiency in the use of resources and energy; it must produce **healthy buildings**, it must use ecological materials, and it must consider the aesthetic sensibility that inspires, affirms, and excites (Valencia, 2018a).

Those encouraged the establishment and implementation of evaluation systems that allowed the global improvement of sustainability. One was the BREEAM (Building Research Establishment Environmental Assessment Method) at England in 1990. As well as LEED (Leadership in Energy and Environmental Design) created in 1993 by the US Green Building Council. These two pioneering systems would measure the environmental performance of buildings through the phases of design, construction, and operation (Diaz Sarachaga, 2017).

Though In Colombia is believed that environmental reform was conceived in the twentieth century since the 1991 Constitution contains 70 articles that refer to environmental problems. As well as in 1993, Law 9 established the Ministry of Environment Housing and Territorial Development (Minvivienda) and strengthened the National Environmental System (SINA) (Rojas Duquino, 2018). It was not until 2008 that the foundation of CCCS (Consejo Colombiano de construccion sostenible) stimulated the implementation of sustainable building policies and international sustainable building certifications in the country.

Regarding the rating systems, since 2010, LEED has become Colombia's main sustainability certification system for real estate projects in institutional and commercial use; in 2019, the number of certified buildings in the country was 178, and more than 216 are in the process of certification. However, the most common standards for residential projects are EDGE, a rating system for developing countries created by the IFC and Casa Colombia, designed by the CCCS. Currently, with the Casa Colombia standard, more than 2.500 housing units are in the process of certification in Antioquia, Cundinamarca, Huila, Nariño, and Valle del Cauca; there are already 6 VIS projects in the certification process (Vargas Rubio, 2020).

In respect of the EDGE rating system, there are 113 projects certified, about 52.000 dwelling units. Of these, 29 projects are social housing, and 5 are in Barranquilla. Some other standards have been implemented, HQE with 7 projects of which 5 are residential buildings; WELL, with 25 office projects health-safety rated; and Living Building Challenge [LBC] with 1 project in certification process. An analysis of the thermal comfort assessment methodology was made in each rating system, identifying their objective, standard, assessment methodologies and measures (Table 3).

As seen in Table 3, all the certifications evaluate the thermal comfort variable except for the EDGE standard, which focuses on energy efficiency; however, the bioclimatic measures applied to improve the energy consumption also raise the thermal housing performance. The hygrothermal comfort target is assessed mainly by **ASHRAE 55 & NTC 5316** for naturally ventilated spaces and **ISO 7730:2005: PMV&PPD** for mechanically ventilated areas. It is mandatory in Casa Colombia, HQI, WELL, and LBC labels; and optional in one of Colombia's most used rating systems (LEED).

Besides, the climatic differentiation between cold and hot is considered only in the "local" certification systems.

Most of the certifications are born in the idea of mechanically conditioning spaces (HVAC systems); for that reason, thermal comfort loses significance. It only boils down to a dynamic model verification as happens in the Casa Colombia, LEED, EDGE, and HQI labels. Consequently, all the strategies analogous to thermal optimization are placed in their energy chapter. Indeed, in the peoples' well-being standards (WELL & LBC), thermal equilibrium in the buildings becomes more relevant while considering a deeper assessment using sensor data and post-occupancy surveys.

The most significant passive criteria used is the orientation based on the solar chart; solar control (external shading devices, WWR less than 25%); natural ventilation (sufficient operable windows, night-time ventilation); and bioclimatic envelope (reflective roof and wall; roof and wall insulation; radiant ceilings, walls, or floors; and high-performance glazing). In addition, some active strategies are considered, such as ceiling fans, heating and cooling controls, humidity control, and controls for windows operation.

On the other hand, regarding the main **regulations related to sustainable housing** we have at the national level the primer Criterios ambientales para el diseño y construcción de vivienda urbana (Ministerio de Ambiente y Desarrollo Sostenible [Minvivienda], 2012). This guide was for new residential buildings' design, construction, and operational stages. The model is established over the climate classification of Colombia (Cold, temperate, hot-dry, and hot-humid), and tries to give detailed bioclimatic measures to improve the energy performance of the buildings, always understanding thermal comfort as a relevant variable for quality of life. Its fulfilment is optional, and the verification is done through a strategies checklist (Table 4).

Rating system	Housing projects in Colombia	Description	Aproach	Stages	Thermal comfort					
					Objetive	**Standards**	**Assesment**	**Passive meassures** **Strategies from other credits	**Active meassures** **Strategies from other credits	**Compliance**
Casa Colombia	2500	In the CASA Colombia certification system, we analyze the relationship with the Sustainable Development Goals (SDG) to determine its contributions to the Global Agenda.	People's well-being and Energy and water efficiency	Design Construction Operation	Demonstrate through an analysis of the climatic conditions of the place how the design strategies allow adequate thermal comfort inside the houses. *Divide the measures between cold and hot weather. For this work, only measures for hot weather are considered.	*ASHRAE 55 - 2010 *NTC 5316 *NTC 5183	*Dynamic thermal simulation	*Climate conditions analysis *Define comfort ranges *Shading elements (balconies or overhangs) *High performance window (SHGC < 0.45, U < 3 W/m²*K) *WWR 25% - 30% *Reflective roof **Energy eficiency: - Orientation based on the solar chart. - Solar control design through sunlight analysis. - Natural ventilation. - Envelope.	*Ceiling fans	Mandatory (at the discretion of the design team)
EDGE	11	EDGE stands for Excellence in Design for Greater Efficiencies, and the certification has the goal of reducing the environmental impact of buildings in three areas: direct energy consumption, water consumption, and the energy footprint of construction materials.It is a rating system for developing countries.	Energy and water efficiency	Design Construction	Regarding thermal comfort, EDGE's goal is to reduce energy consumption. *Divide the measures between cold and hot weather. For this work, only measures for hot weather are considered.	-	*HVAC energy consumption. Virtual HVAC system for naturally ventilated buildings.	** Energy: - Window-to-wall ratio less than 25% - Reflective Roof: Solar reflectance index greater than 45. - Reflective exterior walls: Solar reflectance index greater than 45. - External shading devices - Roof and wall insulation - Insulation of Ground/Raised Floor Slab - Green Roof - High performance glazing - Air infiltration of envelope lees than 0.61 L/s-m² - Natural ventilation in bedrooms, living room & kitchen. Room Depth to Ceiling Height Ratio	** Energy: - Ceiling fans - Cooling system efficiency - Fresh air pre-conditioning system	-
LEED V4.1 Residential	14	Its objective is to optimize the use of natural resources, promote regenerative and restorative strategies, maximize the positive and minimize the negative consequences in terms of the human and environmental health of the construction industry, and promote high-quality indoor environments for the building residents.	People's well-being and Energy and water efficiency	Design Construction Operation Maintenance	It is a credit to promote occupants' comfort and well-being by providing quality thermal comfort.	*ASHRAE Standard 55-2017 **ISO 7730:2005: PMV & PPD	*Dynamic thermal simulation *Check list	*Walls, floor, and roof components meet the insulation value requirement (2009 IECC Commercial code). *Have no thermal bridges in the envelope. *Windows meet the maximum U-value and SHGC.	*Heating and cooling controls	Optional
HQI	5	It recognizes the environmental commitment obtained through construction projects; Furthermore, it is divided into four components: Eco-management, Eco-construction, Health and Comfort.	People's well-being and Energy and water efficiency	Design Construction Operation	The intent is to demonstrate a healthy indoor environment.	* GIVONI polygon	*Dynamic thermal simulation *HVAC energy consumption	**Target 4: Energy - Thermal design - Bioclimatic design of envelope - Orientation - Management of solar gains - Natural Ventilation **Target 10: Visual comfort - Natural lighting - Have an aperture index greater than or equal to 15%.	*Equip each residence with a thermo-hygrometer **Target 4: Energy - Thermal design - Thermal insulation and solar protection of air-conditioned spaces. - Nigth time ventilation. - Misting.	Mandatory
WELL	0	It is a system to monitor, measure and certify how buildings' operation and characteristics influence people's health and well-being.	People well-being	Design Construction Operation	The WELL Thermal Comfort concept aims to promote human productivity and provide a maximum level of thermal comfort among all building users through improved HVAC system design and control and by meeting individual thermal preferences.	*ISO 7730:2005: PMV & PPD *ASHARE 55 - 2020	*Dynamic thermal simulation *Sensor Data *Post-occupancy Surveys	* Ratio between area and people *Blankets *Radiant ceilings, walls or floors (heating & cooling) *Window design: At least 70% of operable windows may be opened; If project is equipped with heating, at least 30% of operable windows may be opened. ** Light: Daylight design strategies - All vertical transparent envelope glazing has shading: Manual or automated shading.	*Thermostats in each space *Desk fan or ceiling *Electric parabolic space heater *Humidity control *Controls for windows operation	Mandatory

LBC	0	The end goal of the Living Building Challenge is to encourage the creation of a regenerative built environment. The challenge is to raise the bar for building standards from doing less harm to contributing positively to the environment. It rapidly diminishes the gap between current limits and the positive end-game solutions we seek by pushing architects, contractors, and building owners out of their comfort zones.	People's well-being and Energy and water efficiency	Design Construction Operation	The intent of this Imperative is to demonstrate ongoing high-quality indoor air and a healthy indoor environment.	-	*Check list	*Sufficient operable windows to provide natural ventilation for at least six months of the year. *Residential projects must provide operable windows for 100% of the project occupants.	*Ability for the occupants to influence their local airflow and temperature through direct input or controls.	Mandatory

Table 3. Thermal comfort assessment in sustainable standards. Source: Compilation based on some sustainable standards.

Moreover, after the signing of the 2030 Agenda on September 25, 2015, the policies that lead to sustainable development and growth of nations have increased worldwide. This phenomenon has also been happening in Colombia, which prompted Resolution 549 (2015). Facing the problem of encouraging the application of the regulations, Resolution 463, 2018, was heralded, establishing the procedure to access VAT and income tax incentives regarding the strategies applied to comply with energy and water savings.

As seen in the Table 4, Resolution 549, 2015, intends to reduce water consumption and greenhouse gases [GHG] in new buildings through energy and water efficiency measures and passive air conditioning strategies. The regulation divides Colombia's climate into four, cold, temperate, hot-dry, and hot-humid. It also characterizes eight types of buildings, hotels, hospitals, offices, malls, schools, No VIS housing, VIS housing, and VIP housing. For compliance, concerning the building's baseline (not specified in the resolution) are established savings ranges depending on the climate and type; these ranges vary between 20% and 40%.

The policy is mandatory for all buildings except for VIS and VIP housing. Given that the national government intends to reduce CO2 emissions, that is contradictory when the MME reports that 40% of the energy consumed in Colombia is from the residential sector supply. Furthermore, the highest consumption in this sector corresponds to the strata to which the VIS and VIP belong (Giraldo, 2018). Further, the entire body of the regulation provides only generalities and lacks depth when specifying the procedures to follow to put it into practice in architectural design. Neither was established a calculation procedure nor an implementation procedure for the verification (Table 4).

In light of both regulations, the most significant passive criteria mention is:

- **Building shape:** rectangular and perimeter circulation, sloping roof with slopes greater than 35°, minimum free height of 2.50 m, raised floor, the window area must be between 25% and 10% of the space area.
- **Orientation:** the longer façade faces the north.
- **Shading elements:** horizontal or vertical shading system.
- **Natural ventilation:** open facades, chimney effect, avoid wet currents, cross ventilation, airtightness.
- **Bioclimatic envelope:** Light walls with low density and low thermal conductivity, Trombe walls, Low glass solar gain coefficient.

				Thermal comfort in hot-humid climate			
Regulation	**Description**	**Aproach**	**Stages**	**Building Type**	**Objetive**	**Meassures**	**Compliance**
Criterios ambientales para el diseño y construcción de vivienda urbana (Minvivienda, 2012)	The proposal for environmental criteria is developed around three primary environmental management objectives constituted in fundamental principles of sustainable architecture: - The rationalization of the use of natural resources. - The substitution with alternative systems or resources. - Environmental impact management.	People's well-being and Energy and water efficiency	Design Construction Operation	New low-rise housing & New high- rise housing	**Adequate configuration of the habitable space** Design spaces with an exemplary configuration, distribution, shape, size and height, given appropriate ergonomic parameters and environmental conditions. It will foster healthy, comfortable, and efficient homes.	*Building with a rectangular shape and perimeter circulation. *Corridors covered by eaves that protect from rain and sun. *Open facades *A Sloping roof with slopes greater than 35º. *Minimum free height of 2.50 m, with an average of 2.70 mm. *Light walls, so they do not retain moisture, low density and low thermal conductivity. *Large windows on the facade to improve ventilation. *Open corridors with large eaves, where fresh air circulates and allows room ventilation. *Raised floor to avoid ground moisture. *The main facade (longer) faces north. *The main facade is towards the wind axis with inlets and outlets. *The roof plans with the most significant area to the north.	
					Apply the physical properties of materials Selection of materials and passive systems for managing the building's temperature, lighting and acoustic conditions according to the characteristics and physical properties, mass or thermal inertia and lighting and acoustic behaviour, taking advantage of their contribution to reducing energy consumption and improving indoor air conditioning conditions.	* Materials with low conductivity and low density are used as thermal and acoustic fillers in construction joints or double walls between rooms. *Materials with high porosity, permeability or cavities allow perspiration from the interior environment, managing humidity or condensation. * According to their transparency and conductivity, colour or texture, materials allow or reject the passage of light, heat or sound. *Trombe walls, which drive the internal air through solar heat, are applicable as heaters by injecting air or refrigerants. *Ducts and thermosyphons with chimney effect propel the air by aerodynamic pressure difference or convection. *Terraces covered with vegetation function as thermal and acoustic buffers and provide green areas that renew the air.	Optional
					Efficient use of natural lighting Implementation of natural lighting through openings such as doors, windows, skylights, skylights, and other devices that allow the transmission, dispersion and reflection of sunlight.	*If the windows face north slightly, northwest orientations are acceptable in hot-humid areas, if required. *Implement control devices for solar radiation, eaves, sunscreens or shades, complying with appropriate lighting levels *The window area must be between 25% and 10% of the space area.	
					Efficient use of natural ventilation Renewal of the interior air of a building through the proper location of openings, steps or ducts, taking advantage of the depressions or overpressures created in the building by the wind, humidity or thermal convection of the air, without the need for systems that involve conventional energy consumption. The efficiency depends on the difference in temperature between the air that enters and the air that leaves and the ventilation flow: the more significant the difference and flow, the greater the cooling capacity.	**One-site ventilation:** * It is not recommended for hot-humid climates since outdoor humidity is generally higher than indoor humidity. *Ventilation between the double deck, the floor and the ground is recommended. *Suction roof. **Cross ventilation:** *It should be in all living spaces, with openings on opposite sides. * Implementation of openings between different roof levels. In general, avoid wet currents as much as possible.	

Resolution 0549, 2015 Annexe No. 1: Sustainable construction guide for saving water and energy in buildings	The Sustainable Construction Guide aims to provide a tool for implementing sustainable construction strategies to be applied in municipalities throughout the country. The guide aims to promote energy efficiency and water conservation during the use of buildings.	Energy and water efficiency	Design	New high- rise housing	**Implementation matrix for hot-humid climate** This matrix determines the strategies to be implemented in housing projects to generate energy and water savings.	*Orientation, a long facade to the north. *Horizontal shading system. *Vertical shading at 1200mm intervals. *Combined vertical and horizontal shading. *Low glass solar gain coefficient (SHGC). *Wall U-value. *Roof U-value. *wall and roof reflectivity. *Natural ventilation *Airtightness	NO VIS Mandatory VIS & VIP Optional

Table 4. Thermal comfort assessment in sustainable regulations of Colombia. Source: Compilation based on some sustainable regulations.

Thermal Comfort fundamentals

Human body as thermodynamic system

The human body, considered as a thermodynamic system, produces mechanical work and low temperature heat, using food (fuel) and oxygen as input. This system requires in healthy conditions, to **maintain a constant internal temperature around 37±0.5°C**, otherwise the functionality of important organs like liver, spleen, etc, maybe severely damaged (Butera, 1998, p. 1).

The sensation of comfort arises from generating a microclimate that allows healthy thermoregulation; it means that the rate of heat generation of the body must be equal to the rate of heat loss from it. **The human body is susceptible to increases in internal temperature, and 5 or 6 degrees higher can cause death**. It tolerates even less the low temperatures, and at 35°C, hypothermia estate starts (Czajkowski & Gómez, 2002).

Within the human body, chemical and physical transformations keep us alive, i.e. when the body is releasing more energy than it is producing: (1) Increase skin thermal resistance using the vasoconstriction mechanism constricts the blood vessels under the surface of the skin leading to a reduction of the blood flow, a reduction in the body surface temperature and a reduction of heat loss; If this action is not sufficient; (2) the system start to produce energy by muscular tension and shivering (Butera, 1998).

On the other hand, when heat loss is not balancing heat production, the body: (1) Reduces the skin thermal resistance using vasodilatation that expands the blood vessels increasing the skin temperature and the heat losses rate; if this action is not enough; (2) The body starts to sweat improving evaporative heat loss.(Butera, 1998).

This permanent energy flow is called metabolism and varies according to people's activity level, age, gender, and psychological state. **It is often measured in met (metabolic rate); 1 met equals 50 kcal/(h*m²) or 58.2 W/m² equals**, which is the energy produced per unit skin surface area of an average person seated at rest.

According to the activity for an average adult, it can be classified into: (1) **resting**, in which sleeping equals 0.7 met and standing relaxed equal to 1.2 met; and (2) **active,** depending on the type of activity, it can vary from 1.1 met for office activities to 4.0 met for exercise. **When the metabolic rate (met) increases above 1, the evaporation of sweat becomes an increasingly important factor for thermal comfort** (ANSI/ASHRAE STANDARD 55, 2017).

	Metabolic rate		
Activity	Met Units W	/m²	kcal/(h*m²)
Resting			
Sleeping	0.7	40 3	5
Reclining	0.8	45 4	0
Seated, quiet	1.0	60 5	0
Standing, relaxed	1.2	70 6	0
Active			
Walking	2.0 to 3.8	115 to 220	100 to 190
Offices activities (reading, writing, typing)	1.2	70 6	0
Cooking	1.6 to 2.0	95 to 115	80 to 100
House cleaning	2.0 to 3.4	115 to 200	100 to 170
Dancing, social	2.4 to 4.4	140 to 255	120 to 220
Exercise	3.0 to 4.0	175 to 235	150 to 200

Table 5. Metabolic Rates for Typical Tasks. Source: (ANSI/ASHRAE STANDARD 55, 2017, p. 6).

The human body also loses heat by:

1. Heat lost by evaporation: Heat loss by water vapour diffusion through the skin; the thermoregulatory system does not control it, but instead by sweat glands. It is a function of air relative humidity (RH), air temperature (Tair), relative air velocity (Vair), skin temperature, the thermal resistance of clothing, and skin wittedness[1].

2. Respiration heat loss: As stated by Butera (1998, p. 42) "When breathing, expired air contains water vapour saturated at internal body temperature; the vaporization heat is taken from the lungs: this is the latent respiration heat loss. The dry heat loss derives from the temperature difference between inspired and expired air".

3. Covective heat loss: The convective heat flow rate from the body to the environment is a function of air temperature, the average temperature of the clothed body surface, the kind of clothing, and relative air velocity.

4. Radiative heat loss: It is the rate of radiative energy exchange between the human body and its environment. It is a function of the average temperature of clothed body surface, meant radiant temperature (Tmr) and kind of clothing. "Where the mean radiant temperature (Tmr) is defined as the uniform blackbody temperature of an imaginary enclosure with which man exchanges the same heat by radiation, as he would in the actual complex environment" (Butera, 1998, p. 43).

5. Heat loss by conduction: This is the loss occurring between the body and the objects through contact. It is challenging to evaluate and usually ignored as a separate item but consider in the clothing's thermal resistance.

Evidently, the thermal resistance of clothing is an essential variable in the human body's energy flow. Due to its complexity, a simplification has been adopted, and the properties of clothing have been included in an overall thermal resistance (Clo). 1 clo equals 0.155 m²°C/W which represents the thermal resistance of a long suit with regular underwear (ANSI/ASHRAE STANDARD 55, 2017).

Clothing Description	Typical clothing ensembles	Icl, clo
Nude	-	0
Shorts	-	0.1
Typical tropical clothing ensemble		
Women	Knee-length skirt, short-sleeve shirt, sandals	0.54
Men	Walking shorts, short-sleeve shirt, shoes, and socks	0.36
Light summer clothing	Long light-weight trousers, open neck shirt with short sleeves, light socks, and shoes	0.50
Typical indoor winter clothing ensemble	Shirt with long sleeves, trousers, jacket or sweater with long sleeves, heavy socks, and shoes	1.0
Heavy traditional European business suit	Shirt, suit including trousers, jacket and waistcoat, woollen socks, and heavy shoes	1.5

Table 6. Typical clothing ensembles. Source: compilation based on (ANSI/ASHRAE STANDARD 55, 2017) and (Butera, 1998).

1 Skin wittedness, i.e., the fraction of the whole skin covered with a film of unevaporated sweat (Butera, 1998).

Thermal Comfort definition and variables

Thermal comfort must be understood as a fundamental variable of social sustainability that supplies the need for thermal balance, adequate living conditions and, therefore, quality of life. In addition, thermal comfort based on bioclimatic contributes to reducing the environmental impact and energy consumption (Fergus et al., 2012). This denotes the relevance of the concept, which pitifully, until now, in Colombia has not been outstanding.

From a scientific point of view, thermal comfort is the psychological perception of an individual concerning the immediate thermal environment, that is, the subjective thermal sensation that the occupant has towards a space. The thermal sensation depends on indoor and outdoor environmental circumstances and personal factors like metabolism, age, ethnicity, weight, clothing, health status and acclimatization capacity (CIBSE, 2006; Rodríguez Hidalgo, 2022). Consequently, the circumstances required to achieve thermal equilibrium are different for everyone. However, laboratory and field research have made it possible to establish the conditions most people are thermally comfortable with statistically. Steady-state experiments showed that cold discomfort is strongly related to the mean skin temperature and warm discomfort is strongly related to the skin wetness caused by sweat secretion (Djongyang et al., 2010).

The thermal environment[1] for Givoni (1971) depended mainly on the interrelation between air temperature (Tair) and relative humidity (RH).

1 Thermal environment: a combination of microclimatic variables influencing the thermal sensation like air temperature, relative humidity, wind speed, etc.

However, other indices, such as Fanger (1970), state that it is necessary to balance more variables such as metabolic rate (Met), clothing (Clo), airspeed (Vair) and mean radiant temperature (Tmr). Some of the thermal comfort variables are defined below:

1. **Air temperature (Tair):** It determines the heat transfer between two objects; it means the skin and air interaction. This interaction is called heat transfer by convection.

2. **Mean radiant temperature (Tmr):** Each material with a temperature greater than absolute zero emits radiant energy, radiant temperatures (Tr). It is generated due to the particle movement charged by a radiation source and does not require any energy transmission source. The average heat transfer of the surrounding elements Tr through electromagnetic waves is called Mean radiant temperature (Tmr). This is determined by the uniform surface temperature of a radiantly black enclosure where an occupant would exchange the same amount of radiant heat as in the actual non-uniform space (CIBSE, 2006).

   Dittmar (1995) found that Tmr is the most influential factor in thermal comfort; he evaluated what was experienced by people inside an environment with controlled conditions; the occupants experienced a cold sensation when the Tai was 48°C, and the walls had radiant temperatures (Tr) close to 10°C. While in an environment with Tair 10°C they felt suffocated because the Tr of the walls were close to 40°C (Giraldo, 2018).

   Although optimal welfare levels for Tmr are not strictly defined, Fanger and ASHRAE recommend that they not differ from Tair. Therefore, the range is between 22°C and 28°C; in contrast, for Givoni, the range for summer conditions or hot climates is between 22°C and 29.5°C.

3. **Operative temperature (To):** The To index combines the effects of air temperature (Tair) and mean radiant temperature (Tmr). the operative temperature is defined as the uniform temperature of an imaginary enclosure in which human being will exchange the same dry heat by radiation and convection as in the actual environment. For thermally moderate environments and for Tmr – Tair < 4°C, it may be assumed that To = (Tmr – Tair)/2 (Butera, 1998; CIBSE, 2006).

4. **Airspeed (Vair):** This parameter is measured in meters per second (m/ s). The fluctuation and air velocity are produced for the mass's heating and cooling. The air movement considerably affects thermal comfort due to the user's heat loss. "Where air speeds in a room are greater than 0.15 m/s the operative temperature should be increased from its 'still air' value to compensate for the cooling effect of the air movement" (CIBSE, 2006).

5. **Relative humidity (RH):** It is the relationship between the quantity of air water vapour and the maximum quantity the air could have, measured in percentage. CIBSE (2006) states a humidity range of 40–70 % RH as acceptable. **Higher relative humidity could negatively affect the thermal sensation in a hot-humid climate because it stops the heat transfer by evapotranspiration**. Otherwise, the ANSI/ASHRAE 62.1, (2010) set an acceptable RH humidity between 40-65% to avoid the proliferation of viruses, allergies, or respiratory diseases.

Thermal comfort evaluation methodologies

Graphic Comfort Zone Method

Givoni proposed one of the first evaluation methodologies through the psychrometric diagram, which conforming to Tair and RH, shows the comfort zone and the possible strategies according to the climate.

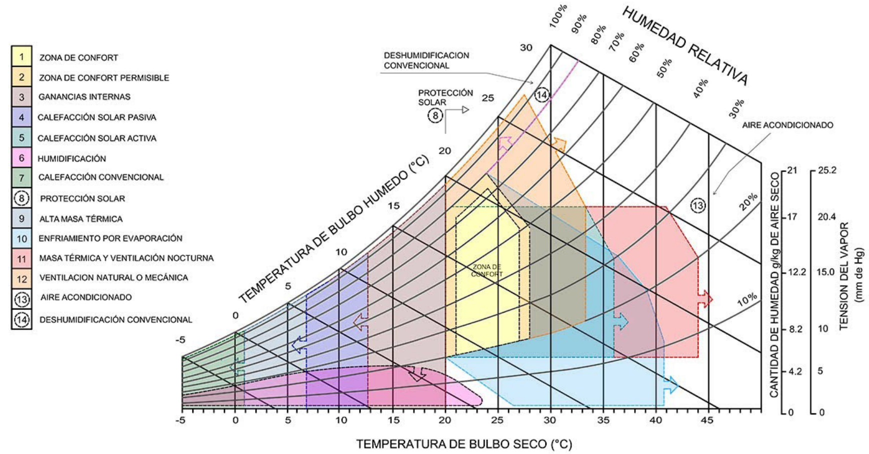


Illustration 3. Givoni's Psychrometric Chart.Source: (Czajkowski & Gómez, 2002).

The predicted mean vote

Later, Fanger derived a general comfort equation including Tair, RH, Tmr, Vair, Met, and Clo. He proposed two indices to evaluate the thermal situation of spaces: **(1)** The thermal index, called predict mean vote (PMV), and **(2)** The percentage of Dissatisfied index (PDD).

1. **Predicted Mean Vote (PMV):** it is an index that predicts the mean value of the votes of a person on a seven-point thermal sensation scale between -3 to +3.

Thermal sensation scale used by Fanger

+	3	Hot
+	2	Warm
+	1	Slightly warm
	0	Neutral
-	1	Slightly cool
	2	Cool
	3	Cold

Table 7. Thermal Sensation scale used by Fanger. Source:(ANSI/ASHRAE STANDARD 55, 2017).

Fanger related PMV to the imbalance between the actual heat flow from a human body in a given environment and the heat flow required for optimum comfort at a specified activity. The index is derived for steady-state conditions but can be applied with good approximation during minor fluctuations of one or more variables. The PMV is given by the equation:

$$PMV = (0.303e^{-0.036M} + 0.028)\{(M-W) - 3.05\times10^{-3}[5733 - 6.99(M-W) - p_a] \\ -0.42[(M-W) - 58.15] - 1.7\times10^{-5}M(5867 - p_a) - 0.0014M(34\text{-}t_a) \\ -3.96\times10^{-8}f_{cl}[(t_{cl}+273)^4 - t_{mr}+273)^4 - f_{cl}h_c(t_{cl}-t_a)\}$$

Where

$$t_{cl} = 35.7 - 0.028(M-W) - I_{cl}\{3.96\times10^{-8}f_{cl}[(t_{cl}+273)^4 - t_{mr}+273^4] + f_{cl}h_c(t_{cl}-t_a)\}$$

$$h_c = \begin{cases} 2.38(t_{cl}-t_a)^{0.25} & \text{for } 2.38(t_{cl}-t_a)^{0.25} > 12.1(v_{ar})^{1/2} \\ 12.1(v_{ar})^{1/2} & \text{for } 2.38(t_{cl}-t_a)^{0.25} < 12.1(v_{ar})^{1/2} \end{cases}$$

$$v_{ar} = v_a + 0.005(M/A_{DU} - 58.15)$$

$$f_{cl} = \begin{cases} 1.00 + 1.290\cdot I_{cl} & \text{for } I_{cl} < 0.078\,\mathrm{m^{2\circ}C\,W^{-1}} \\ 1.05 + 0.645\cdot I_{cl} & \text{for } I_{cl} > 0.078\,\mathrm{m^{2\circ}C\,W^{-1}} \end{cases}$$

2. **Percentage of Dissatisfied (PDD):** it is used to predict the number of people likely to feel uncomfortably warm or cold. It has been introduced, which establishes a quantitative prediction of the number of thermally dissatisfied persons. It is given by the equation:

$$PPD = 100 - 95\cdot exp[-(0.03353\cdot PMV^4 + 0.2179\cdot PMV^2)]$$

Institutions such as ISO in Europe through the ISO 7730 Standard and ASHRAE in the United States have adopted these methods as the most suitable and complete to evaluate thermal comfort and suggest that an ideal PMV is between -0.5 to +0.5, which translates into a PPD of less than 10%. However, it is aimed at the uniform and steady-state traditional air conditioning environment and does not consider the non-uniform and non-steady-state environment, let alone the effect of local hot and cold sensation on the overall thermal sensation (Djongyang et al., 2010; Zhao et al., 2021).

The predicted mean vote in sleeping environments

As CIBSE (2006) stated, there are insufficient data about residential buildings' hydrothermal comfort. However, some studies suggest that people are less sensitive to temperature changes in their homes than at work, and in general, people have more adaptive opportunities at home. Even so, attention must be given to the bedroom temperature at night since they are likely to be more critical than the living area. Research has shown that high bedroom temperatures can result in poor sleep quality and poor performance the following day at work.

However, research on thermal comfort for sleeping environments at night is limited. Most thermal environmental guidelines or standards were formulated to satisfy awakened people instead of sleeping people, even though studies have shown a significant difference between the thermal requirements of sleeping people and their awakened counterparts. The exploration in this field must be expanded concerning that it is one of the primary human physiological needs, and a human being spends approximately one-third of his/her life in sleep (Tsang et al., 2021).

Human sleep comprises two states (1) REM, rapid eye movement, and (2) NREM, non-rapid eye movement; both alternate cyclically across a sleep episode. Sleep begins in NREM stage N1 and progresses through deeper NREM stages (N2, N3) before the first episode of REM sleep occurs approximately 80-100 min later, after which it reoccurs every 90-120 min in distinct episodes. Stage N3 is called slow wave sleep (SWS) or deep sleep and is vital to both body and mind (Lan et al., 2017).

"Sleep typically occurs when the core body temperature decreases, and body heat loss is at its peak. (…) a low temperature (i.e., 20–26°C) in the sleeping environment is associated with a shorter time awake before entering the sleep cycle. (…) Body temperature continues to decrease after sleep onset"(Ngarambe et al., 2019, p. 4). Further, in heat exposure at about 35°C, shortened sleep duration and increased wakefulness was observed (Tsang et al., 2021). Available field study data show that thermal discomfort and sleep quality decrease if the bedroom temperature rises above a range of 24 - 26°C (CIBSE, 2006). The WHO (1988) recommends a minimum air temperature of 18°C for bedrooms, and the European Standard [EN15251] recommends a minimum bedroom temperature for heating of 20°C and a maximum temperature for cooling of 26°C.

As Ngarambe et al. (2019) stated, in the existing literature, the room temperature optimal for sleep has a wide range between 20 - 32°C, in which the optimal temperatures for clothed subjects were reported to be between 20 and 22°C and for naked subjects were up to 32°C. **This study also confirmed that low temperatures (20 -26°C) are appropriate in the waking phase of sleep; however, in subsequent phases of sleep, a mild increase in temperature is required to facilitate uninterrupted deep sleep, reaching temperatures between 28 - 30°C**. Sekhar & Goh (2011) suggest that in a hot-humid climate, a mechanically ventilated bedroom has a wider and hotter range of acceptable temperatures (27 – 30.5°C) than one with air conditioning (22.5 – 25.5°C) and ascribe the difference to the greater level of personal control which they have over the indoor conditions.

It must be remarked that people may adopt behavioural thermoregulation to reduce heat stress, e.g., changing sleeping posture, using airflow to reduce heat stress, etc. However, this behavioural thermoregulation in mid-sleep indicates wakefulness, degrading sleep quality (Tsang et al., 2021). Nicol (2019) set some ways in which people avoid the problem of overheating in bed in hot climates without the use of mechanical cooling: **(1)** using a bed without an insulated mattress, **(2)** using a fan to provide air movement, **(3)** passive or mechanical cooling, **(4)** light sleepwear and bedding, **(5)** moving to another place (for instance, to the roof to take advantage of radiant cooling to the sky) or into a cool basement. **Hence, the maximum temperature in bedrooms to avoid discomfort and sleep loss is a function of the bedroom environment (temperature, air movement and humidity) and the available adaptive opportunities.**

In most of the research studies related to sleep, only ambient air temperature was referred to, but the mean radiant temperature or operative temperature, relative humidity and air velocity were not considered. Furthermore, as Lin & Deng (2008) expound, the establishing thermal comfort models do not respond to the sleep environment particularities, given that, in the ANSI/ASHRAE STANDARD 55 (2017) is pointed out that "the standard does not apply to occupants who are sleeping, reclining in contact with bedding, or able to adjust blankets or bedding". As well as it has been recommended in ISO Standard 7730 to use the PMV index when the metabolic rate (M) is between 46 and 232 W/m² (0.8 and 4 met). The metabolic rate of a sleeping person is 40 W/m² (0.7 met), which is slightly out of the above range. Lastly, the clothing area factor (fcl) included in the PMV-PPD model is meaningless when a body is lying on a bed.

Overall, for the present work, the bedroom's thermal comfort evaluation at night will be carried out considering the thermal comfort model developed by Lin & Deng (2008), in which some modifications to the PMV model were applied; "for a sleeping person in a reclining posture with a specific bedding system which consists of a bed and mattress, bedding and sleepwear, it is assumed that the sleeping person is immobile during the whole period of sleep, therefore,"

$$M = 40\,\mathrm{W/m^2},$$

$$W = 0\,\mathrm{W/m^2}.$$

Since the model suggests that the total thermal insulation of the bedding system significantly influences the thermal neutral temperature, the clothing resistance, Rcl, and clothing area factor, fcl, are rearranged in terms of the total thermal resistance (Rt) provided by a bed, pillow, bedding, sleepwear, and the air layer surrounding a human body, as follows:

$$E_{sk} = \frac{i_m L_R w (p_{sk,s} - p_a)}{R_t},$$

where Lewis ratio (L_R) equals approximately to 16.5 K/kPa at typical indoor conditions [2].

Based on all the assumptions and modifications introduced above for sleeping environments, the heat balance for a human body is

$$40 = \frac{\bar{t}_{sk} - t_o}{R_t} + \frac{i_m L_R w (p_{sk,s} - p_a)}{R_t} + 0.056(34 - t_a) + 0.692(5.87 - p_a).$$

An essential condition for thermal comfort in sleeping environments is that thermal neutrality is achieved during sleep. But heat balance alone is insufficient to achieve thermal comfort; it must consider the evaporative heat loss from the skin. Lin & Deng (2008) mention, in a state of physiological thermal neutrality during sedentary (M=58.15W/m², W =0), the mean skin temperature is around 34°C, and there is no regulation of body temperature by sweating (i.e., sweating does not occur). So, in a state of thermal neutrality for a sleeping person whose activity level is lower than sedentary (M=40W/m², W=0), the mean skin temperature would increase, and sweat would not occur. Therefore, the second and third conditions for thermal comfort in a sleeping environment may be changed to:

$$\bar{t}_{sk,req} = 35.7 - 0.0275(M - W) = 34.6(^\circ C),$$

$$E_{rsw,req} = 0.$$

With no regulatory sweating for normal conditions, the skin wettedness (w) equals to 0.06, caused by E_{dif} alone [5]:

$$w = 0.06.$$

“Using an im=0.38, LR=16.5 K/kPa, hr=4.7 W/(m²K), a comfort equation for sleeping environments, which combines both environmental and personal variables to produce a thermal neutral sensation, may be derived from” (Lin & Deng, 2008b):

$$40 = \frac{1}{R_t}\left[\left(34.6 - \frac{4.7\bar{t}_r + h_c t_a}{4.7 + h_c}\right) + 0.3762(5.52 - p_a)\right] + 0.056(34 - t_a) + 0.692(5.87 - p_a).$$

Lin & Deng (2008) assumed that the sensitivity coefficient α, obtained by Fanger, is also applicable to sleeping environments. In other words, extrapolation was applied to extend the range of metabolic rate down to 40 W/m² (0.7 met when sleeping). Hence, the PMV for a sleeping environment can be calculated by:

$$\mathrm{PMV} = 0.0998\left\{40 - \frac{1}{R_t}\left[\left(34.6 - \frac{4.7\bar{t}_r + h_c t_a}{4.7 + h_c}\right) + 0.3762(5.52 - p_a)\right]\right\} - 0.0998\left[0.056(34 - t_a) + 0.692(5.87 - p_a)\right].$$

Finally, The PPD for a sleeping environment can be determined by the equation mentioned in the previous section.

The adaptation model

On the other hand, Givoni (1992), in a later work, shows the comfort ranges differ between the inhabitants of temperate and cold zones such as Europe or North America and those of countries with warm climates, which are used to living in naturally ventilated buildings. Likewise, he shows that the inhabitants of warm zones are acclimatized to these conditions and consider a broader range of Tair y Vair to be pleasant. Besides, “people adapt by changing their physical parameters, their physiology or activity level, their clothing, their expectations, and the way they use rating scales” (Butera, 1998).

> The adaptive method, unlike the heat-exchange method, does not require knowledge of the clothing insulation and the metabolic rate in order to establish the temperature required for thermal comfort. Rather it is a behavioural approach, and rests on the observation that people in daily life are not

passive in relation to their environment, but tend to make themselves comfortable, given time and opportunity (CIBSE, 2006, p. 16).

As Djongyang et al. (2010) stated, the Adaptive approach derives from field studies that analyse the actual acceptability of the thermal environment, which strongly depends on the context, the behaviour of occupants and their expectations. There are three ways to adapt to the internal environment as reported by Hernández Sánchez (2018):

1. Behaviour adjustment: Activity adjustments, putting on and taking off clothes, regulating air conditioning, taking a nap on a hot day, etc.

2. Physiological: Changes in psychological response due to exposure to thermal environmental factors. Those can lead to a gradual decrease in the thermal stress produced by this exposure. However, these processes happened with prolonged exposure to extreme conditions.

3. Psychological: Refers to altered perception and subsequent reaction to sensory information due to past experiences and expectations.

Over time, the authors have carried out experiments showing that studies focused on thermal comfort cannot be based on analysis in thermal cameras to acquire reliable information. That is why the Fanger model establishes a static comfort range for the Tair between 21 °C and 25 °C without considering the evaluated climate; In contrast, the adaptive model considers comfortable even 3.5 °C above and below the average Tair of the evaluated climate (Giraldo-Castañeda et al., 2021).

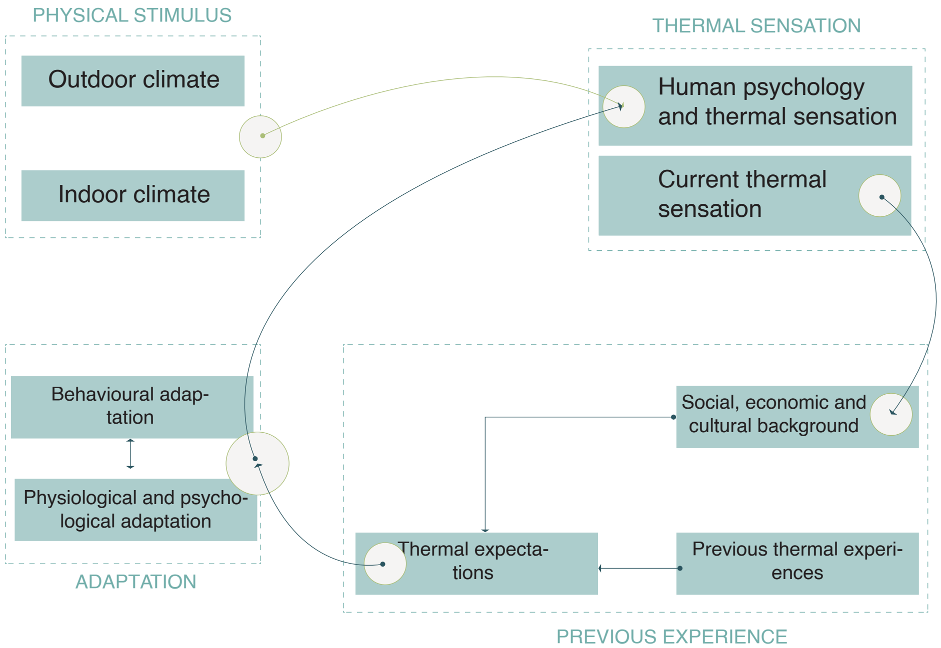


Figure 8. Operation of the adaptive process in buildings. Source:(Djongyang et al., 2010; Hernández Sánchez, 2018)

Chapter 3

Climate change in the Colombian tropics

Climatic change and well – being

Climate change must be understood in conjunction with the level of human intervention in the environment, such as uncontrolled urbanization and destruction of ecosystems, as well as its relationship with other associated risk factors, such as poverty, inequality, and corruption. Therefore, there is widespread concern about the current and future implications of natural disaster risk for urban areas in developing countries, where cities proliferate the fastest and many urban populations are poor. So, disaster risks are strongly related to social vulnerability, and impact assessment must be viewed from the perspective of society (Martínez González et al., 2021; Mora Díaz, 2021).

Latin America and the Caribbean are one of the regions most affected by Climate Change and external meteorological phenomena causing severe damage to health, life, food, water, energy, and socioeconomic development. **In Latin America, climate-related events and their impacts claimed more than 312,000 lives and affected more than 277 million people between 1998 and 2020. In 2020 was one of the three warmest years in Central America and the Caribbean, and the second warmest year in South America, with 1.0 degrees Celsius, 0.8 and 0.6 above the period 1981-2010, respectively** (Mora Díaz, 2021).

The impacts of climate change can affect human development in different ways, in five areas of life, according to UNDP (2007): first, agricultural production and food security; second, water stress and water insecurity; third, rise in sea level and exposure to meteorological disasters; fourth, transformation of ecosystems and biodiversity decline; **and fifth, impacts on human health**.

The last one, as stated by Sánchez Zavaleta (2016), refers not only to the absence of disease but also to the person's general well-being, and each **person's surrounding "environment" is the primary condition of that well-being.**

The most critical impacts of climate change may be due to changes in extreme events, infectious diseases, injuries, cancer, and heat stroke, among others. As reported by Cuartas & Méndez (2016) Five mechanisms take place for climate change to produce health effects:

1. **The rise of the burden of disease and mortality from injuries produced by climatic stress and precipitation**. It results in floods, storms, fires, droughts, and people's heat or cold stress. E.g., "**Heat discomfort and heat stress increase** mortality and morbidity for the most vulnerable, especially the elderly, children, and pregnant women. Additionally, children's learning ability significantly decreases with increased heat exposure". Nonetheless, the overheating of the human body is not an exclusive consequence of the increase in temperature. Also, when **the relative humidity** rises, the risk of heat illness increases, as it prevents the evaporation of sweat, preventing the body from cooling down (Sánchez Zavaleta, 2016; The World Bank Group, 2021a).

2. **The Proliferation of microorganisms, bacteria and viruses that contaminate food and water**. In Latin America, the main health effects associated to climate change are malaria, dengue fever and cholera. **In turn, the risk of contracting dengue is very sensitive to temperature changes, even very small ones.**

3. **Changes in the ecology of the vectors[1] and the vector-pathogen-host relationship**. It can undergo temporal and spatial modifications, i.e., the area of vector presence can be expanded or reduced, undergo seasonal changes, or accelerate the vectors' life cycle or the pathogens' reproduction cycle; like malaria and zika.

4. **Affect crops, livestock, and fish production**, with effects on access to food, nutrition, and health.

5. **Loss of belongings, goods, and displacement**. A result of extreme climatic events, such as floods, droughts, and landslides, which increase poverty, affect mental health, increase the possibility of infectious diseases, malnutrition, and exposure to physical risks.

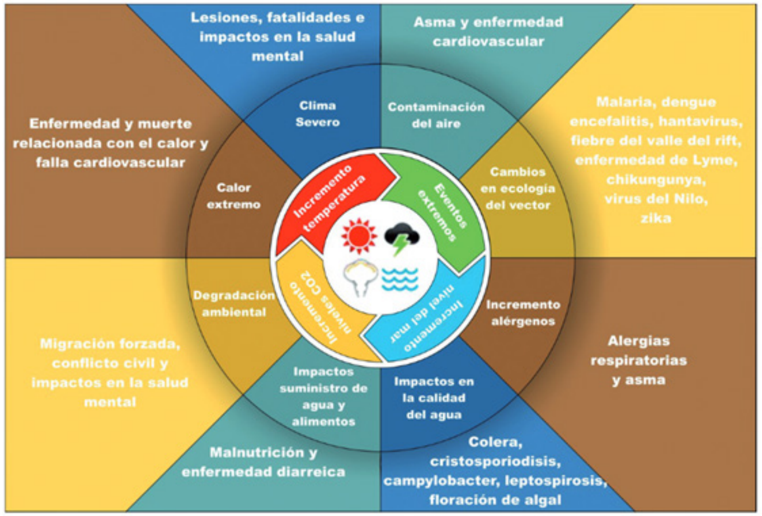


Illustration 4. Impacts of climate change on health. Source:(Cuartas & Méndez, 2016).

The effects of climate change on infectious diseases may become attenuated and, therefore, unrecognizable due to vector control. Otherwise, **extreme weather events can potentially cause the most significant effects due to their condition being acute events that occur in the short term**. In the short and medium term, the effects of climate change on health will be determined mainly by the vulnerability of populations, where vulnerability is the function of **exposition** to the climate conditions associated with climate change, the **sensitivity or response** of the Socio-ecosystems to a specific exposure and the **adaptation capacity** based on the social, institutional and resource capacities available (Cuartas & Méndez, 2016; World Health Organization, 2021).

On the other hand, In the longer term, the effects will depend increasingly on the extent to which **transformative measures** are taken now to reduce emissions and avoid reaching dangerous temperature thresholds and potential irreversible tipping points (World Health Organization, 2021). Considering this, in the following sections, a **recognition of the exposure to climate change** in Colombia and Barranquilla is made, focused on the climate stress, to analyse later in a case study the **sensitivity or response** of the socio-ecosystems and the **adaptation capacity** from the point of view of social housing (VIS) as the main surrounding environment that must provide well-being to people.

1 Vectors are organisms that transmit infectious diseases to people: mosquitoes, sandflies, ticks, fleas, rats, etc. (World Health Organization, 2020)

Recognition of the climate change exposure in the project location

Geographic location

Illustration 5. Colombia Geographic location. Source: Author's elaboration.

Colombia, considered as the **25th largest nation in the word** (1.138.910 km²) located in the northwest corner of South America, is a topographically diverse country traversed by the Andes Mountains (approx. 15.000 ft in elevation), with lowland plains in the east. It has a 3,208 kilometres (km) coastline along both the Pacific Ocean to the east and the Caribbean Sea to the north and the northern edges of the Amazon. Between these mountains lies the Magdalena River valley, home to Colombia's essential oil reserves.

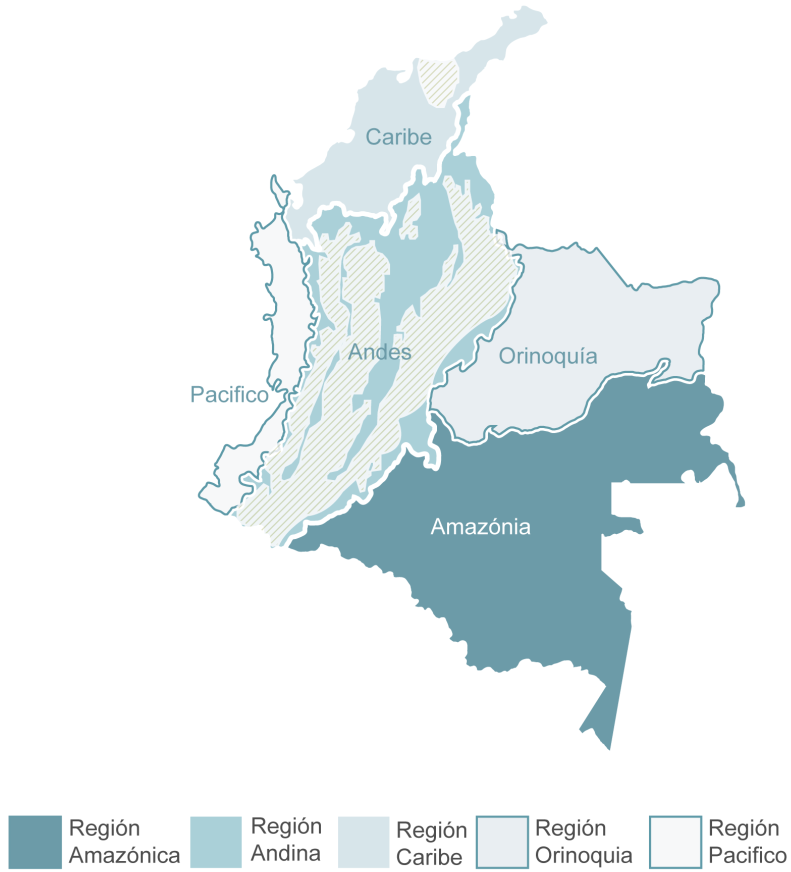


Illustration 6. Colombia regions classification. Source: Author's elaboration.

Considering the topography, altitude, rainy seasons, ground conditions, biodiversity, and multicultural characteristics, Colombia has been divided into **six natural regions** home to more than 100 indigenous cultures.

The most relevant are: **(1) The Andean Region**, crossed by the Andes Mountains, has an extension of 282.450 km² equivalent to 24% of the national territory with 28.863.217 inhabitants; **(2) The Amazon Region**, the country's most jungle, remote and least populated area (264.945 inhabitants), has 483.119 km² equivalent to 41% of the national territory; **(3) The Pacific Region** along the pacific ocean is the home of the largest Afro-American population, with 1.500.753 inhabitants has an extension of 83.170 km² (7% of the national territory); **(4) The Orinoquía Region** is a territory made up of savannahs and forests with 285.437 km² (18% of the national territory) and 1.681.273 inhabitants; and **(5) The Caribbean Region** is located along the Caribbean sea with an extension of 132.288 km² equivalents to 11.6% of the national territory; it is the second most populated region with 10.301.982 inhabitants.

The Caribbean was the first Colombian area to be discovered by the Spanish. Therefore, here can be fine some indigenous communities, Wayúus in La Guajira and Arhuacos and Koguis in the Sierra Nevada, indeed, the African black population is predominant. It has eight departments, six of which have coastal borders (Córdoba, Sucre, Bolívar, Atlántico, Magdalena, and La Guajira), one in the maritime zone (San Andrés y Providencia), and one in the coast's interior of the department (Cesar). **Barranquilla is in the north of the department of Atlántico; It is the most populated in the region**, followed by Cartagena and Santa Marta, as well as the departmental capitals Valledupar, Montería and Sincelejo. The strategic geographical position of the Caribbean region facilitates foreign trade through the Caribbean Sea. The economic base of the Caribbean region is varied; agriculture, livestock, mining, industry, tourism, and maritime transport stand out. **The industry is concentrated in Barranquilla and Cartagena, is not very diversified and is hardly linked to mining and agriculture.**

Climate characteristics in Colombia

Climatic classification: Temperature & Altitude

Colombia is characterized by its climatic diversity with 27 microclimates, which makes it challenging to identify the type of climates. Based on the **climatic classification** of the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) included in Annex 2 of Resolution 549, 2015, **more than 80% of the Colombian territory has a warm climate**; that's why the study of this kind of environmental conditions are so relevant for the country. Some cities with these weather circumstances are Cali, **Barranquilla**, Cartagena, and Buenaventura, among others.

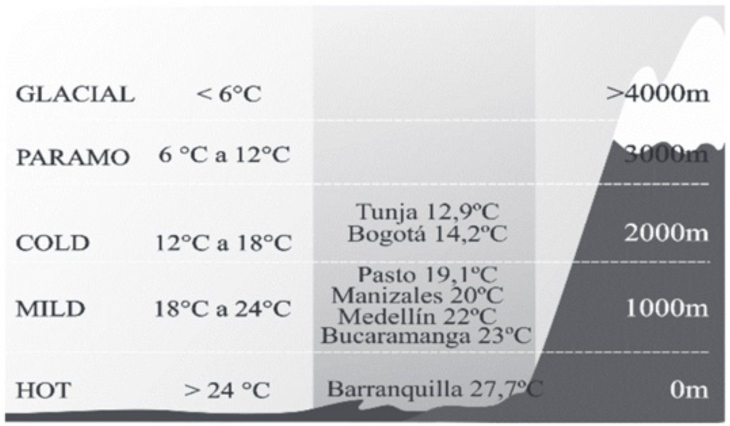


Illustration 7. Thermal Levels in Colombia. Source: (Osma Pinto et al., 2015).

Due to the Andes Mountains, **altitude** is a significant atmospheric condition in classifying the climate. That's why the type of environmental conditions is related to a specific thermal level[1]. (Osma Pinto et al., 2015). As reported by The World Bank Group (2021), the country's topographic diversity defines the three recognized climatic zones: **(1) the high-elevation cold zone**, located above 2,000 masl with mean annual temperatures ranging between 13ºC–17ºC, is in 93.000 km^2 equivalent to 7.9% of the national territory; **(2) a temperate or mild zone**, located between 1,000 masl – 2,000 masl, with mean annual temperatures ranging between 18ºC-24°C is in 10% of the national territory; and
, which covers all areas below 1,000 masl with means annual temperatures of 24ºC–27ºC, **this is the predominant thermal floor with 913,000 km^2 present in the six natural regions but mainly in the Pacific and Caribbean regions** and in valleys of the most important rivers such as the Magdalena, Orinoco, Cauca, Cesar and Amazon rivers.

The previous climate classification is related only to the temperature and Altitude. So, in 1962, Schaufelberger proposed the unification of this model with the Lang climate model[2] that, in addition to temperature, contemplates the parameters of annual precipitation. This is how the Caldas - Lang classification system is implemented, obtaining 25 climatic categories (Castañeda Tiria, 2014).

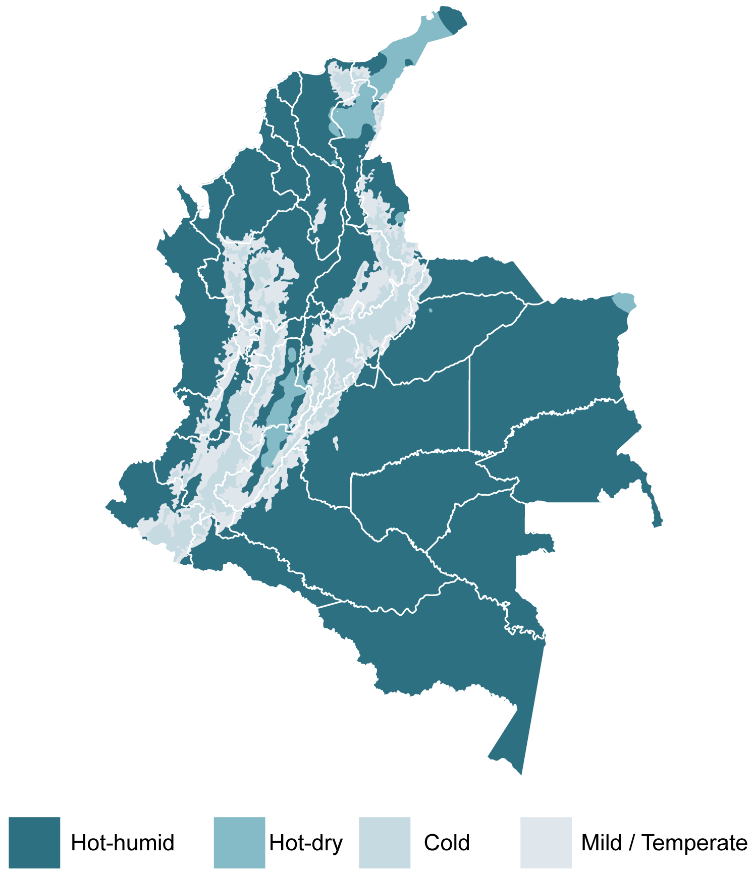


Illustration 8. Colombia climate classification. Source: Author's elaboration based on (Resolution 549, 2015)

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1 Caldas Climate Model: In 1802, the researchers Alejandro Von Humboldt, Aime Bonpland, and Francisco José de Caldas determined that altitude influenced temperature variation. Later, Caldas established the thermal floors for the Andean Tropical region, where the height above sea level is the main factor that characterizes each climate, and proposed five thermal floors (Glacial, Páramo, Cold, Temperate and Warm) (Castañeda Tiria, 2014).

2 Lang Climate model: In 1915, Richard Lang defined a climatic classification based on a ratio between the annual precipitation (P, in mm) and meant annual temperature (T, in °C). This quotient is called the Rainfall Effectiveness Index or Lang's Rain Factor, considered an index of humidity or aridity (Castañeda Tiria, 2014).

Given this, the IDEAM classifies the Colombian territory into four climate zones: **(1) the Cold zone**, located between 2,000 masl – 2,999 masl with mean annual temperatures ranging between 12°C – 18°C; (**2) The temperate zone**, located between 1,000 masl – 1,999 masl, with mean annual temperatures between 18°C – 24°C; **(3) Hot – dry zone** located below 1,000 masl with means annual temperatures above 24°C and relative humidity below 75%; and **(4) Hot – Humid zone** which covers all areas below 1,000 masl with means annual temperatures above 24°C and relative humidity above 75% (Illustration 5) (Resolution 549, 2015).

This climatic classification is constant with few variations through the year; that's why the seasons are defined by the rainfall level (rainy season and dry season).

Rainfall

The average annual rainfall is 2,630 mm, but there is variability in the territory. **The West Pacific coast and the Andean interior receive the highest rainfall amounts, approximately 6,000 mm–7,000 mm per year**. In contrast, the drier steppe climates in the north and southwest receive less than 500 mm per year. The Andean regions experience two seasons of rain during April–June and October–December, while **the northern Caribbean region, due to its proximity to the equator, experiences a single rainy season between May–October** (The World Bank Group, 2021b).

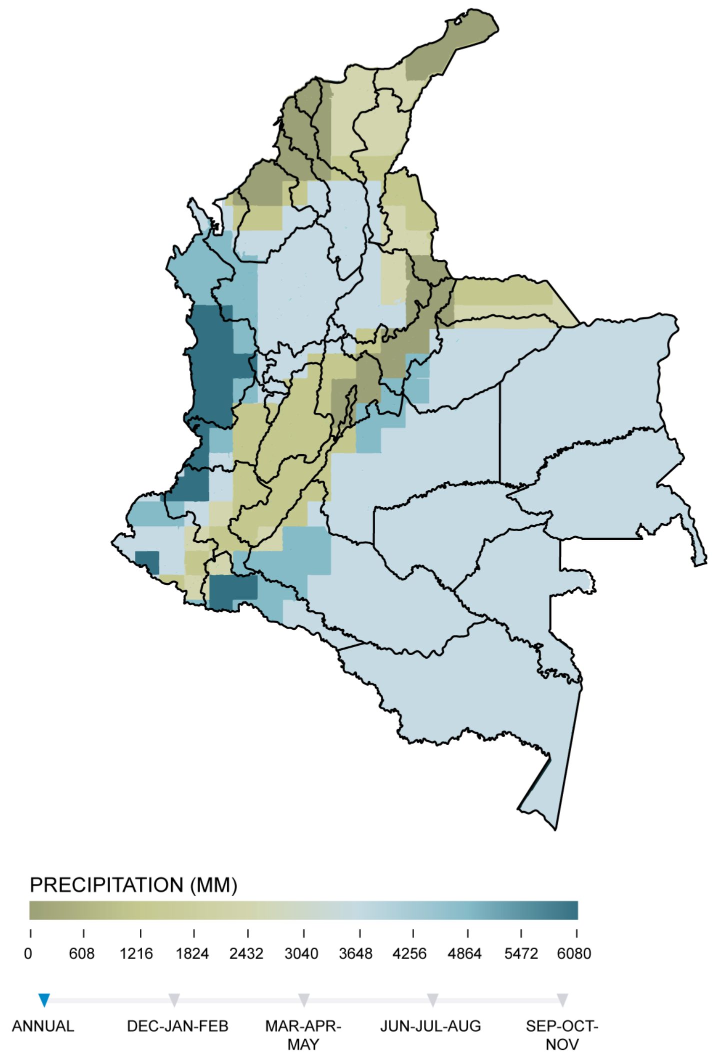


Illustration 9. Observed Climatology of Precipitation 1991-2020. Source: Author's elaboration based on (The World Bank Group, 2021b).

In the expected behaviour of the climate in the Pacific Ocean, the winds that run across the surface are called Trade Winds and go from East to West; the ocean absorbs the solar heat that increases the temperature of the west waters on the coasts of Indonesia and Australia, which when evaporating and condensing generate clouds giving it a tropical climate with rain. Towards the north of the planet, the winds go from West to East, creating a system of air and water circulation that becomes cyclical. The warm water from the equatorial tropical zone that goes west is replaced by cold water from the ocean's interior (Humboldt current). This causes a difference in temperatures throughout the Pacific Ocean, which impacts the climate in Ecuador, Peru, and Chile with dry climates. However, inter-annual rainfall variability influences the continent through the **El Niño/ Southern Oscillation (ENSO) and La Niña phenomena.**

El Niño phenomenon is produced when the Trade winds weaken, then the currents that carry the warm water to the West vary and produce that warm water reaches the East coast (i.e., South America). When the waters of the equatorial Pacific heat up irregularly, they evaporate and condense, resulting in heavy rains in Ecuador, Peru, and Chile. Nevertheless, **In Colombia**, due to its geography, the wind circulation change displacing the clouds and decreasing the possibility of rain, **bringing out droughts and warmer weather** (IDEAM, 2015).On the other hand, **La Niña phenomenon** is associated with **floods and cooler weather in Colombia**, particularly between June and August. It is caused due to the cooling of the water for the intense movement of the Trade winds that push warm water to the West, which causes cold water to rise from the ocean floor, creating climate changes. The main effect lies in the considerable **increase in rainfall while the temperature drops in the Andean, Caribbean, Pacific and Orinoquia regions** (IDEAM, 2016). Both phenomena happen every 2 to 7 years, El Niño phenomena being more frequent.

Solar Radiation

The country is in a tropical area. Therefore, it has significant solar radiation throughout the year. Generally, Colombia shows a monthly average global solar radiation uniformly, approximately from **4,0 kWh/m² to 4,5 kWh/m²** in the year.

Departments or Regions	Insolation [kWh/m²]
Arauca, Casanare, Meta, Boyacá, Vichada and the Caribbean, Coast including San Andrés y Providencia	5.0 – 6.0
Orinoquía, Santander and North Santander, Cundinamarca, Tolima, Huila, Cauca, and Valle del Cauca	4.5 – 5.5
Chocó, Nariño y Putumayo	3.0 – 4.0

Table 8. Average monthly global solar radiation uniform for different country zones. Source:(Osma Pinto et al., 2015).

Climate change in Colombia

Conforming to the 2020 ND-GAIN Index[1], Colombia is recognized as vulnerable to climate change impacts, ranked 89 out of 181 countries. Due to a combination of political, geographic, and social factors. **The territory is highly vulnerable particularly flooding from "La Niña" phenomena. Vulnerability hotspots include the Caribbean and the Andean regions**, with key sectors including housing, transport, energy, agriculture, and health. As reported by the World Bank Group (2021), the temperatures in Colombia have an increasing trend. **The las twenty years, it raises by at least 1°C**. Maximum temperatures have risen between 1°C per decade in the high mountains, and 0.6°C per decade in the sub-paramo.

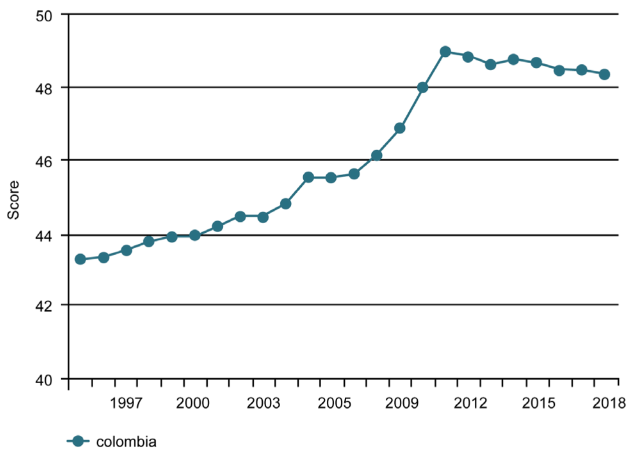


Figure 9. ND-GAIN Index for Colombia. Source: Author's elaboration based on (The World Bank Group, 2021a).

1 ND-GAIN Index: "ranks 181 countries using a score which calculates a country's vulnerability to climate change and other global challenges as well as their readiness to improve resilience. The more vulnerable a country is, the lower its score, while the more ready a country is to improve its resilience, the higher it will bed" (The World Bank Group, 2021a, p. 3).

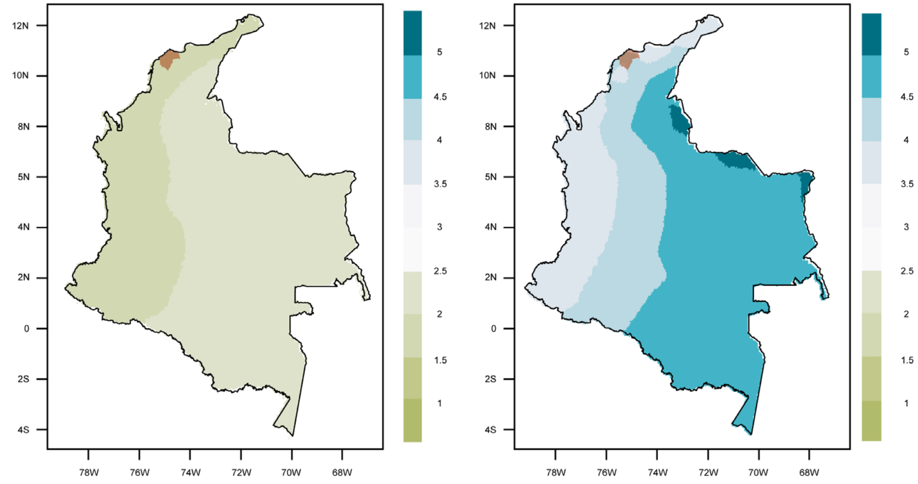
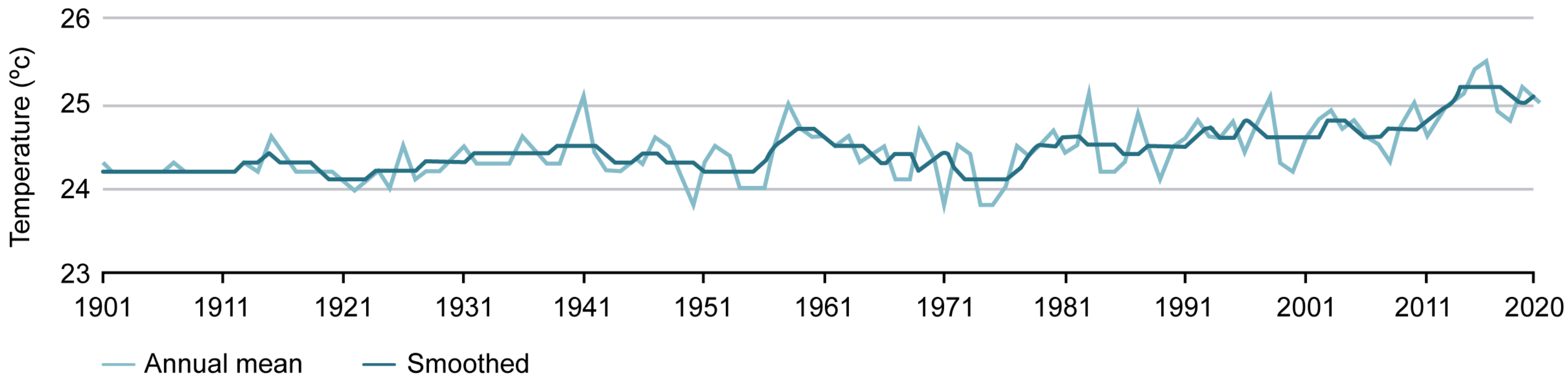


Illustration 10. CMIP5 multi-model ensemble projected change (32 GCMs) by 2040–2059 (left) and by 2080–2099 (right), relative to 1986–2005 baseline under RCP8.5. Source: (The World Bank Group, 2021a).

The CMIP5 (Coupled Inter-comparison Project No.5) built the global climate change projections database and established four Representative Concentration Pathways[1] RCP2.6, RCP4.5, RCP6.0, and RCP8.5. Each scenario represents a level of GHG emissions concentration, from low concentration (RCP2.6) to a medium (RCP 4.5) until high concentration (RCP8.5). Under a critical scenario (RCP8.5) for Colombia, the mean monthly temperature is projected to rise 2.0°C by 2045 and 4.8°C by the end of the century. Besides, in a more optimistic scenario (RCP4.5), mean air temperatures in Colombia will increase 1.3°C by 2045 and 2.0°C by 2100 (Climate Analytics, n.d.) (Figure 10).

1 Representative Concentration Pathways [RCP]: It evaluates climate change from four different scenarios. It depends on the Radiative Forcing [RF] imposed by the expected GHG concentration at the different evaluation times. The RCP scenarios specify the amount of energy the planet retains, a product of the RF: 2.6, 4.5, 6.0 or 8.5 W/m2. (IDEAM et al., 2015).



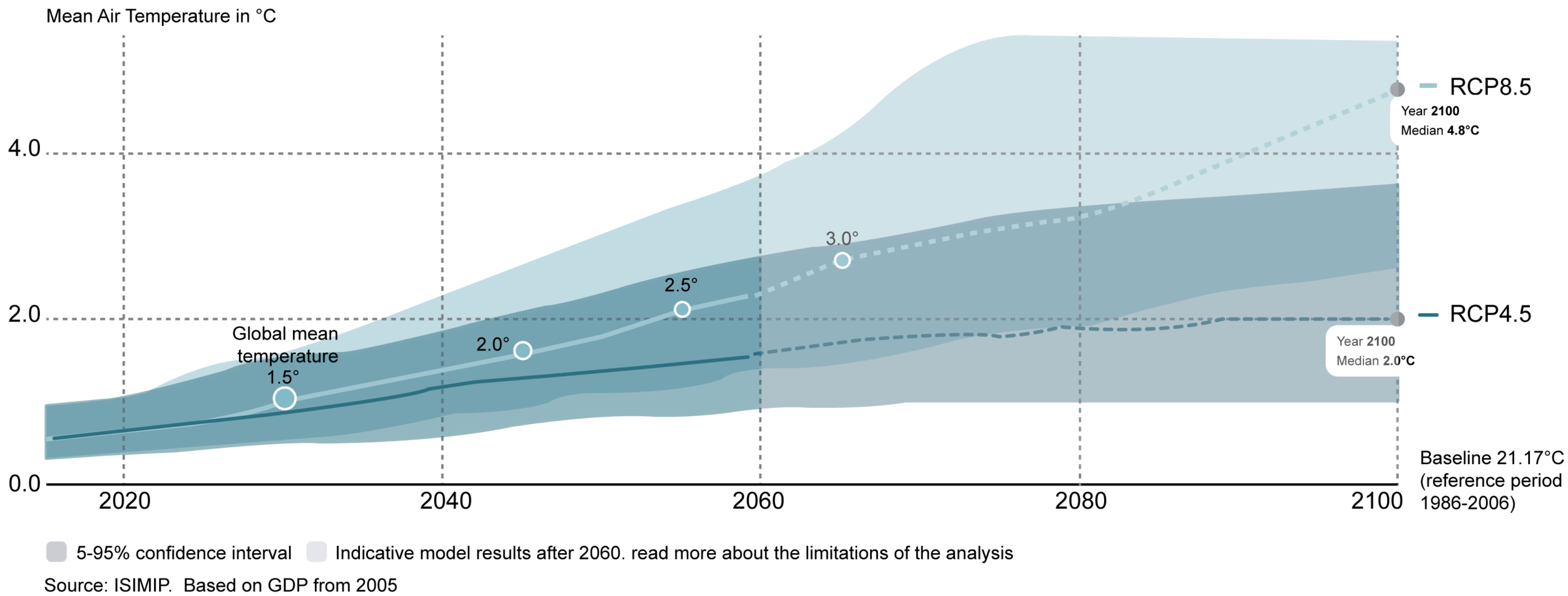


Figure 10. (1) Above: Observed temperature for Colombia, 1901–2020, (2) Below: Historical and projected average temperature for Colombia from 2005 to 2100 (RCP8.5 and RCP4.5 scenarios). Source: Author's elaboration based on (The World Bank Group, 2021a) & (Climate Analytics, n.d.).

Indeed, of critical importance are **the number of days above 35°C**, projected to increase from approximately 16 to 131 days of the year by the end of the century; and **the drought-related conditions** that have increased approximately 2.2 times more frequently than in previous years and could be worst due to the El Niño phenomenon. **This can damage threaten operations at hydroelectric power that generate most domestic energy supplies; consequently, the energy poverty phenomena could grow in Colombia.** (The World Bank Group, 2021a).

Furthermore, as reported by IDEAM et al. (2015), For 2071 – 2100, the average rainfall is expected to decrease between 10 and 30% in about 27% of the national territory. For the same period, precip is expected to increase by 10 and 30% in about 14% of the national territory. The reduction of rainfall, added to the changes in land use, can accelerate and intensify desertification processes and loss of sources and water courses. In contrast, the regions with increased rainfall will raise the possibility of landslides, damage to rural pipelines, deterioration of road infrastructure in mountain areas, and floods in flat areas of the country.

On the report of The Global Facility for Disaster Reduction and Recovery [GFDRR] (2020) the most significant disasters for the country include floods, primarily riverine but also along the coast as the seas rise and increase flash flood events. Furthermore, Colombia has more than a 40% chance of a potentially damaging tsunami occurring in the next 50 years and a 20% chance of a cyclone. **The most affected are the northern regions**, which also will have extreme heat seasons, increasing their probability of water scarcity and wildfire (Illustration 11).

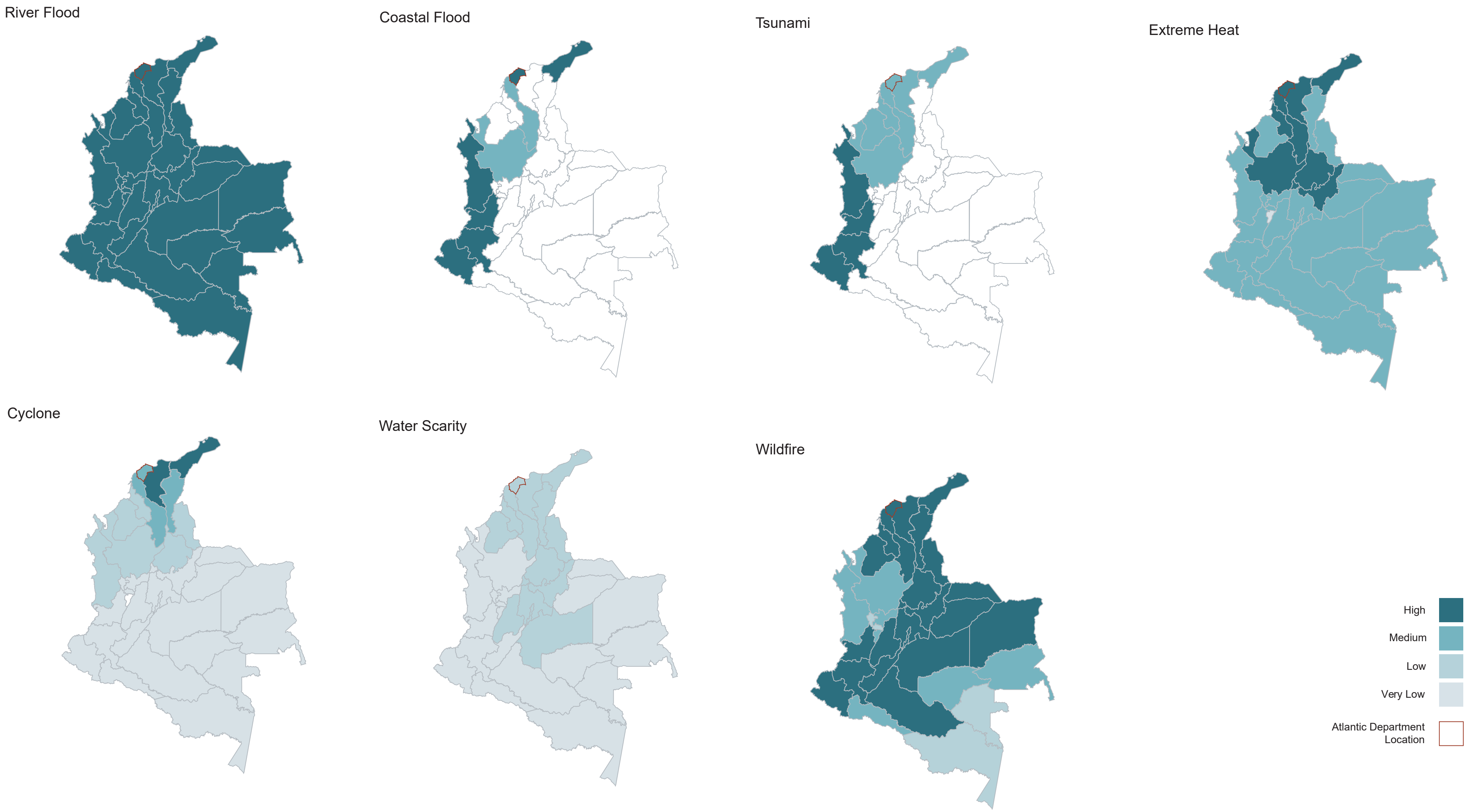


Illustration 11. Level of risk in Colombia for river flood, coastal flood, tsunami, cyclone, extreme heat, water scarcity and wildfire. Source: Author's elaboration based on (GFDRR, 2020).

Climate characteristics in Barranquilla

Temperature (Tair) & Relative Humidity (RH)

The Colombian city of Barranquilla is located on the west riverbank of the Magdalena River, a few kilometres from the Caribbean coast. Due to its location near the sea with flat topography, **Barranquilla has a hot-humid tropical climate characterized by high and stable temperatures and a high humidity content that remains constant throughout the year.**

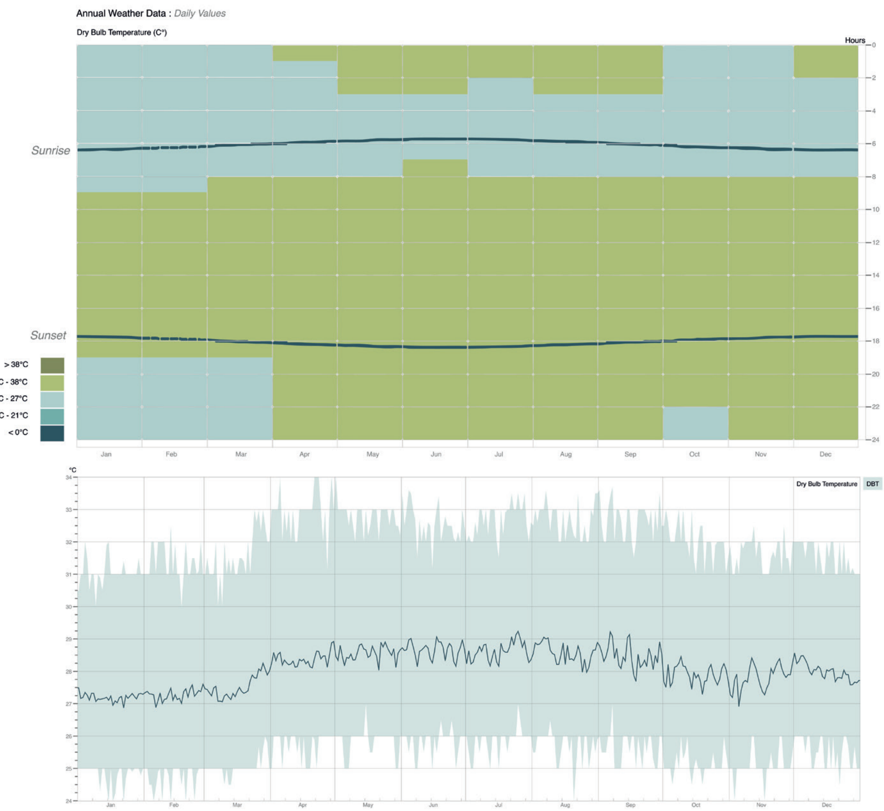


Figure 12. Annual Dry Bulb Temperature (°C) for Barranquilla. Source: Author's elaboration based on (IDEAM et al., 2019).

According to the IDEAM et al. (2019) climate data, the average annual Dry bulb temperature in Barranquilla is 28.08 °C. The warmest months are between March and July, with an average monthly dry bulb temperature of 28°C. The highest temperature is 34°C; this takes place in April and usually at noon. On the other hand, the coldest months are January, February, and March, with an average monthly dry bulb temperature of 27°C. In the coldest months, the lowest temperatures are present in the morning and at night, unlike the others that only have temperatures below 27°C in the morning. **That means that in the year, 66% of the time, Barranquilla have temperatures between 27°C – 38°C and for the other 34%, the temperatures range between 21°C – 27°C.**

In Barranquilla, humidity is high throughout the year; the annual average is 82.5%, with a monthly average humidity of 87% in October and 88% in November, the most moisture months. While in February and March, the humidity drops slightly to 79% and 78%, respectively. The relative humidity decreases in the dry season – between December and April – due to the trade winds blowing from the northeast, which helps to make the climate more bearable and less humid. Between the end of June and the first weeks of July, the trade winds from the southeast cause Veranillo de San Juan, a short period characterized by dry and windy days with sun and clear skies; in this period, the monthly average relative humidity range between 83% and 81%.

The highest humidity levels reach an RH between 90% - 100% from 20:00 until 8:00. Conversely, from 8:00, the humidity decreases, presenting an RH lower than 80% all the afternoon. **This variation is the same throughout the year, in which 64% of the hours, the RH humidity is above 80%, and in 36% of the hours, the RH range between 60% to 80%.**

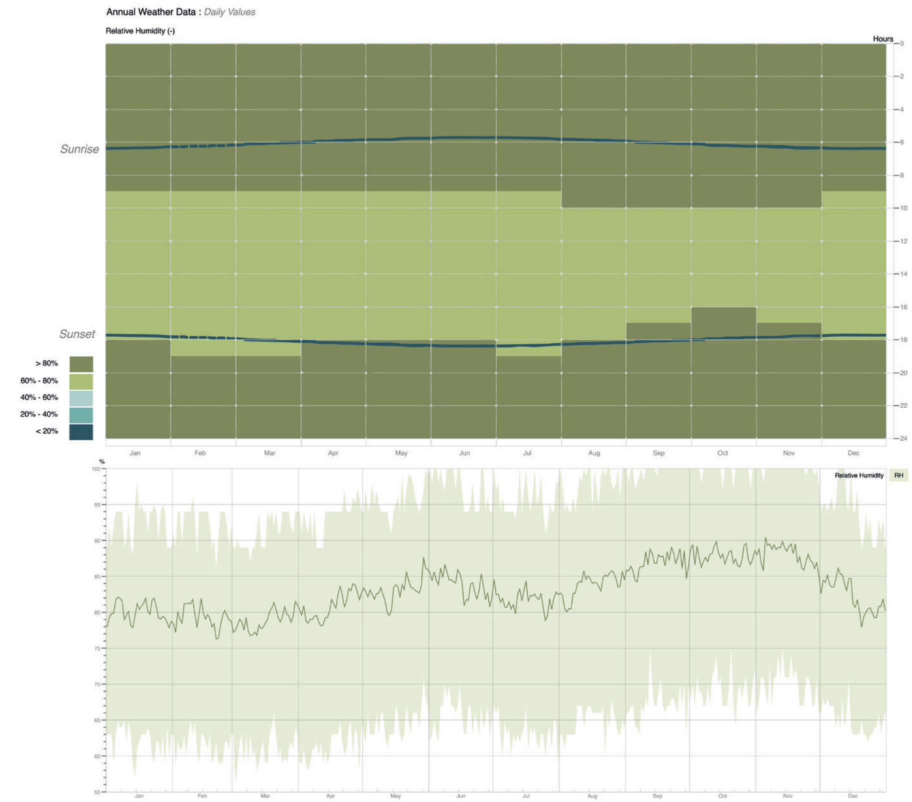


Figure 13. Annual Relative Humidity (-) for Barranquilla. Source: Author's elaboration based on (IDEAM et al., 2019).

Solar Radiation & Sky Cover

Due to its geographical location, Barranquilla has significant solar radiation throughout the year. Its average monthly global horizontal radiation ranges between 352 Wh/m² and 535 Wh/m². Otherwise, its average monthly direct normal radiation fluctuates between 158 Wh/m² to 340 Wh/m². **Hence direct radiation is equivalent to more than 40% of global radiation.**

The months with the highest solar radiation are January, February, and March, with a monthly average global horizontal radiation of 528 Wh/m², 535 Wh/m², and 511 Wh/m², respectively. On the other hand, the months with the lowest monthly average global horizontal radiation are August and October, with 352 Wh/m² and 361 Wh/m², respectively. Indeed, the highest global horizontal radiation reach is 980 Wh/m² in September and 950 Wh/m² in July and February.

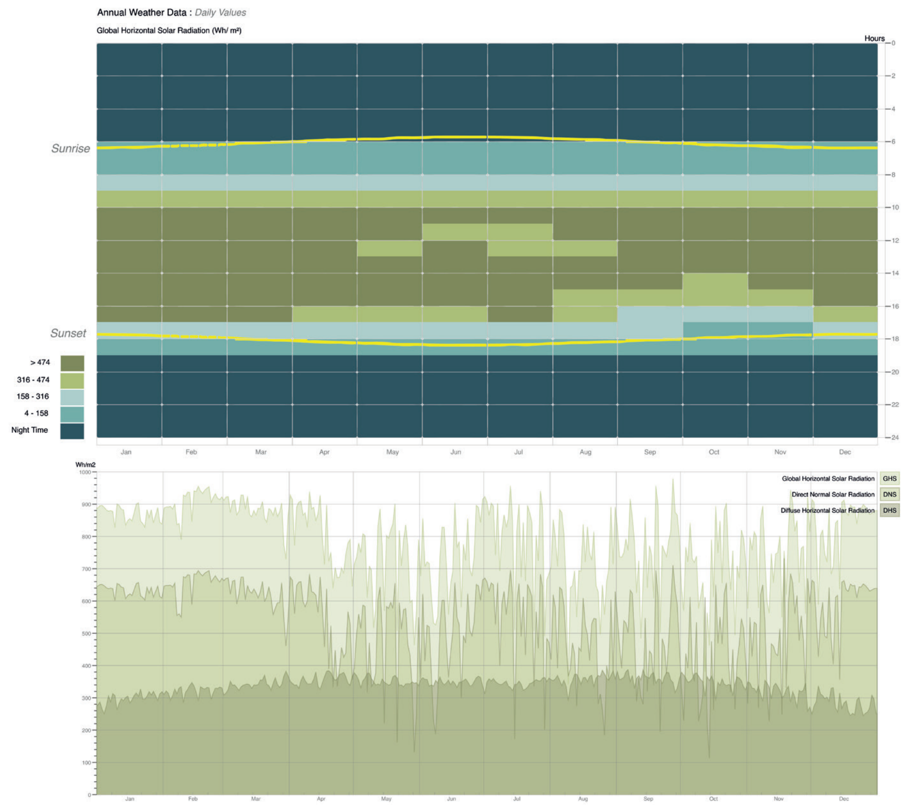


Figure 14. Annual solar radiation (Wh/m²) for Barranquilla. Source: Author's elaboration based on (IDEAM et al., 2019).

Barranquilla has approx. 10 hours of sunshine a day throughout the year without representative variations. The 14% of the hours present radiation levels between 4 Wh/m² to 158 Wh/m², usually close to the sunrise and sunset. **However, in most of the daytime (22%), there are radiation levels above 474 Wh/m², typically between 10:00 and 17:00.**

The annual sky cover has slight variations in the monthly average, in which 72% of the hours have a cloudy sky with a coverage percentage of less than 60%. **By coincidence, the cloudless months correspond to the months with the highest radiation, January, February, and March (25% of the hours).**

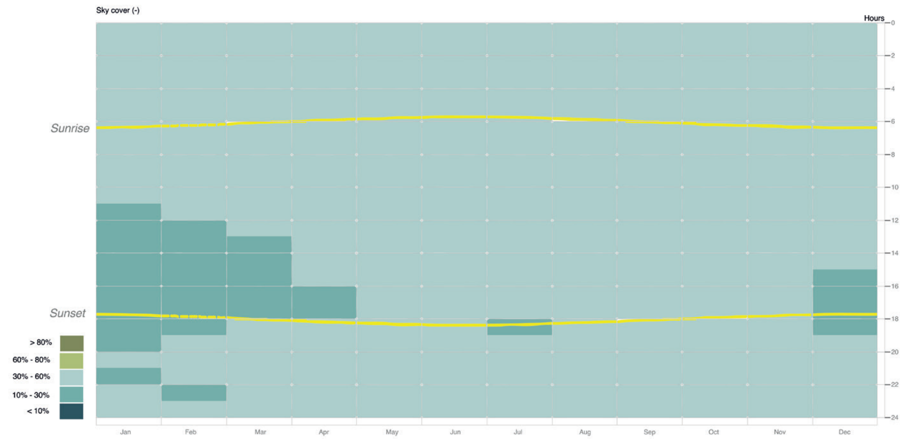


Figure 15. Annual Sky cover (-) for Barranquilla. Source: Author's elaboration based on (IDEAM et al., 2019).

Wind

The wind speed in Barranquilla experiences seasonal variations throughout the year. The windier season lasts five months, from December to April and in three specific hours: (1) in the morning, between 01:00 to 06:00, (2) between 14:00 to 18:00, and (3) at night beginning at 18:00. In this season, the velocities range between 5 m/s to 9 m/s. **It should be clarified that these are the months with the highest radiation and cloudless; even so, they do not have the highest temperatures.**

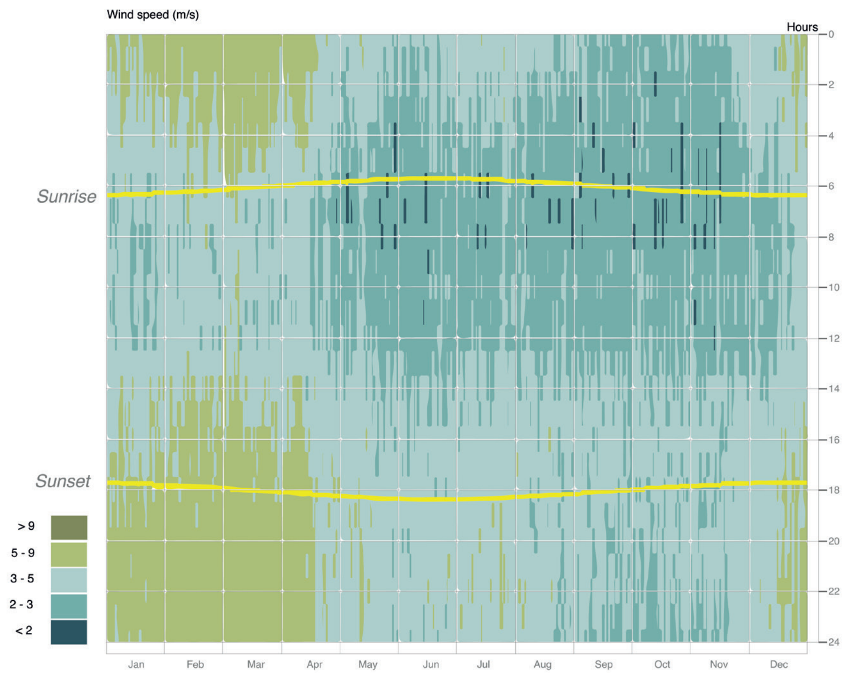


Figure 16. Annual wind speed (m/s) for Barranquilla. Source: Author's elaboration based on (IDEAM et al., 2019).

The season of calm winds lasts seven months, from May to November, with wind velocities below 5m/s. The least amount of wind is in the mornings between 1:00 to 14:00, with less than 3m/s. **The absence of wind happens mainly in September, October, and November, characterised by having the highest humidity and the lowest sun radiation.**

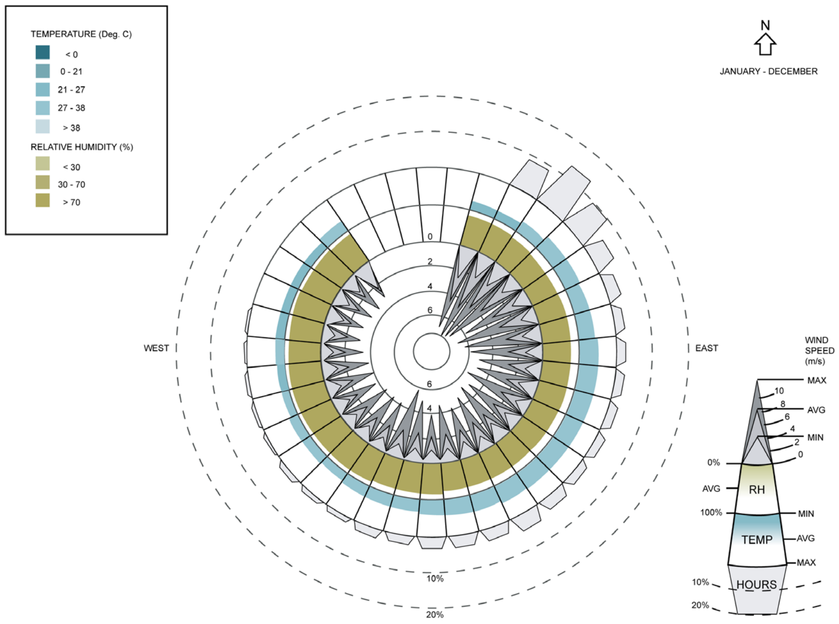


Figure 17. Annual wind direction (m/s) for Barranquilla. Source: Author's elaboration based on (IDEAM et al., 2019).

The predominant direction of the wind is the northeast (trade winds); it is present in more than 10% of annual hours, mainly in January, February, March, April and December, the most ventilated months. Conversely, in the months with less ventilation, east, southeast, and south winds predominate, corresponding to less than 10% of annual hours.

Climate change in Barranquilla

As mentioned, Barranquilla is in Colombia's Caribbean Region and the Atlantic department. Three climate change scenarios have been developed by IDEAM et al. (2015) for the Caribbean region, indicating changes in the average temperature and rainfall concerning the reference period 1976-2005. These are based on a multi-scenario ensemble, which averages each RCP result.

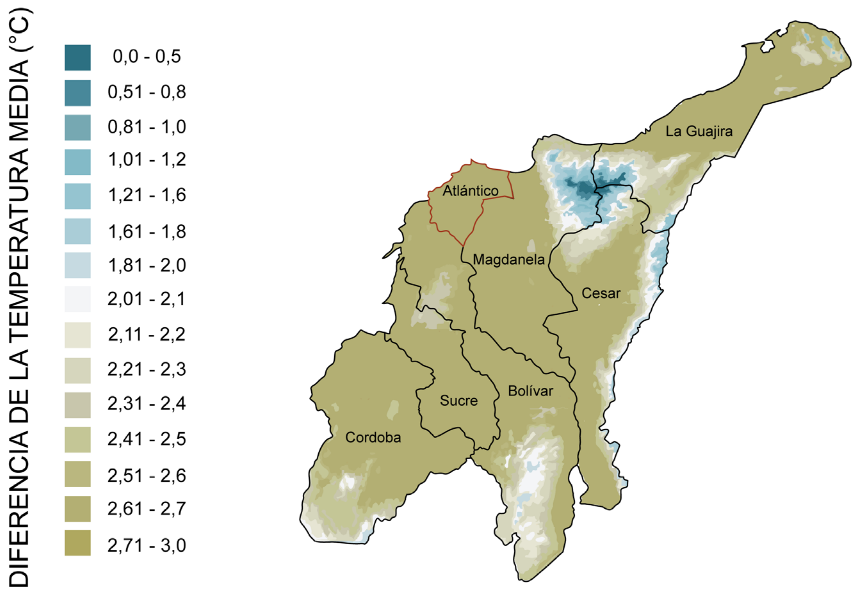


Illustration 12. Projected Change in temperature in Colombia Caribbean region by 2071 – 2100 relative to 1976 – 2005. Source: Author's elaboration based on (IDEAM et al., 2015)

From their study can be concluded that **temperature increases by the end of the century in the Caribbean region will be generalized,** affecting all the departments, including the Sierra Nevada de Santa Marta. According to the average scenario for 2100, the departments with the highest temperature increase will be Cesar with 2.49 °C and Magdalena with 2.42 °C (IDEAM et al., 2015). For the Atlantic department, **In the first period, 2011-2040**, a temperature increases of +1.06 is forecast. **In the second period, 2041-2070**, the temperature increase will be +1.57. **In the third period, 2071-2100**, the temperature variation will be +2.15 (IDEAM et al., 2015; Vargas, 2016).

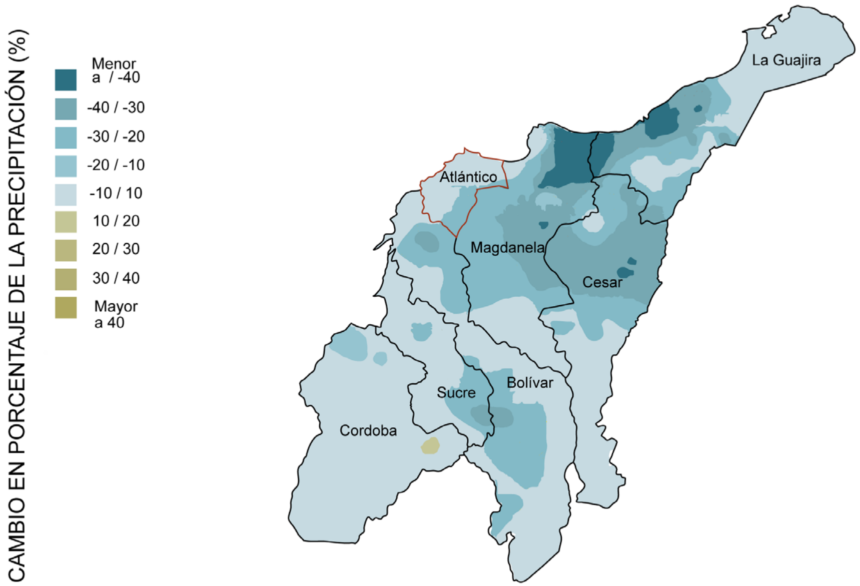


Illustration 13. Projected Change in rainfall in Colombia Caribbean region by 2071 – 2100 relative to 1976 – 2005. Source: Author's elaboration based on (IDEAM et al., 2015).

On the other hand, according to the scenarios, there will be no precipitation increase for 2100. As opposed, **the precipitation Climate change scenario for 2100 shows a decreasing trend**, mainly in San Andrés y Providencia (-33.01), Magdalena (-23.24), y Guajira (-20.02). The department with the slightest variation in average precipitation will be Córdoba (-1.42) (IDEAM et al., 2015).

For the Atlantic department, in 2011 – 2040, rainfall will decrease by -7.39. The second period, 2041 – 2070, varies negatively by -9.52. Last, in 2071 – 2100, a decrease of -11.26 is forecast. Another variable to consider is the probability of **sea level rise between 0.1 to 0.4 meters in the Caribbean region**. (IDEAM et al., 2015; Vargas, 2016). **As is shown, the Colombian Caribbean will be characterized for less rainfall with high temperatures and more floods.**

Respectively for the Atlantic department, the mean monthly temperature under a critical scenario (RCP 8.5) is projected to increase by 1.6°C by 2050 and 4.0°C by the end of the century, with a rise in the daily maximum air temperature of 1.6°C by 2050 and 4.1°C by 2100. Besides, the relative humidity could increment by 0.6pp by 2050 and fall to -0.7pp by 2100. Concerning wind speed has a decreasing tendency until 2060, diminishing -2% by 2050 and rising to 8.6% by the end of the century (Climate Analytics, n.d.).

Moreover, the Atlantic department will be subject to other risks because of the temperature increment; like the river flood mainly in 11 cities of the department in which Barranquilla has one of the higher risks due to its proximity to the Magdalena River. In addition, the city could be subject to tsunamis, cyclones, and wildfires (GFDRR, 2020).

Hot humid climates adaptation capacity

Bioclimatic strategies in Hot-humid climate

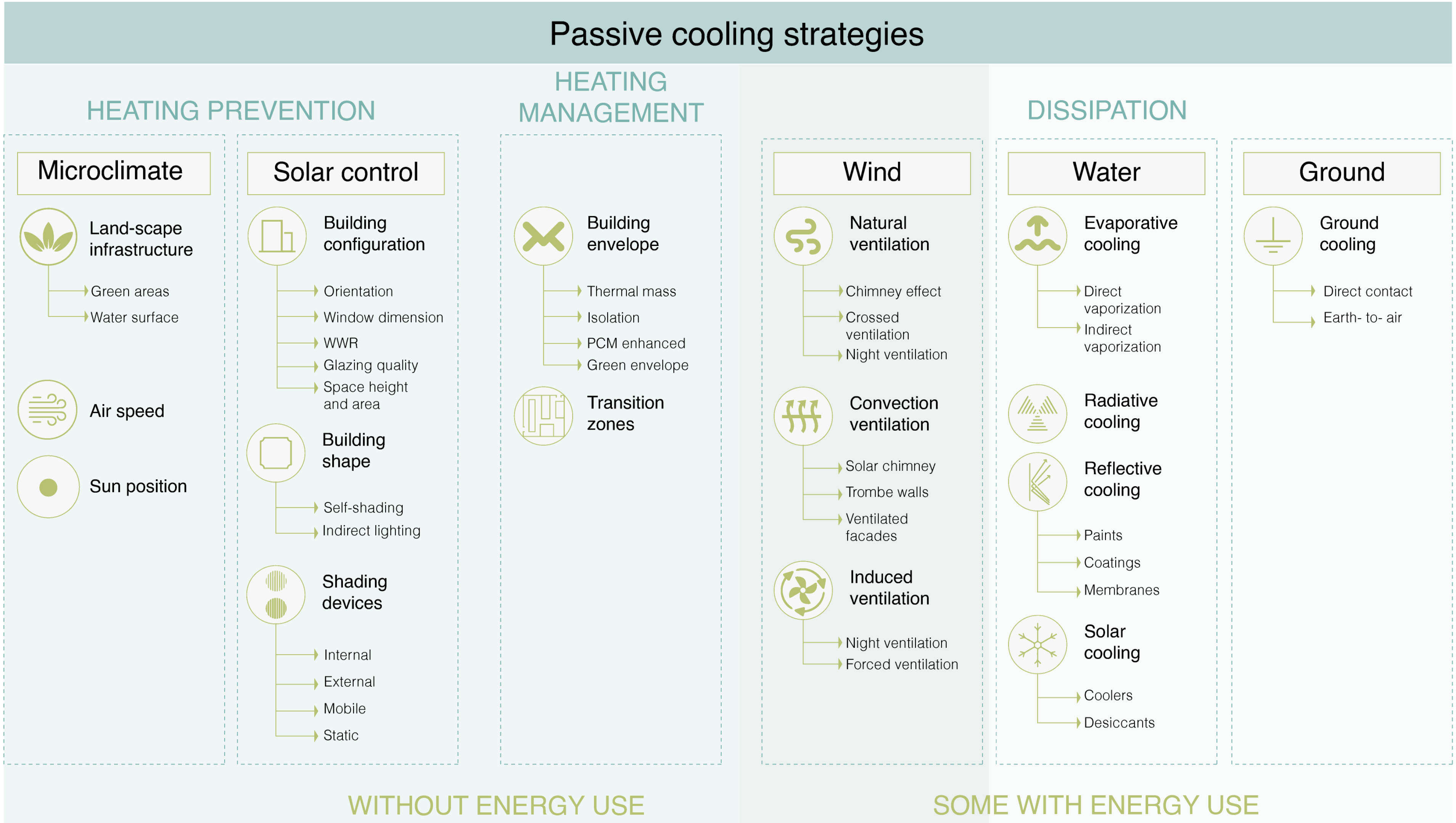


Figure 18. Passive cooling strategies. Source: Compilation based on (Giraldo, 2018), (Geetha & Velraj, 2012), (Hernández Sánchez, 2018), (Varas Vega, 2020), (Architecture 2030, n.d.),

The hot-humid climate has high daytime and night-time temperatures and high humidity. Hence, in the architecture file is necessary to use **passive cooling strategies**. As suggested by Asiain (2003), in this environment: (1) Strong protection against direct and diffuse radiation is necessary, and (2) ensure good daytime and night-time ventilation that increases well-being.

According to the United States Department of Energy ((DOE), 2016), **passive cooling strategies** are measures used in architectural design to cool buildings whose operation does not require energy consumption dissimilar to natural ones. These strategies are mainly used in bioclimatic architecture and can improve thermal comfort in buildings, and reducing internal energy demand (Giraldo, 2018).

As remarked by Geetha & Velraj (2012), the measures related to cooling are classified in (Figure 20):

1. **Heating prevention:** They work by eliminating the possibility of gaining heat and blocking the sun's rays.
2. **Heat management:** They modify heat gains by storing them during the day and gradually releasing them at night.
3. **Dissipation:** Whose objective is to remove the heat of the building through the natural forces of the site.

Sun protection techniques

With this strategy, it is possible to control the overheating of the facades and even the required lighting levels of the spaces. The main types of this technique are (1) Self-shading facades, (2) Shading devices, and (3) the window-to-wall ratio [WWR].

1. **Self-shading facades:**

   The amount of heat transferred through the walls ($\Phi = A \times U \times \Delta t$) depends on three variables: 1) u-value = the measure of the overall rate of heat transfer through a particular section of construction, 2) A= wall area, 3) $\Delta t = (T1 - T2)$ =Temperature difference on both sides of the wall. Thus, when reducing the external surface temperature by shading, Δt will decrease. Subsequently, the amount of heat transferred to buildings is reduced (Shahda, 2020).

Hence, the self-shading facade is considered the building's second skin, provide an aesthetic function, and reduce the insolation on the opaque and transparent envelope. As Giraldo (2018) describes the thermal performance of a simple facade compared to a double system, obtaining a reduction in Tair between 4°C and 5°C inside the space.

2. **Shading devices:**

The shading devices have three functions: (1) provide shade to the building to prevent heating, (2) protect the direct entry of the sun into the interior spaces through the openings and (3) increase or reduce the amount of light that enters the spaces. "Appropriate external shading devices can control the amount of solar radiation admitted into a room, which could largely reduce cooling loads and improve thermal comfort" (Al-Tamimi & Syed Fadzil, 2011, p. 274).

Solar control devices should vary according to latitude and type of weather; the shading element must be designed with accuracy for each façade to balance solar control, lighting, and visibility (Giraldo, 2018). As stated, UN-Habitat (2018), in the tropics, windows should be shaded during all daylight hours. However, the most critical hours are the early morning and the late afternoon when the sun is low in the sky.

By the Colombia regulation Resolution 549, 2015 , Shading systems should not exceed 70 degrees VSA or HAS.

3. window-to-wall ratio [WWR]:

This index is a ratio between the total window area and the total façade area; the value is expressed in percentages where 0% means that there are no windows and 100% means that the entire wall is made of glass. This parameter is critical for the building's thermal performance because windows are the envelope components with less thermal resistance, allowing solar radiation into the space and increasing its temperature. Consequently, a common rule states that the optimal WWR for hot climates should be around 40% or less (Valladares-Rendón et al., 2017).

Santiago, Chile, had studied the influence on the energy consumption of the building when it decreased by 20% the 100% WWR. The investigation found that the initial energy consumption was 155 kWh/m², 130 kWh/m² more than the building with a WWR of 80% (25 kWh/m²). Showing that this strategy effectively reduces the energy consumption and the impact of sun radiation (Giraldo, 2018).

Low absorptivity or cold walls

This passive strategy avoids thermal gain from the sun by applying natural materials, paints, membranes, coatings, and fine veneers, which have very low absorptivity. This kind of surface absorbs less heat and remain cooler. They are characterized by high solar reflectance (SR) and high thermal emittance (Giraldo, 2018).
The currently commercially white or light-coloured materials have high solar reflectance values ranging from 0.4 to 0.85. For a white surface (SR 0.8) the temperature rise is about 10°C. Surface temperature measurements demonstrated that a cool coating could reduce a concrete tile's surface temperature by 7.5 °C and it can be 15 °C cooler than a silver-grey coating (Synnefa et al., 2007).

"Furthermore, new cool-coloured materials that are highly reflective in the near infrared are being developed for cases where the aesthetics of darker colors are preferred. The maximum difference between the solar reflectance of a cool and conventional color-matched coating was 0.22, with a corresponding surface temperature difference of 10.2°C" (Synnefa et al., 2007).

As described (Giraldo, 2018) in a hot-humid climate like Hong Kong, through an experimental method carried out with two enclosures built in a light system, one with white paint and the other with black paint on its envelope, it was discovered that, during the day, the enclosure treated with white paint kept the maximum internal Tair peak 12°C lower, both in summer and autumn. Under 800 W/m2 solar radiation conditions, the maximum Tair inside the white enclosure was 3°C above the Tair exterior, while the black enclosure was 15°C. On the other hand, when the solar radiation presented 300 W/m2, the difference was 1°C and 5°C respectively. Showed that the darker the color, the more sensitive the envelope is to solar radiation, because dark surfaces absorb most of solar radiation. The application of light colors on the external surface of buildings is indeed the simplest, most effective, and most economical way to reduce the interior temperature in a hot-humid climate.

Green walls

Green walls are façade system in which evergreen or deciduous plants grow directly on the walls, in hanging boxes, or on unique support structures with regular maintenance. A green façade can improve buildings' air quality, the sensation of noise and energy efficiency due to the increase in thermal comfort. Likewise, this strategy can capture carbon dioxide and providing a habitat for biodiversity (Perini et al., 2011). Green walls are a good alternative for hot-humid climates like Santiago de Cali because plants can dissipate absorbed solar radiation in both sensible and latent heat through evapotranspiration. Evapotranspiration is the loss of water from a plant during its respiration and evaporation process. The heat is absorbed during the evaporation of the water from the plants, which generates an evaporative cooling that refreshes the temperature of the facades. This process can convert 60% of the solar radiation absorbed into a heat(Giraldo, 2018).

Perini et al. (2011), identify three types of green walls: (1) the traditional one, in which the plants climb and use the façade itself as a support structure, (2) the double vegetal facade, whose plants climb up a structure separated from the envelope, giving rise to an air space between the two. (3) Finally, the living walls, which include small substrate containers where plants are planted and grow around the building. The author stated that "The system with the major impact on the thermal resistance is the system based on boxes, thanks to the "extra" created air cavity and to the thermal resistance of the other material layers involved (HDPE and soil).

Traditionalg reen wall system

Doubleg reen wall system

Living greenw all system

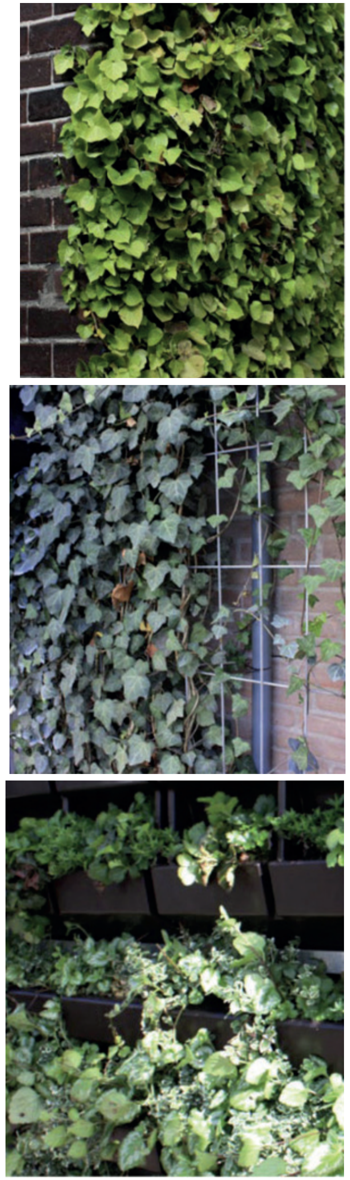


Illustration 14. Types of green walls. Source: (Perini et al., 2011).

Isolate opaque envelope

Use materials or combinations of materials that have low thermal transmittance to prevent heat flow from the outside to the inside by conduction. These materials resist heat flow due to the microscopic cells of trapped air, which suppress convective heat transfer. To achieve the high R, the air trapped inside the insulation is even more influential than the material itself (Giraldo, 2018). There is a wide variety of high thermal resistance insulating materials, which can be classified into two classes: organic and inorganic. Inorganic materials include glass wool, rock wool, calcium silicate, agglomerated perlite, and vermiculite. Organic materials include cellulose, cotton, wood, pulp, cane, synthetic fibres, cork, foam rubber, polystyrene, polyethylene, polyurethane and other polymers (Al-Homoud, 2005).

As reported by Al-Homoud (2005), for climates where cooling is necessary, the best results can be achieved by placing the insulation material close to the heat flow; this means that it is ideal for placing it in the first few centimetres of the envelope from the outside to the inside.When we talk about walls without windows, some research's shows that from the annual energy consumption by cooling was saving 58% through the implementation of isolate walls. However, in walls with a WWR of 30% the isolate walls just achieve 10% of savings. Concluding that the direct solar gain through the windows greatly affects the performance of the insulation and that in these cases the investment is not profitable (Giraldo, 2018). In humid equatorial climates, the potential is less than 70%; e.g., Well-insulated and well-design buildings in Malaysia can decrease energy consumption by 64% compared to conventional buildings. However, the insulation helps to increase indoor hygrothermal comfort; even without using the AC system, the Tair can be reduced by 5 °C by merely installing mineral wool insulation on the ceiling of a house (Aditya et al., 2017).

Chapter 4

Case study evaluation

Project overview

As mentioned, Barranquilla has promoted the development of multiple new residential complexes to supply the increasing housing demand, mainly in the zones in which the POT (2014) appointed expansion zones. Barranquilla has eleven Planes Parciales[1] of urban development, which have already been approved with 12,560,000 m² of land to develop (1,256 hectares). In these projects, 255 hectares of land are for housing, 377 hectares for commercial use, 13 hectares for institutional use, 210 hectares for industry and 51 hectares for ports (Alcaldía de Barranquilla, 2022).

The case study is located in one of the Planes Parciales approved in 2015, called Plan Parcial El Volador. The plan has 183 hectares, of which 84 are for public space between roads and parks and 87 for housing, commerce, and facilities, where 24,000 families from Barranquilla can live. Currently, 32 real estate projects have been developed, of which 18 are VIS, 8 are VIP and 6 are NON-VIS. So, to identify the response of the social housing (VIS) projects to the previously mentioned climate change exposure, one was analysed, the Perdiz project.

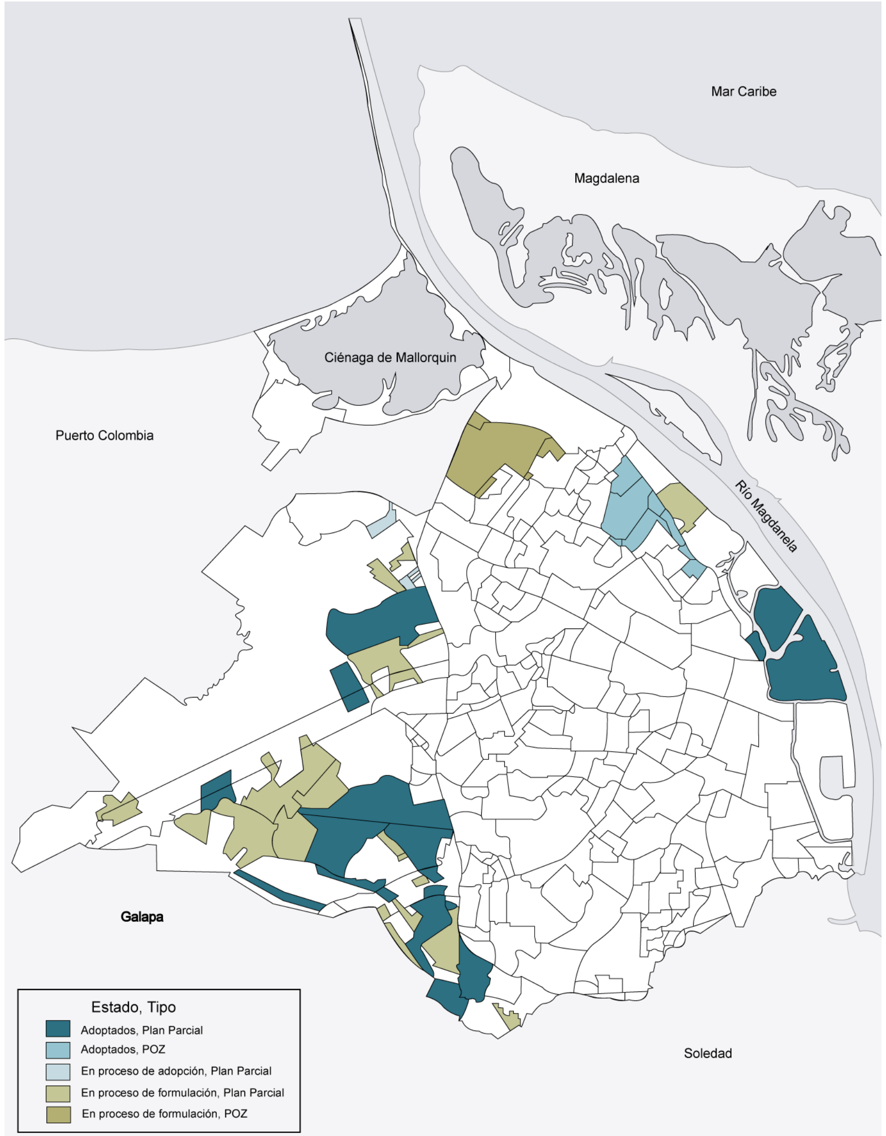


Illustration 15. Planes Parciales approved. Source: Compilation based on (Alcaldía de Barranquilla, 2022).

1 Planes Parciales: Urban development instruments that complement the Land Management Plans, POT. This instrument orders the soil's expansion and renewal (Alcaldía de Barranquilla, 2022).

Perdiz residential complex

Perdiz is a social housing project (VIS) developed by the Prodesa Company between 2019 to 2022. The complex has 600 dwelling units in 6 towers of 12 stories with eight apartments per floor, except for tower "A", with ten apartments per floor. Almost all the apartments have 52 m², and only the ground floor apartment located next to the main entrance has 43m² in each tower.

The project is bordered to the north by Carrera 43 and Olivo Park, to the east by the Olympica supermarket, to the west by another residential complex of 12 stories as well, and to the south by Acacias Park. The residential complex is characterized by having on the ground floor a large concrete tile parking area, a swimming pool, a children's park, bicycle parking and meeting areas for the inhabitants. The complex towers are located with the longest façades in a north-south direction. **It must be clarified that towers "A" and "B" are the most exposed as they do not present neighbouring buildings that could generate shade. Hence, the indoor thermal comfort analysis was carried out mainly in these towers.**

The Below site plan allows qualitative recognition of the residential complex, showing that the distance between towers is equal to or greater than 17.04 meters and **comprises a unique type of tower. This tower typology has a constructive, concrete formwork system with earth colours on the façade. The French-type balconies corresponding to the living room's space are geometrically the tower's most exposed element, marking its verticality**. One of the towers' architectural plans and facades are shown (Tower A).

Below a qualitative and quantitative environmental evaluation is shown to identify the towers' thermal performance and the people's thermal perception. The evaluation has three steps: **(1)** a qualitative observation analysis of the materials and constructive system, **(2)** a quantitative study of the current building envelope, and **(3)** an experimental study of the thermal performance of the building, allowing the understanding of interior spaces' behaviour. Subsequently, design process is carried out regarding the most effective strategies for selection and envelope renewal.

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SITE PLAN

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Structure and envelope materials

The building is characterized by a constructive system called tunnel-type formwork. It is used for the rapid and industrialized construction of reinforced concrete structures using vertical (walls) and horizontal (slabs) plates that allow structures with great strength and lateral stiffness. The thicknesses of the screens and slabs are relatively small, varying between 12 and 25 cm. Among the advantages of this system is the standardization of the structural design, the speed of construction and its relative economy. However, it has some disadvantages: the use of concrete, a cement base material with high C02 emissions; limiting design changes through the building life cycle, which hinders its adaptability and reuse capacity. The main envelope assemblies are the following:

Residential towers' opaque envelope

Type	Element	Materials (Ext - Int)	[m][	U-ValueF W/m^{2}k]	dY [-][	ie W/m^{2}k]	SR [-]
Vertical envelope	Exterior Wall	Graniplast (white, cream,Ocher)	0.0015	**3.79**	0.83	3.15	0.4
		Concrete	0.12				
	Interior WallC	oncrete0	.12	**2.94**	0.69	2.02	-
Horizontal envelope	Dwellings Roof	Waterproofing SIKA	0.009	**1.03**	0.25	0.25	0.2
		EPS E=1' (15Kg/m3)	0.025				
		Levelling mortar	0.08				
		Concrete slab	0.18				

Residential towers' transparent envelope

Type	Element	Materials	[m][	Uw W/m^{2}k]	Ug [W/m^{2}k][	SHGCV -]	LT [-]
Vertical envelope (Exterior Windows)	V-1	Clear simple glazing / Aluminium frame	0.006	**7.19**	5.82	0.82	0.88
	V-2	Clear simple glazing / Aluminium frame	0.006	**7.41**	5.82	0.82	0.88
	V-3	Clear simple glazing / Aluminium frame	0.006	**7.34**	5.82	0.82	0.88
	PV-1	Clear simple glazing / Aluminium frame	0.006	**6.84**	5.82	0.82	0.88
Horizontal envelope (Polycarbonate roof)	R-1	SKYLIGHT- 2P - Arcos	0.02	**2.26**	1.80	.710	.85
	R-2	SKYLIGHT- 2P - Arcos	0.02	**2.24**	1.80	.710	.85

Table 9. Towers' envelope. Source: Developed by author.

As seen in Table 9, the project's envelope is characterized by incorporating constructive systems with a high capability to transfer heat. From the point of **static analysis**, the only envelope element of the building that includes insulating properties is the roof with a U-value close to 1W/m²K; It must be evaluated to identify if it's enough to grant adequate interior temperatures. On the other hand, concerning the **dynamic analysis**, any of the assemblies satisfy the conditions to reduce the oscillations of the interior temperature, exceeding the permissible ranges of periodic thermal transmittance (yie) of 0.12 W/m²K for vertical surfaces and 0.20 W/m²K for horizontal surfaces according to the passive house standard. **Therefore, it could be inferred that a building with these envelope conditions could hardly respond to future temperature increase exposure caused by climate change.**

The field of design and construction must be concerned with incorporating new technologies adapted to the regional environment or reformulating the usefulness and efficiency of existing systems. The lack of regulation related to hygrothermal comfort has led to the implementation of constructive systems that provide a not expected environmental housing quality, directly affecting the well-being of the users, and increasing the GHG emissions due to the cooling system load.

Sensitivity to climate change exposure: Project survey

Thermal comfort survey

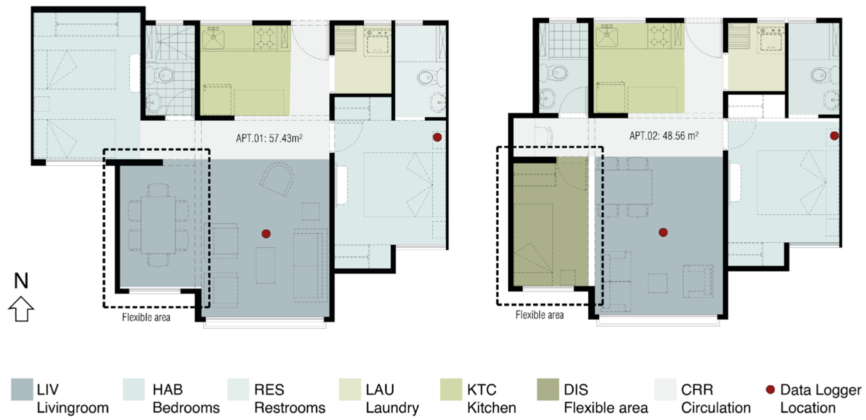


Illustration 16. Typologies' Thermal Comfort zonification. Source: Created by the author.

To develop the thermal analysis, the thermal zones of the two housing typologies were classified. It considered the space type, the conditioning system (Natural or mechanical), and the occupation. Each dwelling comprises six space types: HAB: Bedroom, LIV: Livingroom, KTC: Kitchen, RES: Restroom, CRR: Circulation, LAU: Laundry. According to the gaps found in the literature, the thermal zones analysed were the Livingroom (LIV.001), and the main sleeping area (bedroom - HAB.002).

The selected spaces had the largest façade area exposed to the outside, allowing a global measurement with respect to the other spaces.

Instruments and variables:

The data was measured with a data logger HOBO U12 Temp/RH/2 ext. channels; this device allowed us to obtain the following information: indoor air temperature (ºC), globe temperature (°C), relative humidity (%HR), and illuminance (lx). The equipment was usually located in the centre of the LIV.001 and HAB.002 thermal zones without direct sun radiation (Illustration 16).

Monitoring period & measurement protocol:

As specified in the methodology section, to identify the dwellings' thermal performance and the dwellers' hygrothermal perception, the project environmental conditions were measured from 18/06/2021 to 04/07/2021. The data show the space thermal performance in critical conditions since these are the warmest months with the minor frequency and speed of winds. Each housing unit was monitored for 24 hours in intervals of 5 minutes. The recorder was placed on a wood structure with an average height of 1.1m. At the end of the 24-hour period, the loggers were removed from the dwellings, and their data was downloaded through specialized software called HOBOwarePro. Besides, the rating scale survey was simultaneously filled out at three different times, 9:00, 15:00, and 21:00. Thus, a comparative analysis between the measurement data and the survey answers was conducted to get more reliable conclusions.

The data recorded by the rating scale surveys and the data logger were divided by space type, living room and bedroom. Then each type was analysed into five categories: **(1)** Level, **(2)** Orientation, **(3)** window film, **(4)** Flexible space state, and **(5)** the conditioning system type, given that some apartments have a cooling system in the sleeping area (Table 10).

	Categories	Sub-categories	Description
1	Level	GL – Ground floor	Dwelling located on the 1st floor.
	I	L – Intermediate levels	Dwelling located between 2nd to 11th floor.
	T	L – Top Level	Dwelling located on the 12th floor.
2	Orientation	S - South	
	N	- North	
3	Window film W	IF – With film D	wellings with single clear glazing.
	W	TF – Without film	Dwellings with single glazing with black film.
4	Flexible space state *(Only in living room)*	CLO – Closed space D	wellings with an additional bedroom in the flexible space.
	O	PE – Open space	Dwelling with the flexible space integrated into the living room.
5	Condition system type *(Only in bedroom)*	NTV – Natural ventilation	Dwelling with natural ventilation bedrooms at night.
	C	OL - Cooling D	wellings with cooling system at night.

Table 10. Analysis categories of thermal comfort survey. Source: Created by author.

The indoor air temperature (Tair) measured was analysed in each category to identify the temperature fluctuation through a 24-hour day. Regarding the **level category of the living room** space, the top level presents the higher Tair of 33.2°C at 15:00.

On the other hand, the maximum Tair on the ground floor and intermediate levels are 31.5°C at 13:00 and 32.5°C at noon, respectively. The warmest Tair mostly happen between 11:00 and 15:00, and the Tair begins to decrease to less than 1°C at 16:00. The lowest Tair on the top floor is 29.8°C at 23:00 means a Tair difference of 3.4°C approx. In respect to the highest Tair in a 9-hour interval. Furthermore, the minimum Tair on the ground floor and intermediate levels are 27.9°C and 27.7°C, respectively. **Indeed, most Tair profiles show that the temperature fluctuation in one hour is usually below 1°C.**

Regarding the **living room orientation**, as mentioned in the microclimate section, the façade that receives the most significant solar radiation in June and July is the north façade. Hence, the data measured shows that the north-facing living rooms have higher temperatures than those facing south, with a Tair difference between 0.3°C to 0.5°C in intermediate levels and 1.5°C in ground-floor apartments. On the other hand, the **flexible space modification** does not significantly impact the Tair; those areas that were divided by reducing the living room area have a Tair reduction between 0.03°C – 0.3°C. It could happen because the same natural ventilation openings ventilate less area, and the space has less sun radiation gains due to eliminating the flexible area's window; an increase in Tair can exist in the new closed flexible area. Nevertheless, this area was not considered in this study. Lastly, about the **window film** placed by the owners was found that the living rooms with glazing film have a Tair reduction between 0.15°C to 0.55°C; it can be deduced that r**educing the entry of solar radiation is a successful strategy to reduce air temperatures. However, the films' technical specifications and colour must be re-evaluated for a more significant effect.**

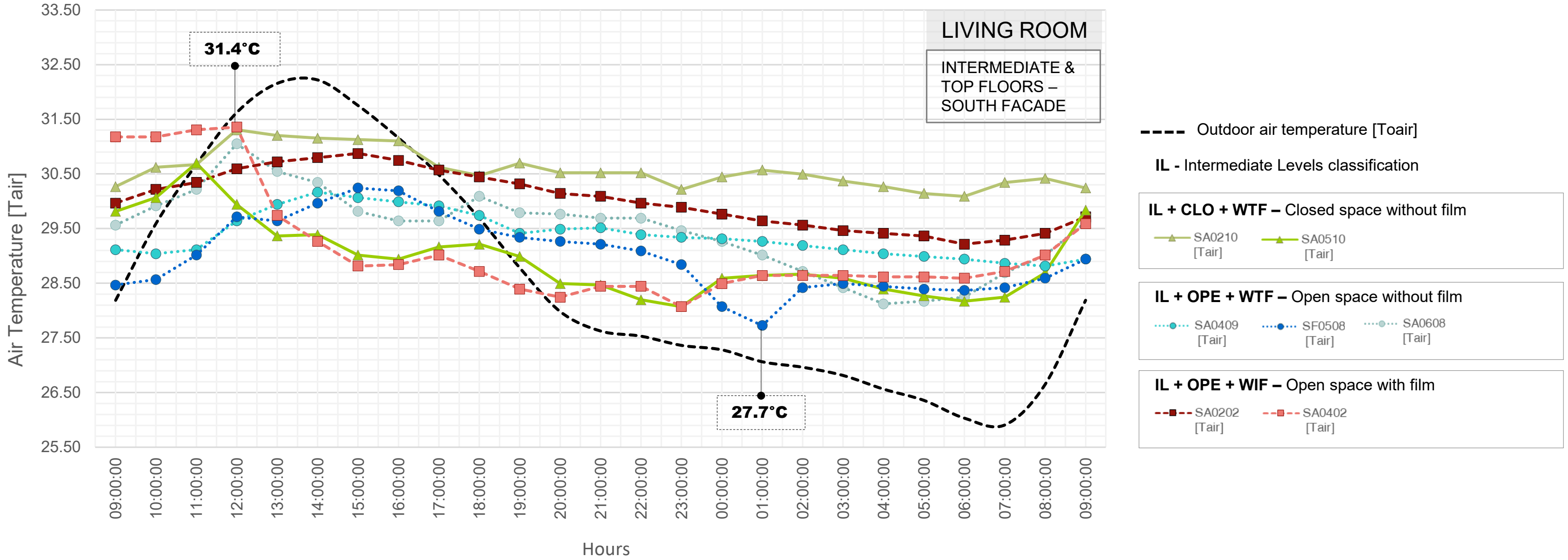


Figure 19. Living rooms air temperature [Tair] in intermediate & Top floors at south façade. The outdoor air temperature daily average was taken from IDEAM climate data. Source: developed by the author with indoor thermal comfort survey data.

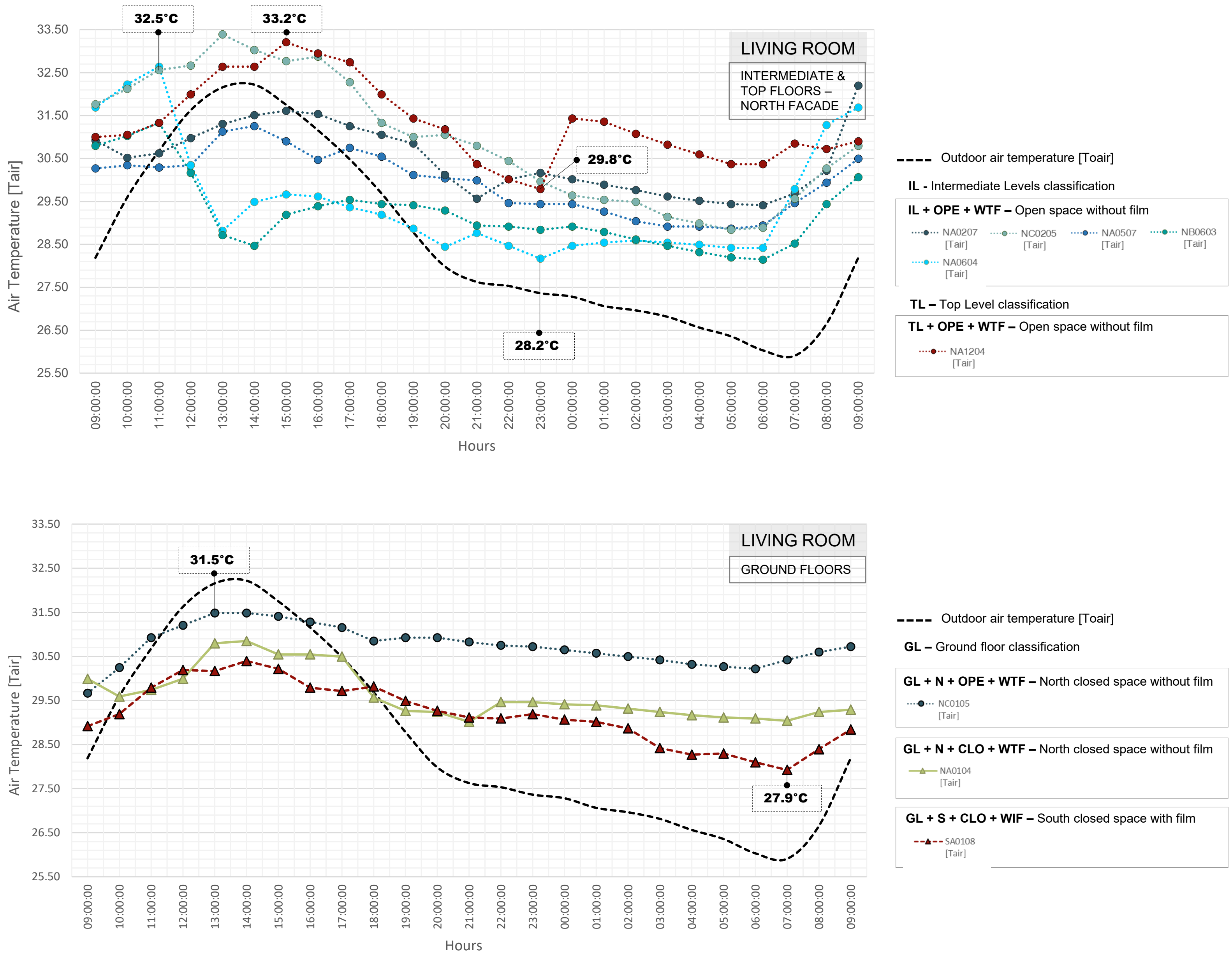


Figure 20. The outdoor air temperature daily average was taken from IDEAM climate data. (1) Above: Living rooms air temperature [Tair] in intermediate & Top floors at north façade. (2) Below: Living rooms air temperature [Tair] on the ground floor. Source: developed by the author with indoor thermal comfort survey data.

In the **bedroom** space, the top floor reaches a maximum Tair of 31.6°C at 17:00 and a minimum Tair of 23.9°C at 6:00. At night, the dwellers use a cooling system with a 21°C setpoint. Hence, it allows space to start the day with a Tair 2°C below the outdoor air temperature (Toair) approx.; that effect happens in all the apartments with a **mechanical condition system** type. The cooling equipment is mostly switched on between 21:00 – 23:00 and shut down between 04:00 – 07:00. The operation of the refrigeration system affects not only the bedrooms' temperature but also the apartments' thermal behaviour and, therefore, the living rooms. Figure 21 and Figure 22 show two behaviours: (1) The living room decreases the Tair and its fluctuations, and (2) by using the cooling equipment, its mandatory to close the windows and the circulation of natural ventilation, so if the internal loads are representative the Tair slightly increases until it stabilizes and the fluctuations decrease. The top floor apartment is the warmest respect to the other apartments with a cooling system.

About the **naturally ventilated bedrooms**, a maximum Tair of 32.7°C at 13:00 and a minimum of 28.2°C at 05:00 are observed. The daily temperature fluctuation is around 2.23°C in a 15-hour interval, which means that the Tair is very stable. In the living room space, the warmest spaces are faced to the **north**, and the **glazing film** gives a Tair reduction between 0.1°C – 0.8°C approx. However, it must be highlighted that the blackout is down almost all day in the bedrooms without glazing film to prevent solar radiation gains.

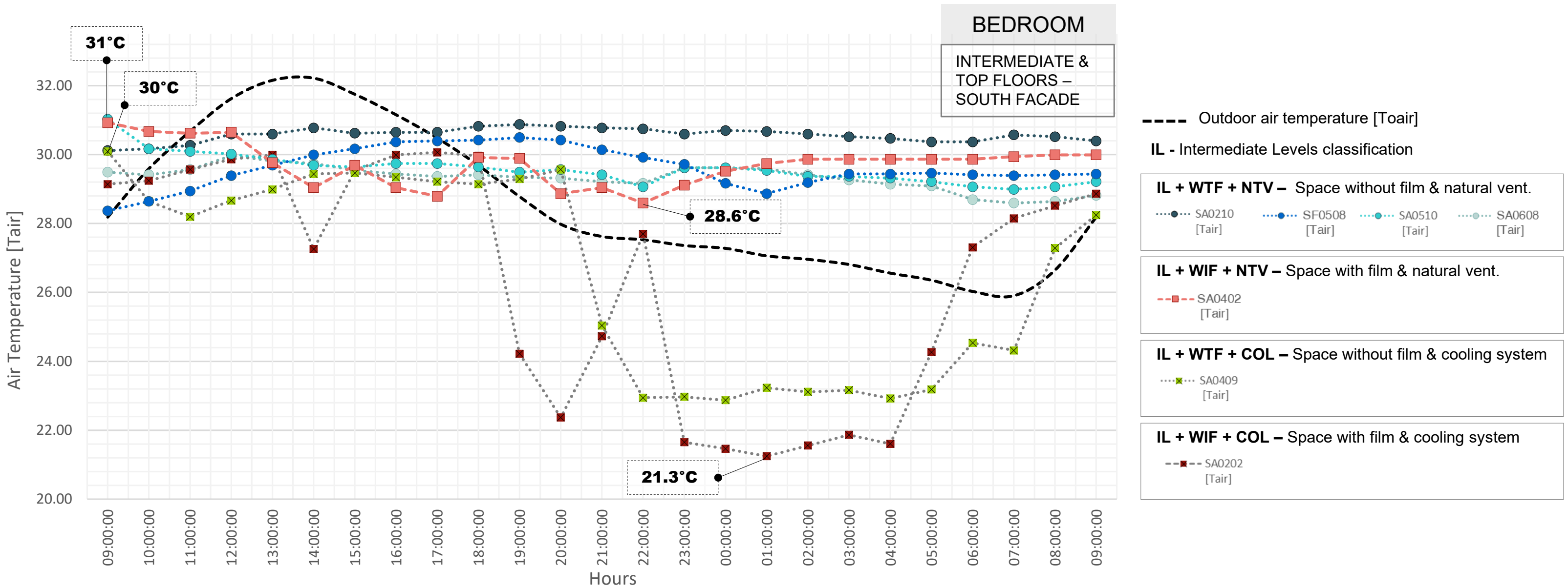
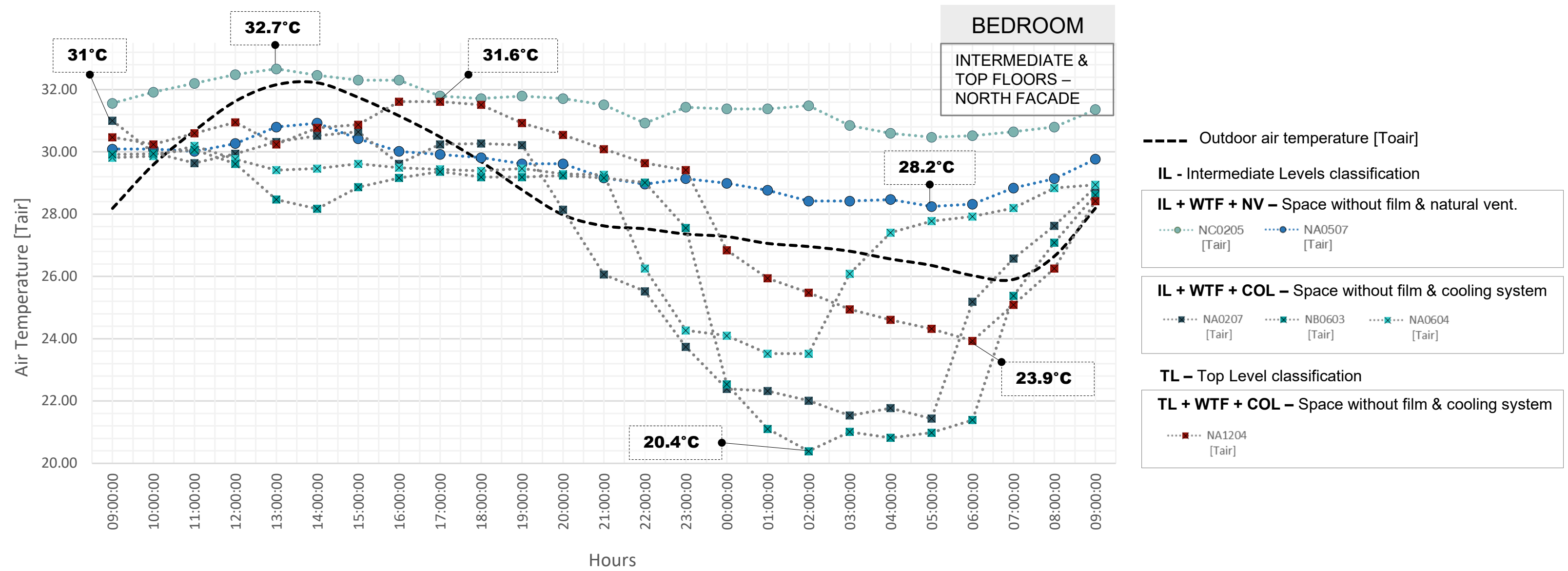


Figure 21. Bedrooms air temperature [Tair] in intermediate & Top floors at south façade. The outdoor air temperature daily average was taken from IDEAM climate data. Source: developed by the author with indoor thermal comfort survey data.



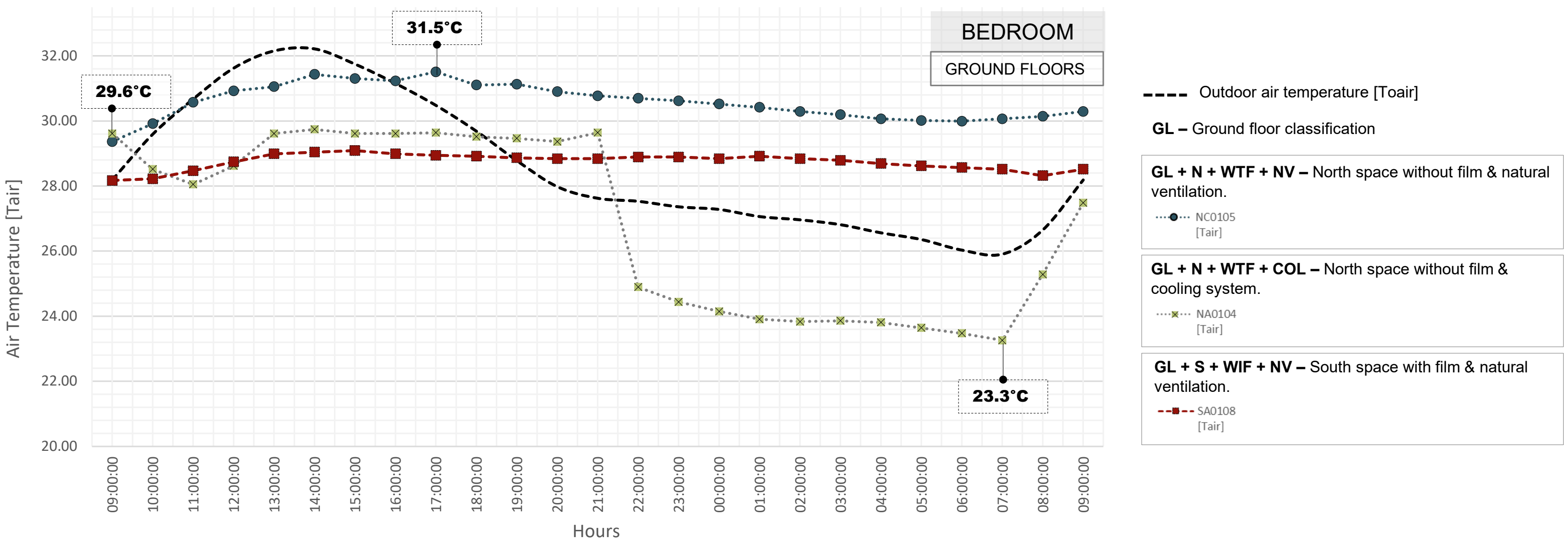


Figure 22. The outdoor air temperature daily average was taken from IDEAM climate data. (1) Above: Bedrooms air temperature [Tair] in intermediate & Top floors at north façade. (2) Below: Bedrooms air temperature [Tair] on the ground floor. Source: developed by the author with indoor thermal comfort survey data

The behaviour of **relative humidity (RH)** is also analysed, only concerning the **conditioning system category** due to its relevance for modifying RH. In the measure RH data, consistent behaviour is observed concerning the Tair. The RH increases when the Tair decreases because its capacity to retain water is reduced. In contrast, when the Tair rise, the RH reduce due to the decrement in the air water-storage capacity. In **naturally ventilated** apartments, the periods of highest humidity usually happen at night and early morning. In the **living room spaces**, a significant variation of approximately 11% in humidity is observed during the day, with values between 61.8% to 82.2% in one of the apartments.

On the other hand, the **naturally ventilated bedrooms** have a more stable RH with a variation of 8% approx. In opposition, the **bedrooms with mechanical conditioning systems** have an RH fluctuation of more than 28%. Due to the system humidity control, the RH at night range between 43.41% - 68.43%. Whilst the RH in the daytime is between 61.71% to 80.94%, with a daytime fluctuation of less than 10%. As well as the bedrooms, the connecting living rooms reduce the RH between 64.33% - 77.74%, approx. 4% less than the living rooms in apartments with naturally ventilated bedrooms. Indeed, if the healthy range of RH set by the CIBSE (2005) and ANSI/ASHRAE 62.1 (2010) is considered, it is evident that the living rooms and naturally ventilated bedrooms are 24 hours a day above the range (40% - 65%). Contrarily, the mechanically ventilated bedrooms have an average of 10 hours a day inside the range, approx. 40% of the day hours, mainly when the cooling system works.

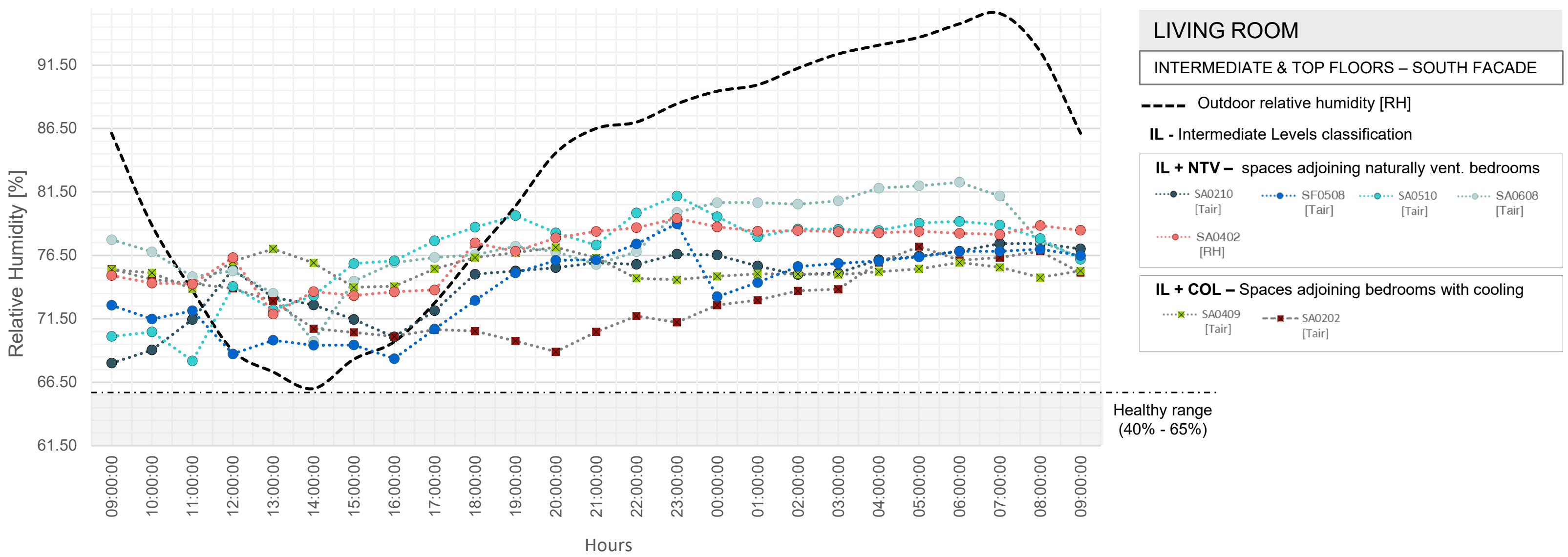
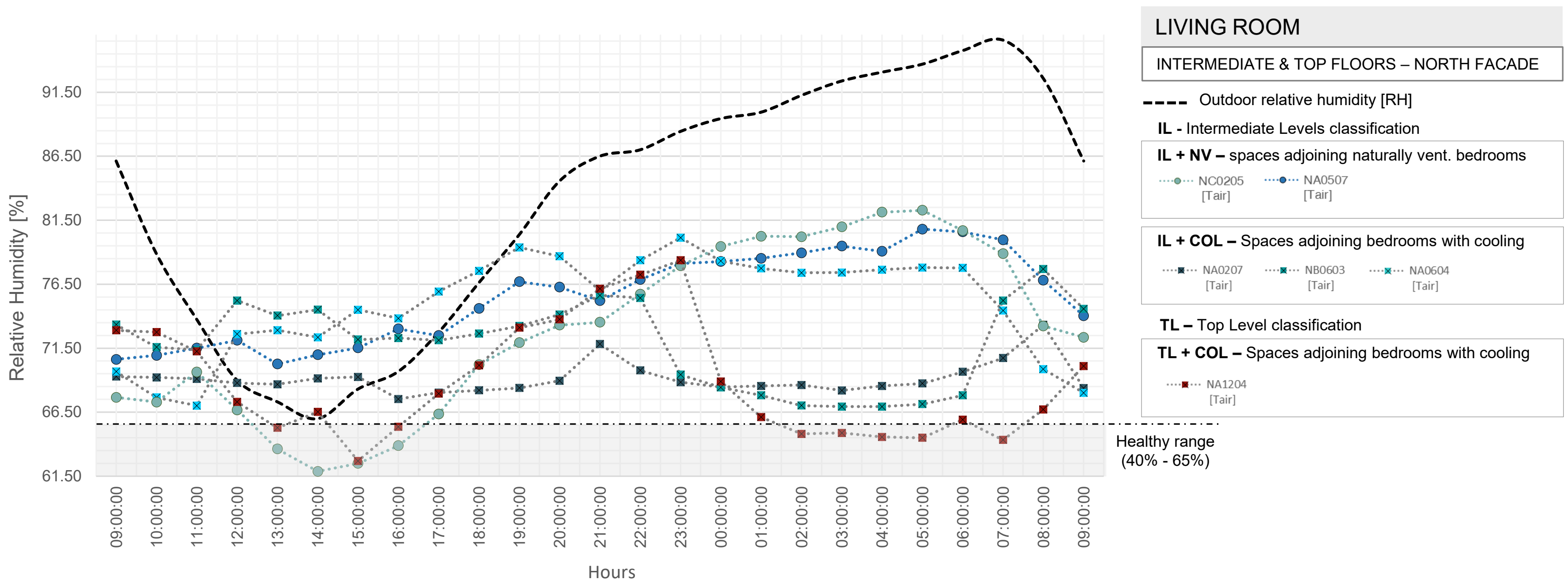


Figure 23. Living rooms relative humidity [RH]. The outdoor RH is from IDEAM climate data. Source: developed by the author with indoor thermal comfort survey data.



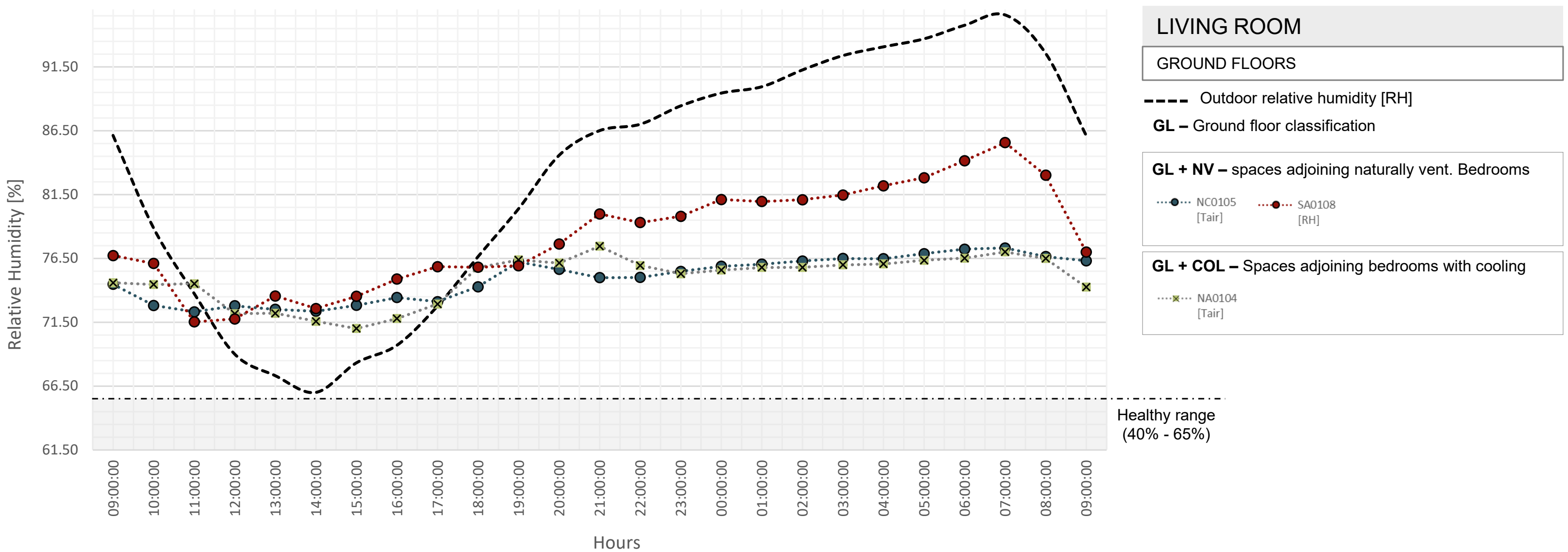


Figure 24. The outdoor RH is from IDEAM climate data. (1) Above: Living rooms relative humidity [RH] in intermediate & Top floors at north façade. (2) Below: Living rooms relative humidity [RH] on the ground floor. Source: developed by the author with indoor thermal comfort survey data.

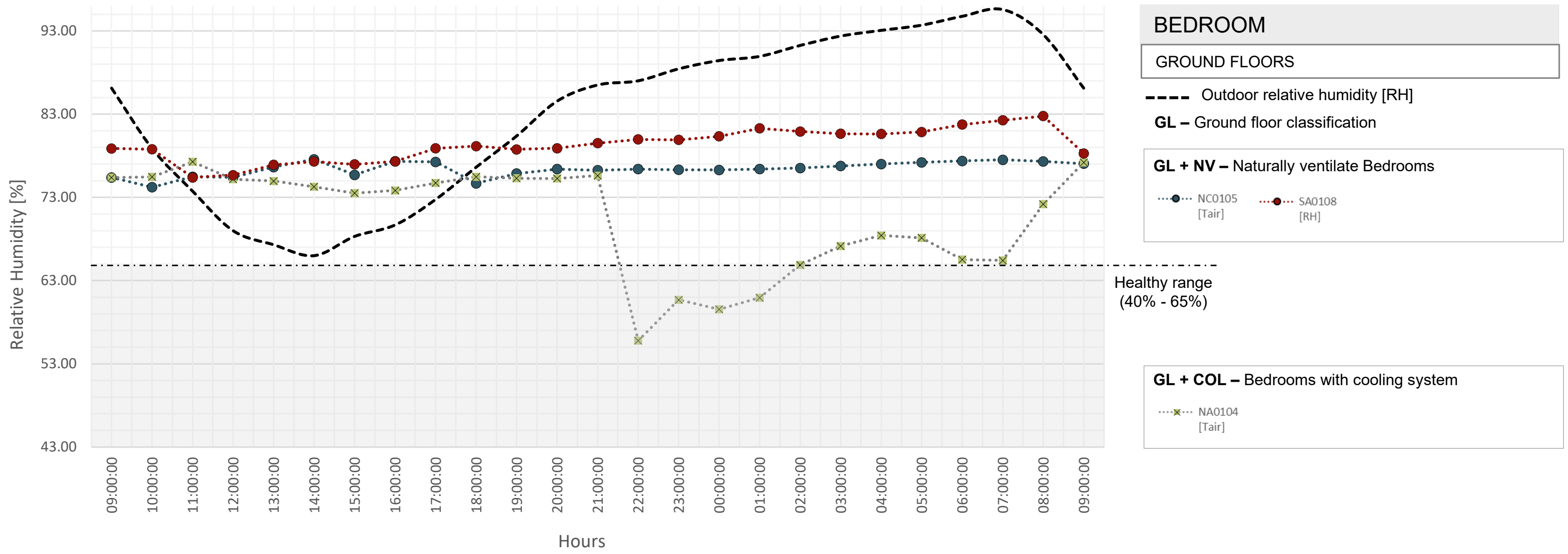


Figure 28. Bedrooms relative humidity [RH] on the ground floor. The outdoor RH is from IDEAM climate data. Source: developed by the author with indoor thermal comfort survey data.

PMV AND PDD evaluation

The PMV (estimated mean vote) analysis was carried out using the air temperature (Tair), and relative humidity (RH) values measured. On the other hand, the meant radiant temperature values were calculated with the Global radiant temperature (GT) data measured and the following equation set up in the ISO 7726:1998 - Ergonomics of the Thermal Environment - Instruments for Measuring Physical Quantities (1998):

$$MRT = \left[(GT + 273.15)^4 + \frac{1.1 \cdot 10^8 \cdot v_a^{0.6}}{\varepsilon \cdot D^{0.4}} (GT - T_a) \right]^{1/4} - 273.15$$

where:

MRT is the mean radiant temperature (°C);
GT is the globe temperature (°C);
v_a is the air velocity at the level of the globe (m/s);
ε is the emissivity of the globe (no dimension);
D is the diameter of the globe (m);
T_a is air temperature (°C);

And for the standard globe (D = 150 mm, ε = 0.95):

By the operation schedule observed in the file survey, the spaces are naturally ventilated for more than 70% of the hours in a day. Considering this, the present research assumes an airspeed (Vair) of 0.3m/s, the minimum airspeed (Vair) in naturally ventilated interior spaces established in the ASHRAE 55 standard.

Mean clothing insulation values (Clo) and metabolic rate levels (Met) were defined from the rating scale survey. For the **living room area** (LIV.001), two types of clothing were identified for the **daytime**: **(1)** A Knee-length skirt, short-sleeve shirt, sandals for women, and **(2)** Trousers, short-sleeve shirt, and sandals for women and men; with a clothing insulation value of 0.54 and 0.57 respectively;14 of the 16 owners have a **0.57 Clo.** All the dwellers wore shorts and a short-sleeve shirt with a **0.36 Clo** for the **nighttime** (Table 6). On the other hand, the most frequent activity done by the dwellers in the living room was being seated, working or studying and relaxing, both equivalent to a 1.2 Met (Table 5).

In the bedroom area (HAB.002), on the contrary, the most frequent activity was reading, seated with a **1.0 Met** equivalent in the **daytime hours**. On the other hand, a sleeping metabolic rate of **0.7 Met** was evaluated in the **nighttime hours**. The clothing insulation of this space in the **daytime** was **0.57 Clo**. However, a bedding system isolation was used for the **nighttime**, as suggested by Lin & Deng (2008a). The bedding system was defined as a bed with a conventional mattress with 48.0% coverage of body surface area by bedding. In light of it, two types of bedding systems were found: **(1)** a blanket with full-slip sleepwear and **(2)** a summer quilt with full-slip sleepwear, with insulation of **1.82 Clo and 1.84 Clo**, respectively.

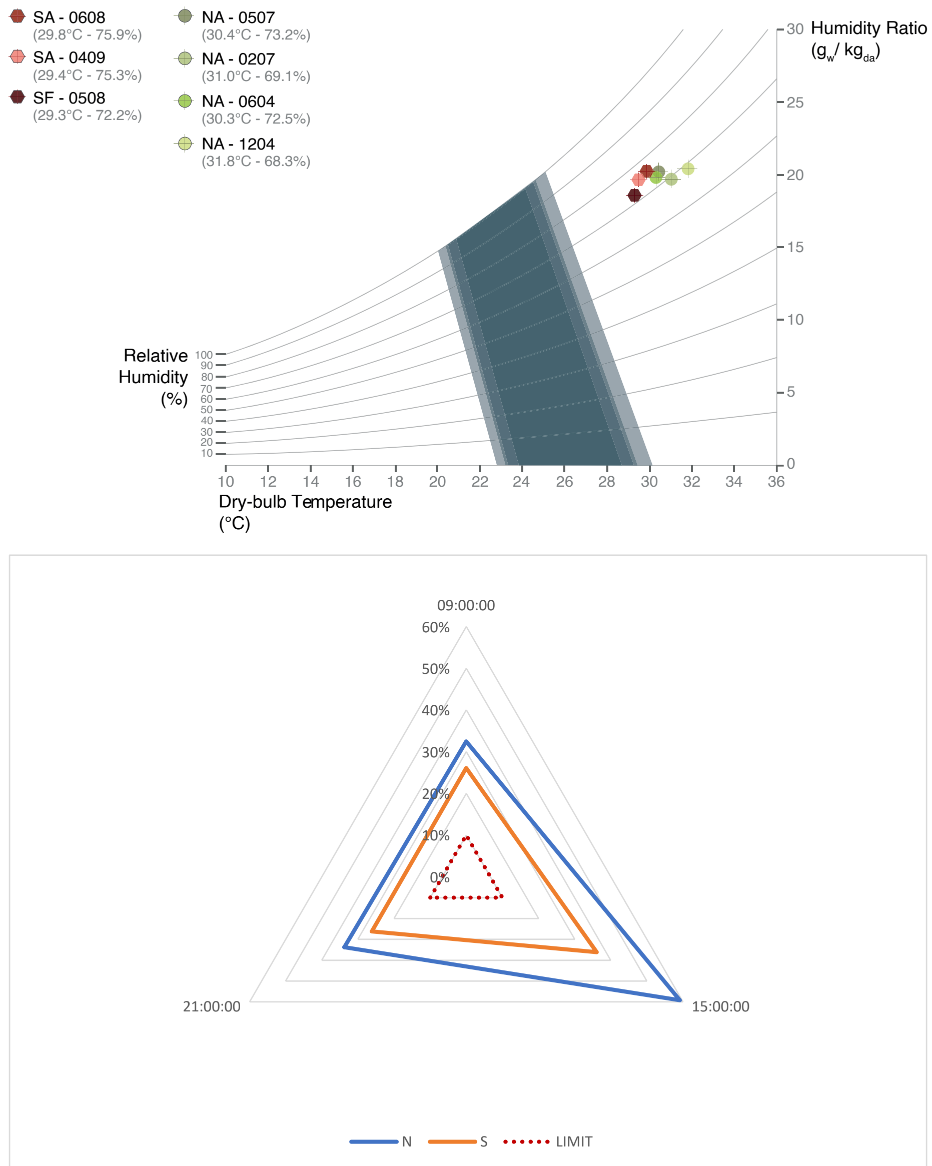


Figure 29. PMV and PDD results. Source: developed by the author with indoor thermal comfort survey data.

Conclusions

As the previous results show, all spaces without HVAC systems have hours above the comfort range. The dwelling units that use HVAC systems at night are below the comfort range of the PMV. It can be inferred that there is a lack of education on how to use the HVAC.

Both the apartments on the south façade and the north façade have a percentage of dissatisfaction greater than 10%. The north façade performs worse due to the solar angle, which gives it a higher incidence in June.

Regarding the location level, dissatisfaction is also higher than 10% in all the dwellings; the story with the most significant dissatisfaction is the roof. On the other hand, the level with minor dissatisfaction is the ground floor, especially in the morning. In both cases, the most significant dissatisfaction occurs in the afternoon.

Chapter 5

Renovation proposal

Renovation approach

The thesis aims to evoke the debate about **what the Perdiz social housing (VIS) project in Barranquilla, Colombia, should do to respond to the future climate change effects** mentioned in a previous section. The implementation approach is based on a speculative design. Mainly focused on **providing minimum habitability conditions related to indoor thermal comfort through the building renovation.**

The scope of the renovation is limited to tower "A" because it is the building in which most of the houses evaluated in the thermal comfort survey are located. Besides, the proposals must consider the existing limitation of doing interventions in private spaces and the feasibility of the proposals in the Latin American social housing context. Likewise, understanding the conclusions of the previous theoretical and experimental studies, the housing quality will be upgraded by implementing architectural measures related to **(1)** heat prevention, **(2)** heat management, and **(3)** heat dissipation. As well as using an architectural approach grounded in a reinterpretation of Atlantic department vernacular architecture, enhancing the local constructive techniques and materials. Furthermore, it will consider the main strengths of the existing building: **(A)** the atrium natural ventilation system (stack effect), **(B)** the self-shading and **(C)** the light façade colours.
Before the final renovation design, two steps were used to identify the appropriate bioclimatic strategies. **(1)** a comparison matrix between weaknesses and bioclimatic solutions (Table 11) and **(2)** a dynamic simulation determining the final renewal strategies.

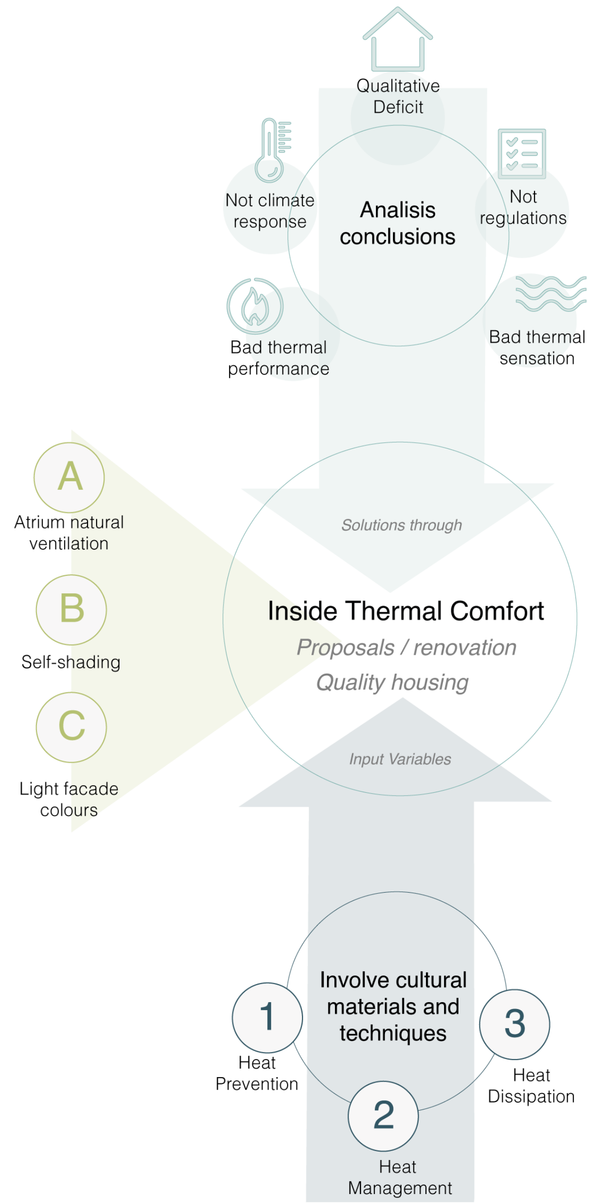


Illustration 19. Implementation approach. Source: Author's elaboration.

Weaknesses vs solutions matrix

			Bioclimatic measures											
			(1) Heat prevention				(2) Heat management			(3) Heat dissipation			Mould prevention & Moisture reduction	
			HP1	HP2	HP3	HP4	HM1	HM2	HM3	HD1	HD2	HD3	M1	M2
			Design shading devices (Fixed, operable, balconies).	Implement a high-performance film with low SHGC, verifying that natural lighting is not drastically affected.	Replace windows glazing with a DGU glazing with low SHG and low U-VALUE.	Provide self shading due to building geometry.	Reflective cooling.Use of light colours and materials with higher albedo.	Adding Insulation to walls, floors and roof.	Provide indirect natural light	Implementation of cross, stack or night ventilation.	Implement a Ventilate roof	Use of ceiling fans	Adding vapor barriers	Implement desiccant panels
Weaknesses – Thermal Comfort	Excess of moisture and condensation	**Mould:** High probability of mould in the vertical opaque envelope.						■					■	
		RH: The living rooms and naturally ventilated bedrooms have an RH above the ASHRAE 62.1 minimum admissible (70%).								■		■		■
	High indoor Temperatures	**Envelope properties:** Windows and walls with high thermal transmission (U-VALUE), windows with high solar heat gain coefficient (SHGC), and walls and roofs with low solar reflectance (SR).		■	■		■	■						
		Overheating rooms: more than 10% of the occupied hours are above the comfort range concerning PMV and Ashrae 55 adaptative model.	■	■	■	■	■	■	■	■	■	■		
		Solar radiation: High solar radiation incidence in the west façade affects the west-corner apartments' bedrooms and living rooms.	■	■	■		■	■						
		Solar radiation: The roof is the envelope element with higher radiation gains.					■	■			■			
		Shading system: Big windows surfaces without sun radiation protection.	■			■								
		Self-adaptation: The dwellers use low-performance black window films to control the solar incidence. It could Increment the probability of overheating.		■	■									
		Self-adaptation: Low adaptation possibility between openings and blackouts as a shading element. Because If they want to open the window, they must allow the sun radiation entrance.	■			■								
	Natural Light quality	Regular use of blackouts decreases the natural light quality.	■	■	■	■			■					
Weaknesses – Climate change exposure	Impact in buildings Thermal comfort	Dry bulb temperature is projected to increase by 1.6°C by 2050.	■	■	■	■	■	■	■	■	■	■		
		Relative humidity incrementation by 0.6pp by 2050.												■
		Wind speed will decrease by -2% by 2050.								■	■	■		

Table 11. Comparison matrix between weaknesses and bioclimatic solutions. Source: Author's elaboration.

Envelope design options for renovation

This section looks to check the efficacy of each bioclimatic measure mentioned in Table 12 to define the specific strategies and their geometric and dimensional parameters, which will be implemented in the final envelope renovation design. **This preliminary design phase is made through dynamic simulations developed in the Design builder software supported by energy plus**. It's performed using a simplified model that considers the geometric, envelope, occupation, operation, lighting, and conditioning system of the dwellings previously measured in tower A.

The dynamic model was calibrated concerning each apartment's Tair and RH in-situ measure data, achieving positive correlations between 0.32 to 0.94. The correlation is classified as moderate and strong by the Person scale, which means that the model has a very similar thermal performance to the one measured. The specific correlation for Tair and RH of each apartment will be found in the Annex 01.

The IDEAM et al. (2019) climate data of Barranquilla was used in the simulations. However, to identify the response of the envelope optimization to future climate change effects, a secondary simulation is performed considering the future impacts on temperature, humidity, and air speed in the year 2050 under an RCP8.5 scenario (1.6°C, 0.66pp, -2% respectively for Barranquilla). As Belcher et al. (2015) suggest, the morphing procedure is used to accurately modify the current climate data. On a final note, in these iterations, only the results of the two apartments with the most critical Tair were analyzed: on the second floor the SA- 210 and on the top floor the NA-1204.

Model input data

Geometry

Illustration 20. (1) Above axonometry of current building geometry, (2) Below – left NA-1204 dwelling, (3) Below – right SA-210 dwelling. Source: Design builder software.

- Simulation running time: **1-year period.**
- Evaluate thermal zones: Main bedroom and Living room. Envelope: the building's opaque and transparent envelope was already described in Chapter 4: Even so, a summary is made at the beginning of Table 14.
- Schedule: The dwellings schedule is variable. Generally, **the apartment is occupied for 24 hours**, but the schedule in each zone varies depending on the behaviour of each dweller.

- System and load: The simulation is run with natural ventilation and the building stack system.
- Occupation: Each house occupation follows the dweller's behaviour. In the SA-210 apartment live two adults and one child, In the NA-1504, Three adults live.

Thermal comfort range

Attended the previous experimental comfort study, where the occupant's perception is closer to the comfort range predictions of ASHRAE 55 adaptative comfort standard than the static methodology or PMV method. The following strategies comparison will be based on the ASHRAE 55 adaptative comfort range. Since To fluctuations in the spaces do not exceed the range of 2°C in 1 hour or 1.1°C in 0.5 hours, a single comfort range was determined for the strategy selection exercise. **Therefore, with a prevailing mean outdoor temperature of 28.08°C is established a comfort range as follows: (1) for people, acceptability of 90% will be 24.0°C to 29.0°C, and (2) for people, acceptability of 80% will be 23.0°C to 30.0°C. Space will have hygrothermal comfort as long as 90% of its occupied hours have a To between the mentioned limits.**

Modeling methodology

The modelling methodology is based on a NOT cumulative analysis, which means that in each design option model, the only variable that changes concerning the base model is the variable to be evaluated (Table 13). This allowed the selection of the most effective strategies. The variable analyzed was each space's annual operative temperature (To). It was evaluated in each apartment's Living room and main bedroom. The design options were compared between the same measure type (S, G, WC, WR, R, VN) except for the ventilated roof (VN1) compared with group R to identify the roof's effectiveness; all roof measurements were analyzed only in the top floor (NA-1504).

		Design options models													
Measure Type		**M01M**	**02**	**M03M**	**04**	**M05M**	**06**	**M07M**	**08**	**M09M**	**10**	**M11M**	**12**	**M13M**	**14**
G	GlazingG	0G	1G	2G	0G	0G	0G	0G	0G	0G	0G	0G	0G	0G	0
S	Shading	S0	S0	S0	S1	S2	S3	S0	S0	S0	S0	S0	S0	S0	S0
WC	Walls conductivityW	C0	WC0W	C0	WC0W	C0	WC0W	C1	WC2W	C0	WC0W	C0	WC0W	C0	WC0
WR	Walls albedo	WR0W	R0	WR0W	R0	WR0W	R0	WR0W	R0	WR0W	R0	WR0W	R0	WR0W	R1
VN	Natural ventilation	VN0V	N0	VN0V	N0	VN0V	N0	VN0V	N0	VN2V	N3	VN1N	V0	NV0N	V0
R	Roof	R0	R0	R0	R0	R0	R0	R0	R0	R0	R0	R0	R1	R2	R0

Table 12. Design option methodology. Source: Author's elaboration.

Matrix of design options parameters

Envelope design options

	Code	Design options	Design parameter	Bioclimatic measures related with		
Base building envelope parameters	G0	Clear glassing	5.84 W/m²k SHGC 0.82 VLT 0.88			
	S0	Without shading system	-			
	WC0 WR0	Concrete wall with graniplast finished	3.59 W/m²K SRI 0.4			
	NV0	Currently Windows, vents & stack system (only daytime operation as evidenced in the survey)	-			
	R0	Concrete roof with EPS and black exterior waterproofing finishing	SRI 0.37			
(1) Heat prevention design options	S1	Fixed vertical shading system. *Located in front of the living room and the bedrooms windows.	Light permeability: 50%	HP1	HM3	M2
	S2	Balconies *Located in the living room and main bedroom area.	Depth: 1.5m	HP1		
	S3	Mobile folding panels *Located in the living room and main bedroom area.	Light permeability: 50% Operation: As reported in survey (10:00 - 15:00)	HP1	HM3	M2
	G1	Add a window film (NV35 single pane)	5.84 W/m2K SHGC 0.48	HP2		
	G2	Double glazing	2.79 W/m2K SHGC 0.46	HP3		

(2) Heat management design options	WC1	Add in the inside face of the wall a reflective layer of insulation + superboard	0.69 W/m2K	HM2	M1
	WC2	Add in the inside face of the wall a 1' EPS insulation + superboard	0.98 W/m2K	HM2	M1
	WR1	White paint	SRI 0.83	HM1	
	R1	White waterproof paint	SRI 0.83	HM1	
	R2	Reflective water proofing Layer UltraPly™ TPO	SRI 0.98	HM1	
(3) Heat dissipation	VN1	Ventilate roof with high reflectance roof tile	SRI 85	HD2	HM1
	VN2	Vents (Constant ventilation) *Located at the top of each window	Height: 10 cm	HD1	
	VN3	Night ventilation through windows.	Glazing area opening: 24% of the window area	HD1	

Table 13. Matrix with the envelope design options VS the bioclimatic solutions. Source: Author's elaboration.

Thermal evaluation of design options

SA-210
LIVING ROOM

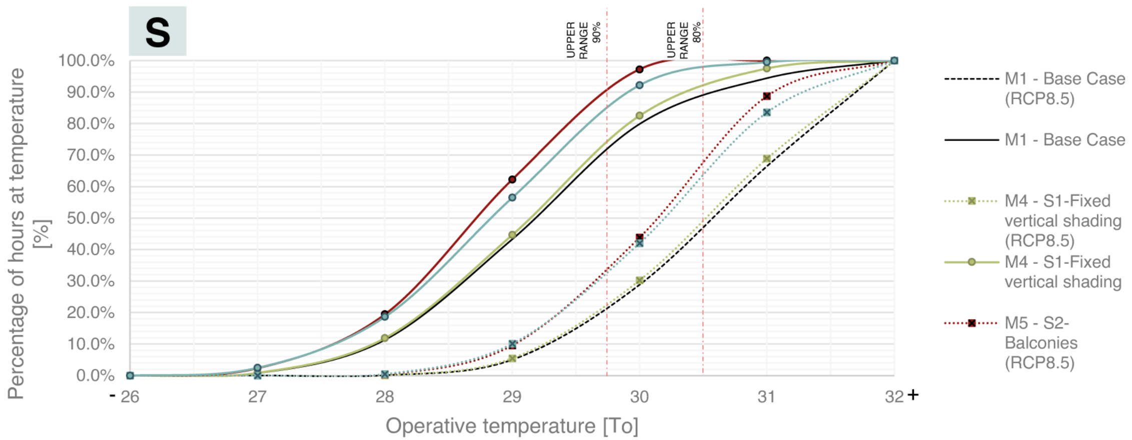
Comfort Range: 23°C - 30°C

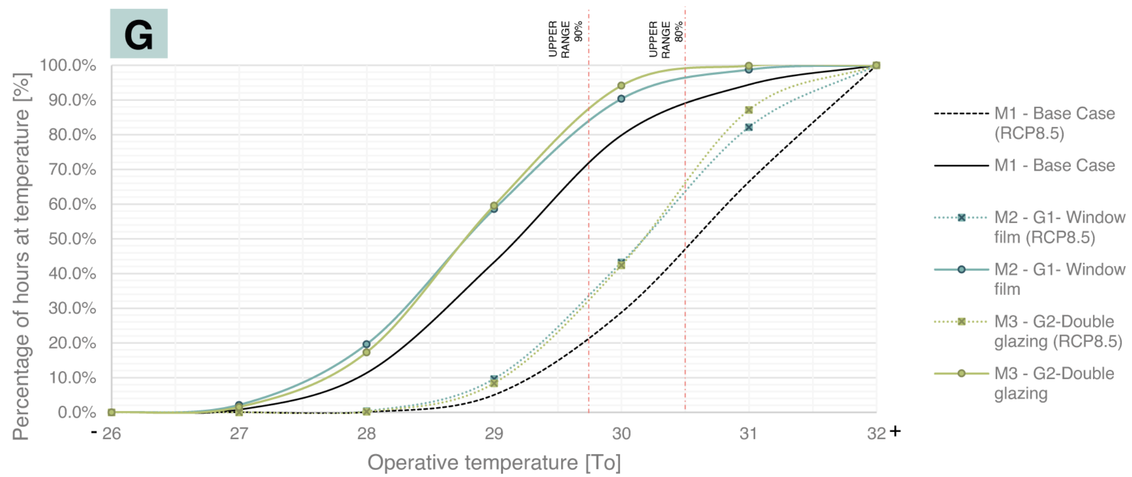
Total Occupation hours/ year: **5110**

		Below 23 °C		between 23°C and 30 °C		Above 30 °C	
		Hours	%	Hours	%	Hours	%
Current scenario	Base	0	0%	2211	43%	2899	57%
	S1	0	0%	2281	45%	2829.25	55%
	S2	0	0%	3180	62%	1930	38%
	S3	0	0%	2885	56%	2225	44%
	G1	0	0%	2993	59%	2116.75	41%
	G2	0	0%	3044	60%	2066.5	40%
Future scenario 2050 - RCP8.5	Base	0	0%	255	5%	4855	95%
	S1	0	0%	279	5%	4831	95%
	S2	0	0%	489	10%	4621	90%
	S3	0	0%	515	10%	4595	90%
	G1	0	0%	493	10%	4617	90%
	G2	0	0%	428	8%	4682	92%

● Regarding the shading elements, the ones that present the best performance are the horizontal overhangs, which make sense due to the solar angle, which is almost vertical. The folding panels also provide excellent thermal behaviour increasing the hours inside the range of 13% approx.

●On the other hand, the glass with the best performance in the current climate and the RCP 8.5 prediction is the solar control glass. On the contrary, double glass has a negative effect. This may be because it does not facilitate heat dissipation, generating overheating.



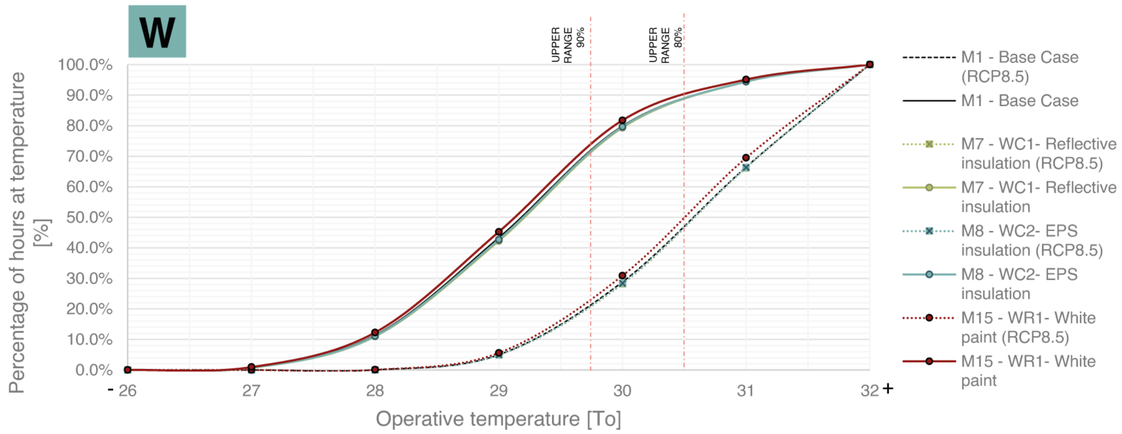


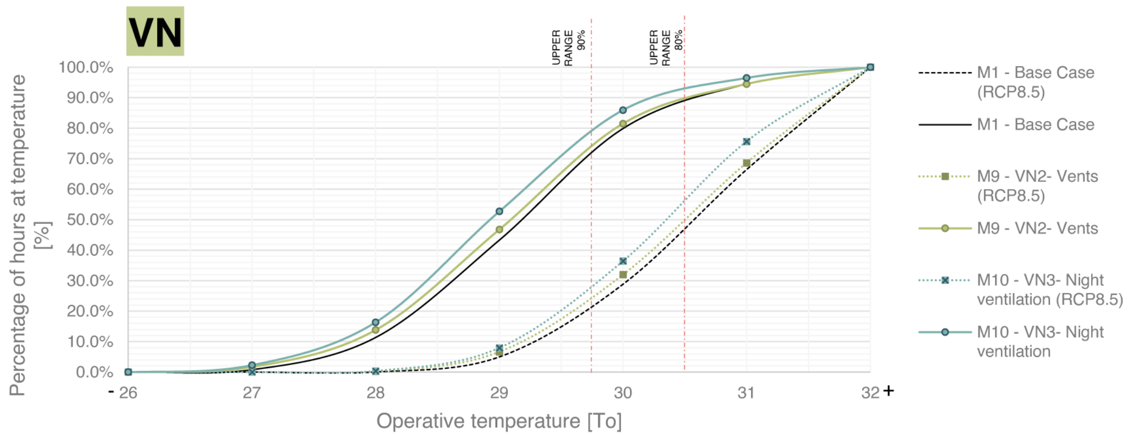
SA-210
LIVING ROOM

Comfort Range: 23°C - 30°C

Total Occupation hours/ year: **5110**

		Below 23 °C		between 23°C and 30 °C		Hours above 30 °C	
		Hours	%	Hours	%	Hours	%
Current scenario	Base	0	0%	2211	43%	2899	57%
	WC1	0	0%	2158	42%	2951.75	58%
	WC2	0	0%	2178	43%	2932	57%
	WR1	0	0%	2311	45%	2798.75	55%
	VN1	0	0%	2390	47%	2720.25	53%
	VN2	0	0%	2693	53%	2417.25	47%
	VN3	0	0%	2243	44%	2867.25	56%
Future scenario 2050 - RCP8.5	Base	0	0%	255	5%	4855	95%
	WC1	0	0%	251	5%	4860	95%
	WC2	0	0%	251	5%	4859	95%
	WR1	0	0%	286	6%	4824	94%
	VN1	0	0%	340	7%	4770	93%
	VN2	0	0%	406	8%	4704	92%
	VN3	0	0%	259	5%	4851	95%





- Regarding the wall system, an isolated wall decreases the thermal performance of the space, mainly in the climate change scenario. This could be because the isolation does not allow heat dissipation by conductivity.

- On the other hand, the reflective wall's performance improvement is minimal.

SA-210
BEDROOM

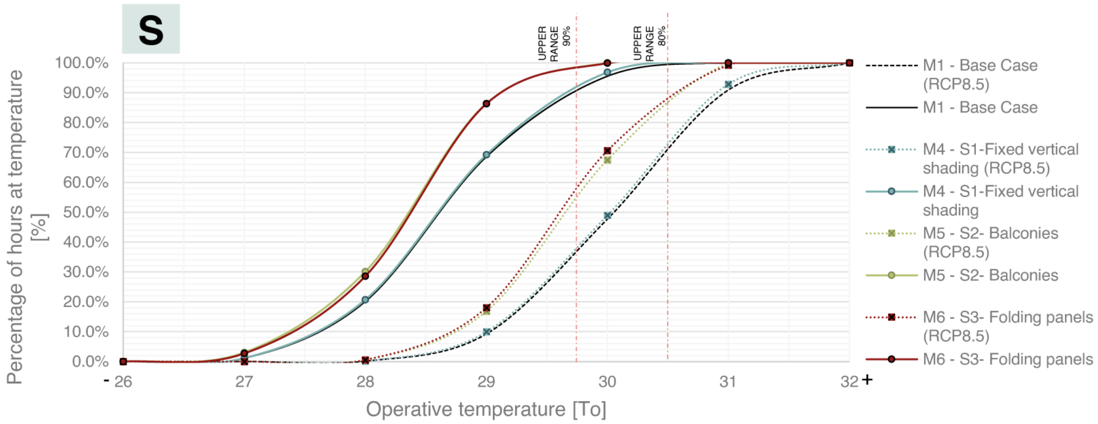
Comfort Range: 23°C - 30°C

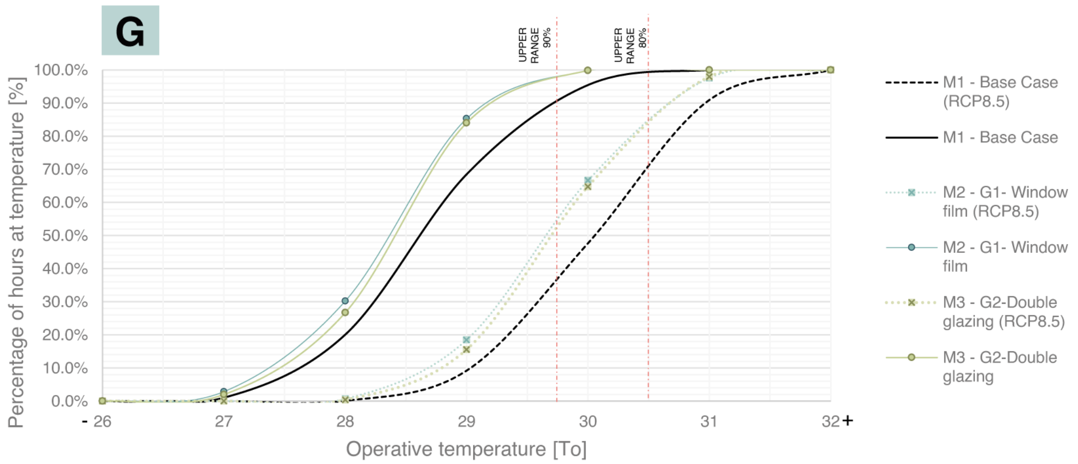
Total Occupation hours/ year: **3650**

		Below 23 °C		Hours		Hours above 30 °C	
		Hours	%	Hours	%	Hours	%
Current scenario	Base	0	0%	2501	69%	1148.75	31%
	S1	0	0%	2526	69%	1124	31%
	S2	0	0%	3154	86%	496.5	14%
	S3	0	0%	3149	86%	500.75	14%
	G1	0	0%	3115	85%	534.75	15%
	G2	0	0%	3068	84%	582.25	16%
Future scenario 2050 - RCP8.5	Base	0	0%	337	9%	3314	91%
	S1	0	0%	362	10%	3288	90%
	S2	0	0%	674	18%	3036	83%
	S3	0	0%	659	18%	2992	82%
	G1	0	0%	675	19%	2975	82%
	G2	0	0%	567	16%	3083	84%

- Unlike the living room in this space, the shading element that provides better thermal performance is the mobile panels. Nevertheless, the improvement by balconies or overhangs of 1.5m is also relevant.

- As in the living room space, solar control glazing is the best (G1).



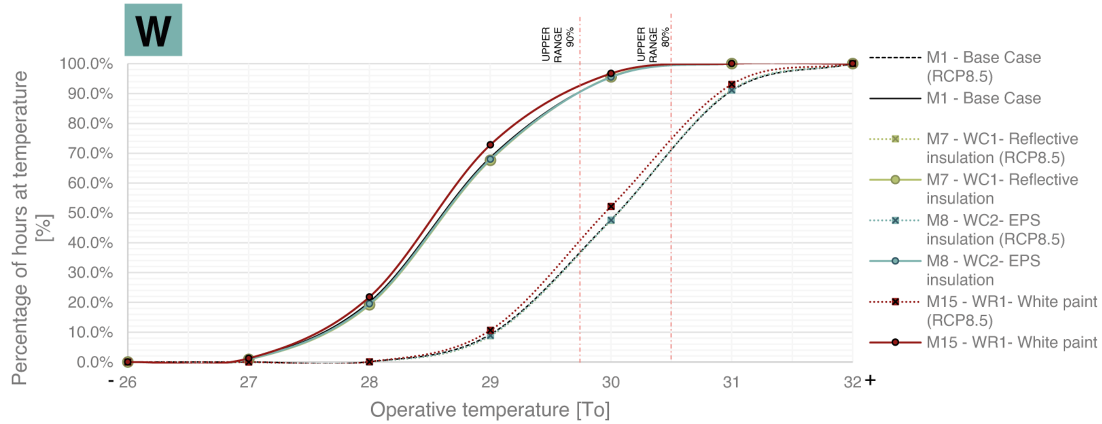


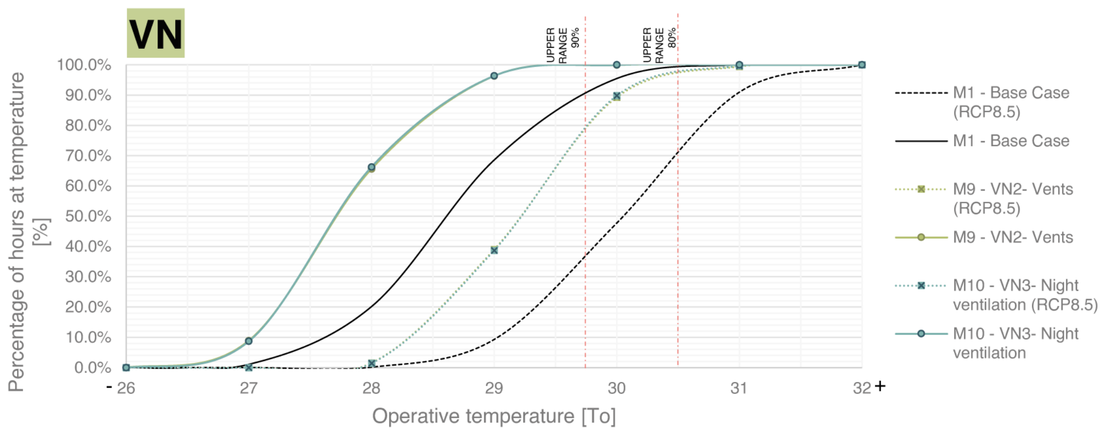
SA-210
BEDROOM

Comfort Range: 23°C - 30°C

Total Occupation hours/ year: **3650**

		Below 23 °C		Hours		Hours above 30 °C	
		Hours	%	Hours	%	Hours	%
Current scenario	Base	0	0%	2501	69%	1148.75	31%
	WC1	0	0%	2469	68%	1180.75	32%
	WC2	0	0%	2481	68%	1169	32%
	WR1	0	0%	2657	73%	993.5	27%
	VN1	0	0%	3516	96%	134	4%
	VN2	0	0%	3517	96%	132.75	4%
	VN3	0	0%	2521	69%	1129	31%
Future scenario 2050 - RCP8.5	Base	0	0%	337	9%	3314	91%
	WC1	0	0%	320	9%	3330	91%
	WC2	0	0%	325	9%	3325	91%
	WR1	0	0%	389	11%	3261	89%
	VN1	0	0%	1423	39%	2228	61%
	VN2	0	0%	1412	39%	2239	61%
	VN3	0	0%	338	9%	3312	91%





- The isolated walls decrease the thermal performance of the space. This could be because the isolation does not allow heat dissipation by conductivity. On the other hand, the reflective wall's performance improvement is minimal, increasing the comfort hours by 4% in the current scenario and 1% in the climate change scenario.

- Natural ventilation systems are the most effective strategies to improve the thermal performance of the space, increasing the time between the range by 28%.

NA-1204
LIVING ROOM

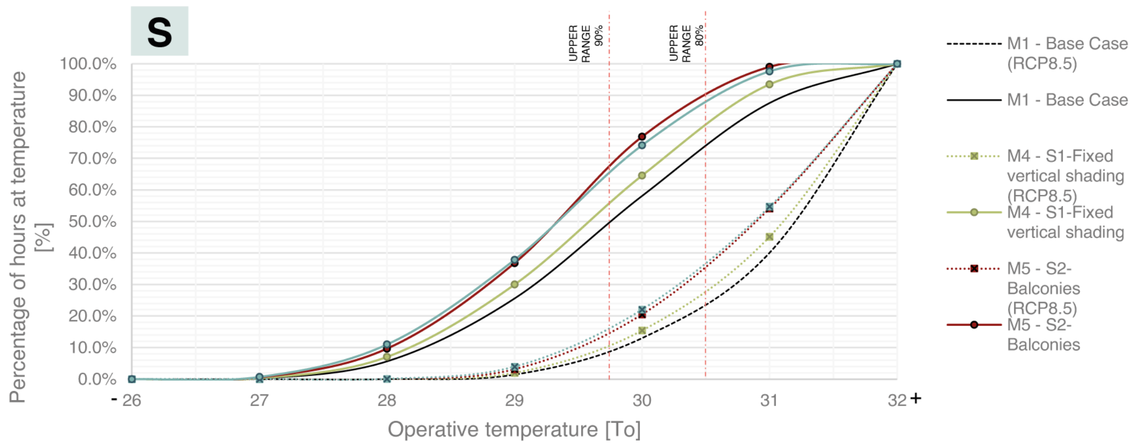
Comfort Range: 23°C - 30°C

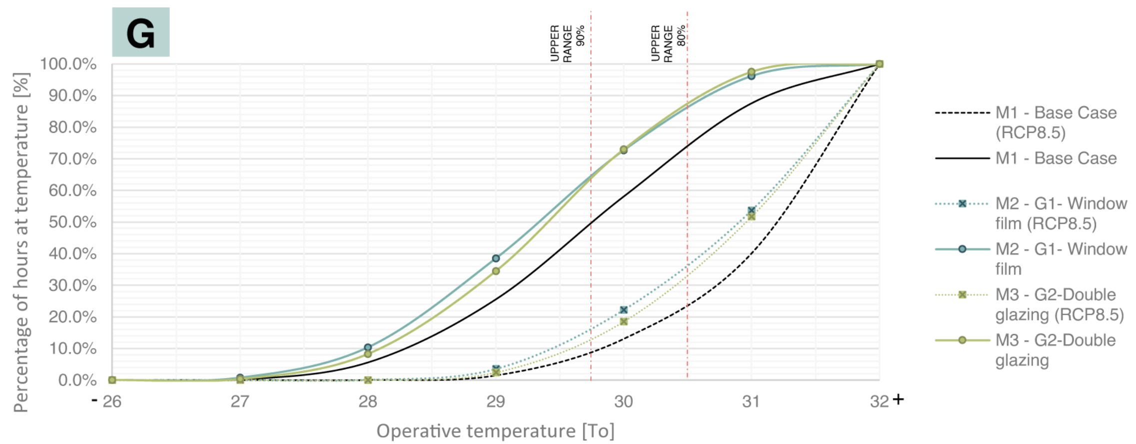
Total Occupation hours/ year: **5110**

		Below 23 °C		Hours		Hours above 30 °C	
		Hours	%	Hours	%	Hours	%
Current scenario	Base	0	0%	1306	36%	3804	104%
	S1	0	0%	1533	42%	3577.5	98%
	S2	0	0%	1880	52%	3229.75	88%
	S3	0	0%	1933	53%	3177.5	87%
	G1	0	0%	1967	54%	3143	86%
	G2	0	0%	1762	48%	3348.5	92%
Future scenario 2050 - RCP8.5	Base	0	0%	74	1%	5037	99%
	S1	0	0%	102	2%	5008	98%
	S2	0	0%	160	3%	4950	97%
	S3	0	0%	201	4%	4909	96%
	G1	0	0%	181	4%	4930	96%
	G2	0	0%	123	2%	4987	98%

- In the living room, the measure that provides more occupied hours in comfort is the folding panel. However, the balcony and horizontal overhangs have almost the same performance. They are increasing the hour in comfort by 17% and 16%, respectively. This improvement decreased to 3% and 2% in the climate change scenario, respectively.

- On the other hand, the solar control glass is the best option for the project, with an increase of 18% of hours in comfort. In the climate change scenario, it is also the glass with the best performance.





NA-1204
LIVING ROOM

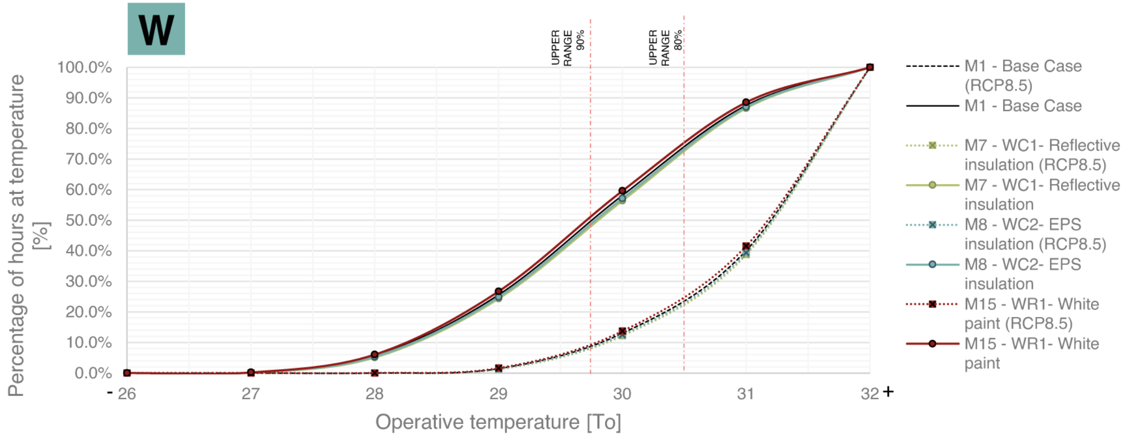
Comfort Range: 23°C - 30°C

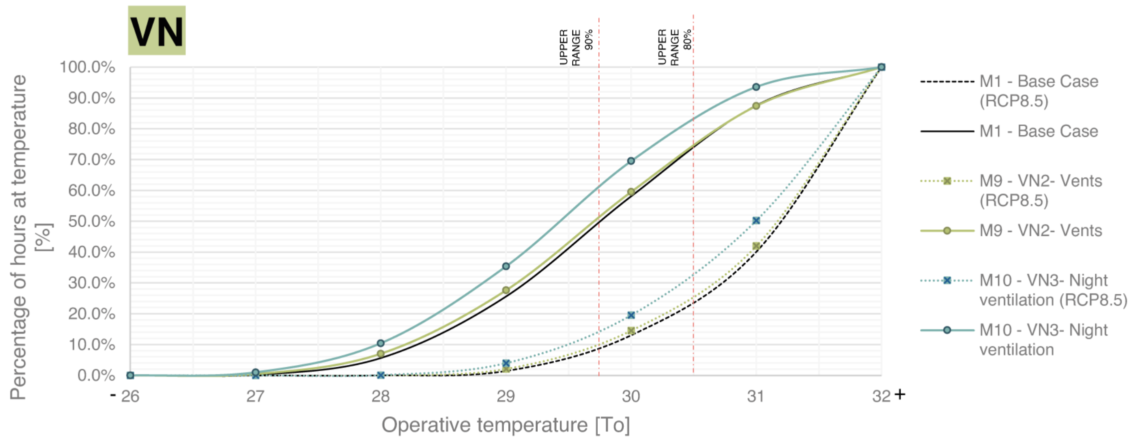
Total Occupation hours/ year: **5110**

Scenario	Case	Below 23 °C Hours	Below 23 °C %	Hours	%	Hours above 30 °C Hours	Hours above 30 °C %
Current scenario	Base	0	0%	1306	36%	3804	104%
	WC1	0	0%	1243	34%	3867	106%
	WC2	0	0%	1268	35%	3842.25	105%
	WR1	0	0%	1365	37%	3745.5	103%
	VN1	0	0%	1409	39%	3701	101%
	VN2	0	0%	1806	49%	3303.75	91%
	VN3	0	0%	1758	48%	3351.75	92%
Future scenario 2050 - RCP8.5	Base	0	0%	74	1%	5037	99%
	WC1	0	0%	62	1%	5048	99%
	WC2	0	0%	66	1%	5044	99%
	WR1	0	0%	81	2%	5029	98%
	VN1	0	0%	107	2%	5003	98%
	VN2	0	0%	203	4%	4907	96%
	VN3	0	0%	135	3%	4976	97%

- Regarding the wall system, an isolated wall decreases the thermal performance of the space, mainly in the climate change scenario. This could be because the isolation does not allow heat dissipation by conductivity.

- On the other hand, the reflective wall's performance improvement is minimal.





NA-1204
BEDROOM

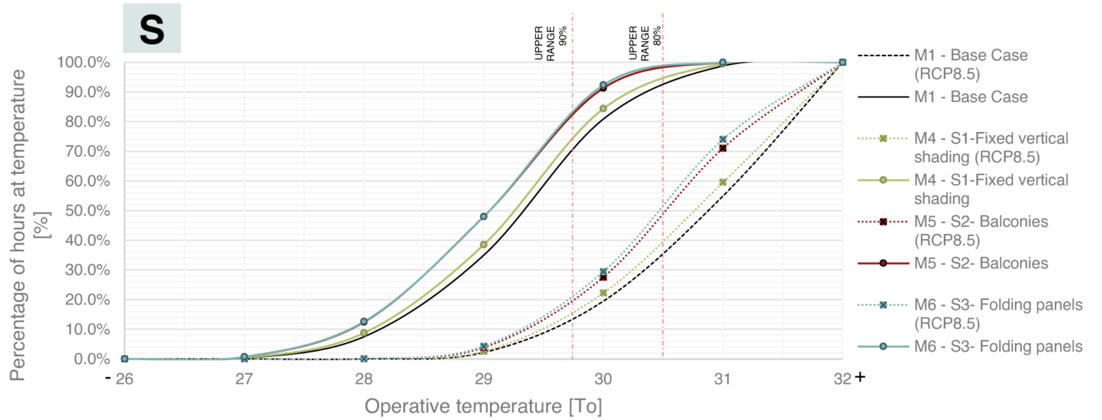
Comfort Range: 23°C - 30°C

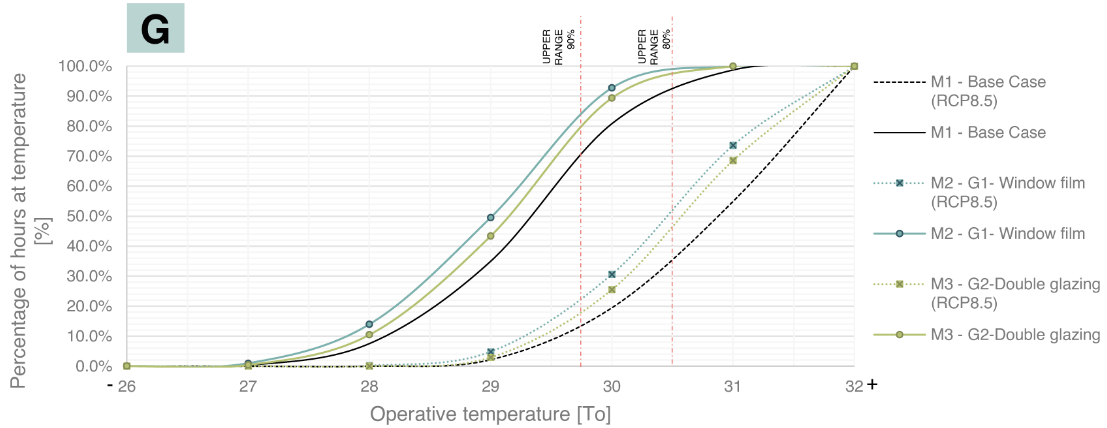
Total Occupation hours/ year: **3650**

Scenario		Below 23 °C		Hours		Hours above 30 °C	
		Hours	%	Hours	%	Hours	%
Current scenario	Base	0	0%	1275	35%	2374.75	65%
	S1	0	0%	1404	38%	2246	62%
	S2	0	0%	1750	48%	1900.25	52%
	S3	0	0%	1749	48%	1900.75	52%
	G1	0	0%	1807	50%	1843.25	51%
	G2	0	0%	1583	43%	2067	57%
Future scenario 2050 - RCP8.5	Base	0	0%	79	2%	3571	98%
	S1	0	0%	93	3%	3557	97%
	S2	0	0%	139	4%	3511	96%
	S3	0	0%	156	4%	3495	96%
	G1	0	0%	175	5%	3475	95%
	G2	0	0%	107	3%	3543	97%

- The shading element that provides better thermal performance is the mobile panels. Nevertheless, the improvement by balconies or overhangs of 1.5m is also relevant.

- As in the living room space, solar control glazing is the best (G1).





NA-1204
BEDROOM

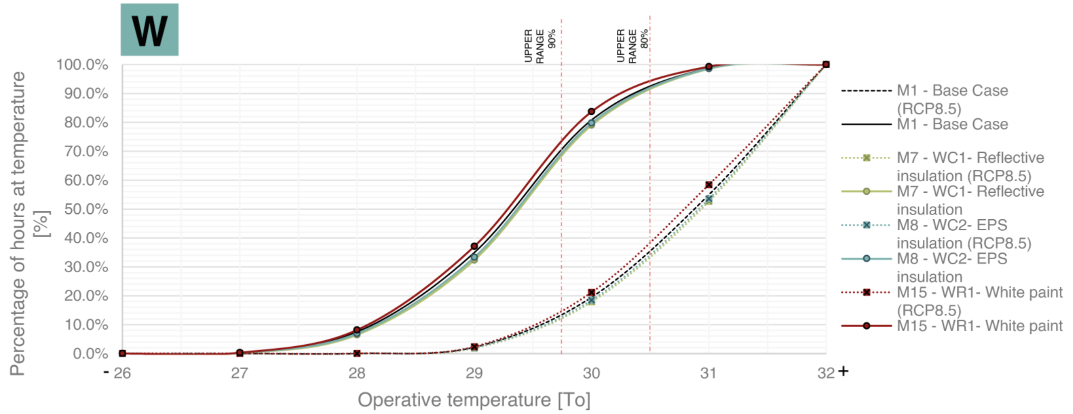
Comfort Range: 23°C - 30°C

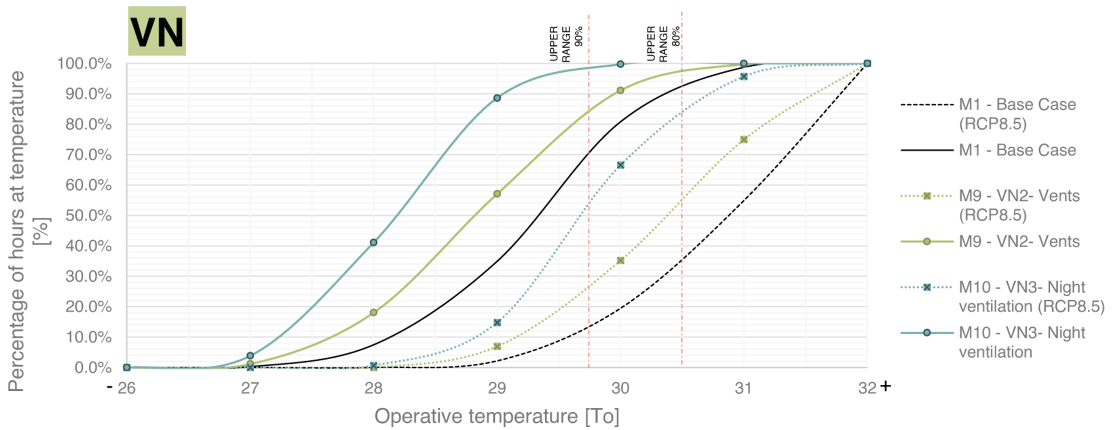
Total Occupation hours/ year: **3650**

		Below 23 °C		Hours		Hours above 30 °C	
		Hours	%	Hours	%	Hours	%
Current scenario	Base	0	0%	1275	35%	2374.75	65%
	WC1	0	0%	1180	32%	2470.5	68%
	WC2	0	0%	1214	33%	2435.75	67%
	WR1	0	0%	1353	37%	2297	63%
	VN1	0	0%	2083	57%	1566.75	43%
	VN2	0	0%	3235	89%	415	11%
	VN3	0	0%	2165	59%	1484.75	41%
Future scenario 2050 - RCP8.5	Base	0	0%	79	2%	3571	98%
	WC1	0	0%	67	2%	3583	98%
	WC2	0	0%	73	2%	3577	98%
	WR1	0	0%	85	2%	3565	98%
	VN1	0	0%	253	7%	3398	93%
	VN2	0	0%	539	15%	3111	85%
	VN3	0	0%	144	4%	3506	96%

● The isolated walls decrease the thermal performance of the space. This could be because the isolation does not allow heat dissipation by conductivity. On the other hand, the reflective wall's performance improvement is minimal, increasing the comfort hours by 2% in the current scenario and 0% in the climate change scenario.

● Natural ventilation systems are the most effective strategies to improve the thermal performance of the space, increasing the time between the range by 54%.





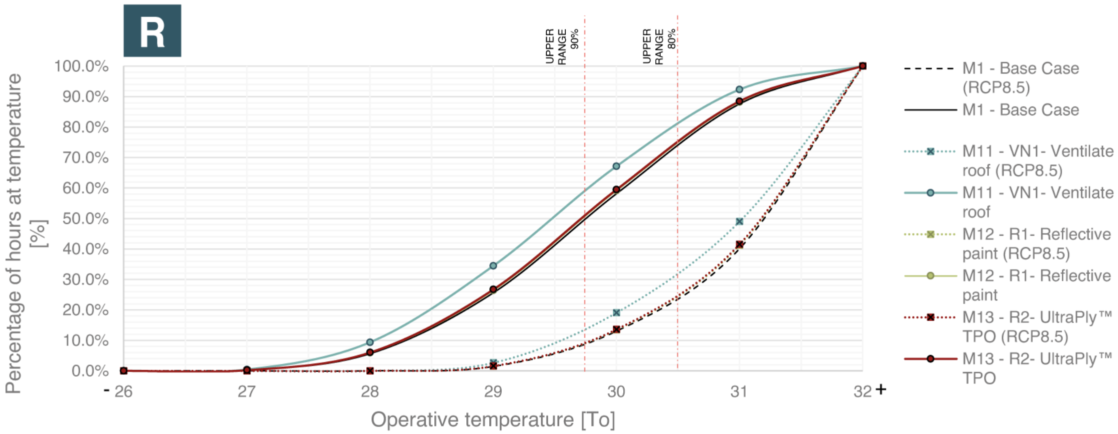
NA-1204

Comfort Range: 23°C - 30°C

LIVING ROOM

Total Occupation hours/ year: **5110**

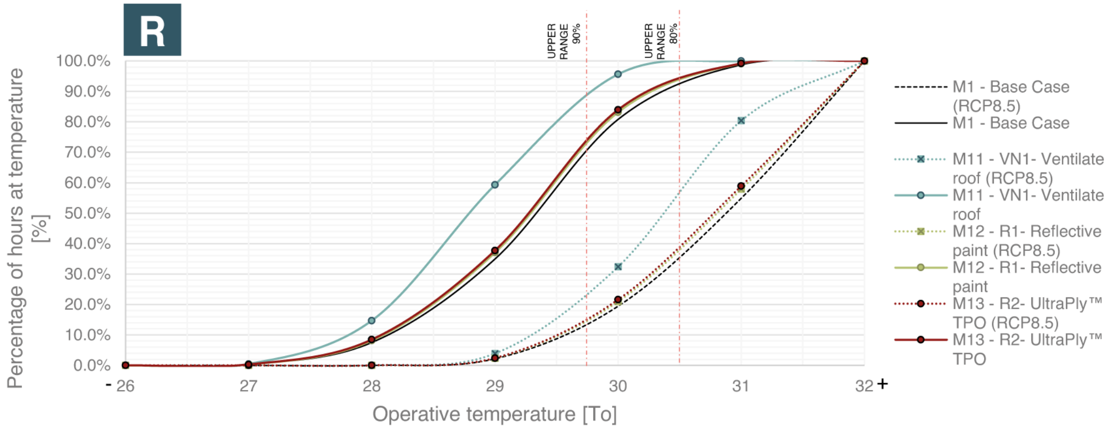
		Below 23 °C		Hours		Hours above 30 °C	
		Hours	%	Hours	%	Hours	%
Current scenario	Base	0	0%	1306	36%	3804	104%
	R1	0	0%	1347	37%	3763.5	103%
	R2	0	0%	1363	37%	3747	103%
Future scenario	Base	0	0%	74	1%	5037	99%
	R1	0	0%	79	2%	5032	98%
	R2	0	0%	80	2%	5030	98%



BEDROOM

Total Occupation hours/ year: **3650**

		Below 23 °C		Hours		Hours above 30 °C	
		Hours	%	Hours	%	Hours	%
Current scenario	Base	0	0%	1275	35%	2374.75	65%
	R1	0	0%	1353	37%	2296.75	63%
	R2	0	0%	1378	38%	2272.5	62%
Future scenario	Base	0	0%	79	2%	3571	98%
	R1	0	0%	86	2%	3564	98%
	R2	0	0%	88	2%	3562	98%



Design options selection

In the **base model (current envelope)**: **(1)** the spaces have an overheating in the current scenario in more than 30% of their hours and more than 91% in the future scenario. **(2)** In both apartments, the space with the highest tendency to overheating is the living room, with overheating in 57% - 74% of the time and more than 95% in the future scenario. **(3)** The top floor has more overheating hours than the apartment on the second floor. The bedroom has around 34% more hours with overheating, and the living room has around 17%. The difference is reduced to 7% and 4% in the climate change scenario.

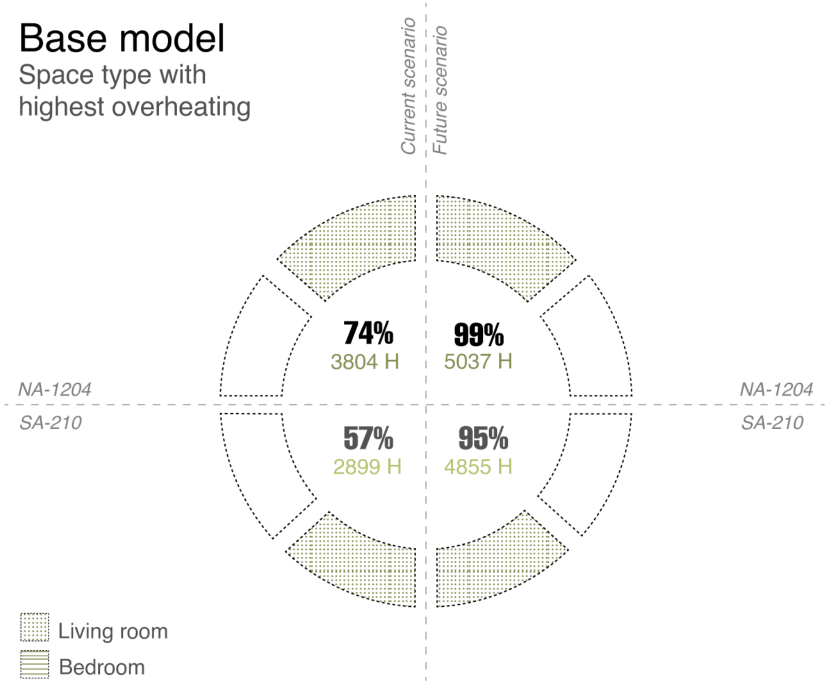


Illustration 21. Base model – spaces overheating. Source: Author's elaboration.

Considering the base model's performance, the conclusions for each group of measures analyzed are summarized below.

(S) Shading: The best design options for shading devices are the S2 – balconies/ overhangs and the S3- folding panels. The reduction of overheating hours is almost the same with both systems in both apartments' spaces, with a minimum reduction of overheating hours of 11% and a maximum of 19% in the current scenario. On the other hand, in the future scenario, the minimum reduction is 2%, and the maximum is 9%.

(G) Glazing: The glazing with good behaviour in both spaces is the G1- Window film, with the best performance in the bedroom area, reducing the hours of overheating between 13% - 17%, a 2% - 9% reduction in the climate change scenario. On the contrary, the performance of both glasses is almost the same in the living room, with a reduction of overheating between 9% - 16% in the current scenario and 1% -3% in the future scenario. Therefore, it is concluded that **the best glazing option for the entire house would be G1 glass** since it provides better thermal behaviour in both spaces of the evaluated apartments.

(W) Walls: Regarding the wall options, the worst performance happened when the walls were isolated (WC1 & WC2), increasing by 1% in the overheating hours. On the other hand, **the WR1- Reflective paint is the design option with the best performance,** decreasing the overheating hours between 1% - 2% in the current scenario. However, in the future scenario, the impact of isolated wall measures (WC1 & WC2) is non-existent. Regarding the WR1 measure, this gives a reduction of the overheating hours of 1% in the spaces of the second-floor apartment; nevertheless, on the top floor, the improvement it non- exist; this could be because, on the top floor, the roof is the more critical envelope element.

(VN) Natural ventilation: The natural ventilation design options are the most effective strategies to improve the thermal comfort in the apartments. **The best option is the VN2- Vents (constant),** which in the current scenario reduces the hours of overheating in all spaces from 9% on the lower floor to 54% on the upper floor, from which it can be inferred that its effect is better at a higher height in the apartment. Further, decrease the overheating hours between 3% - 29% in the future scenario.

(R) Roof: The primary analysis of the roof was made only on the top floor, showing that **the best strategy is the VN1- ventilated roof,** which in the current scenario reduces the overheated hour by 2% in the living room and 22% in the bedroom. The reduction in the climate change scenario is 1% and 5%, respectively. Regarding the roof albedo, it was evident that with an SRI greater or equal to 0.83, the scapes increase their time in comfort by around 1%-2% in the current scenario. Otherwise, in the future scenario, the improvement is non-exist. **The best design option will be the VN1- ventilated roof with a high albedo**.

In short, the best design options to apply in the envelope renovation of tower A of the Perdiz project are: a combination of the balconies/ overhangs (S2) and folding panels (S3) shading systems, the low SHGC window film (G1), the use of reflective paint in walls (WR1), the implementation of vents (VN2), and the use of ventilated roof with high albedo (VN1+R2).

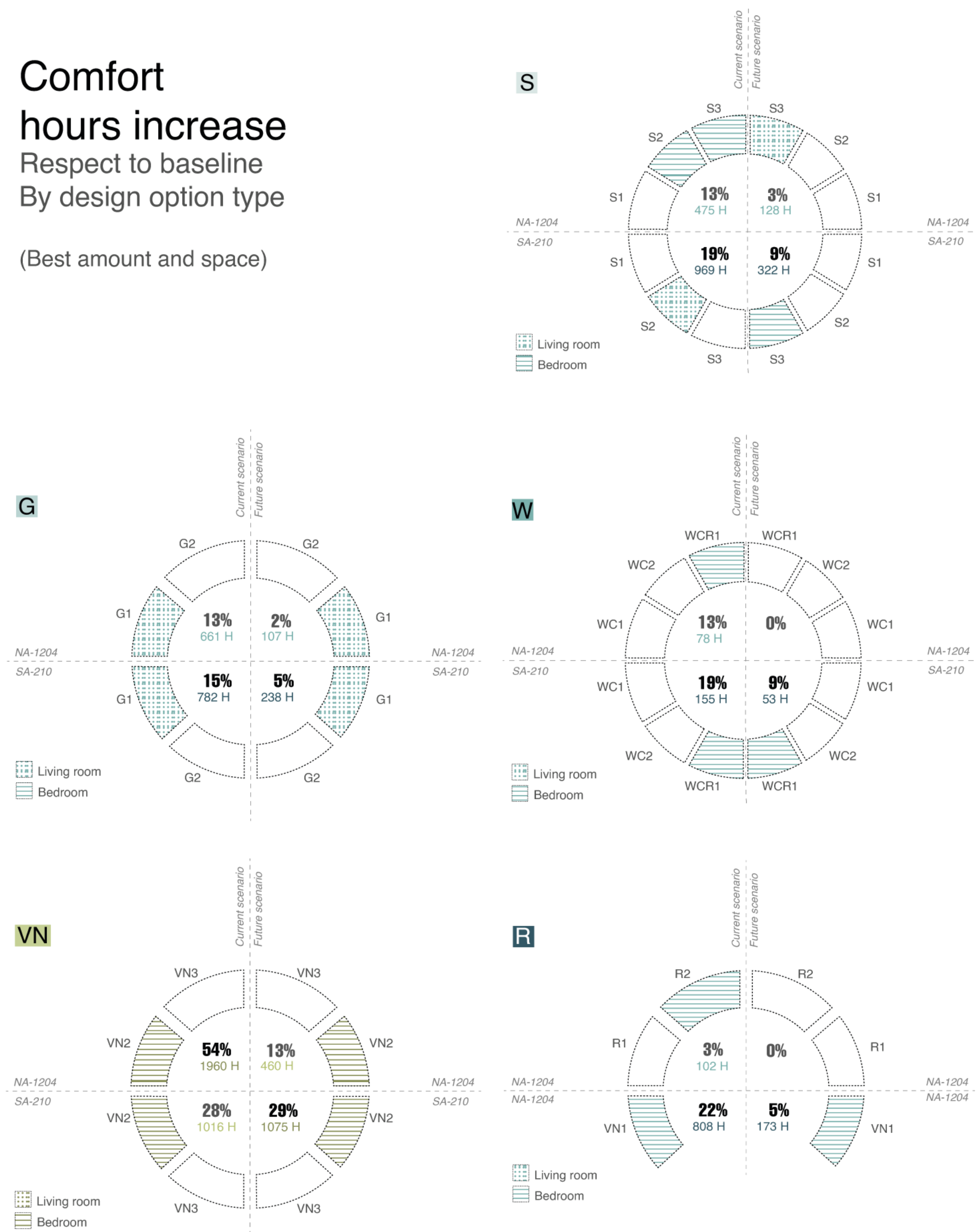
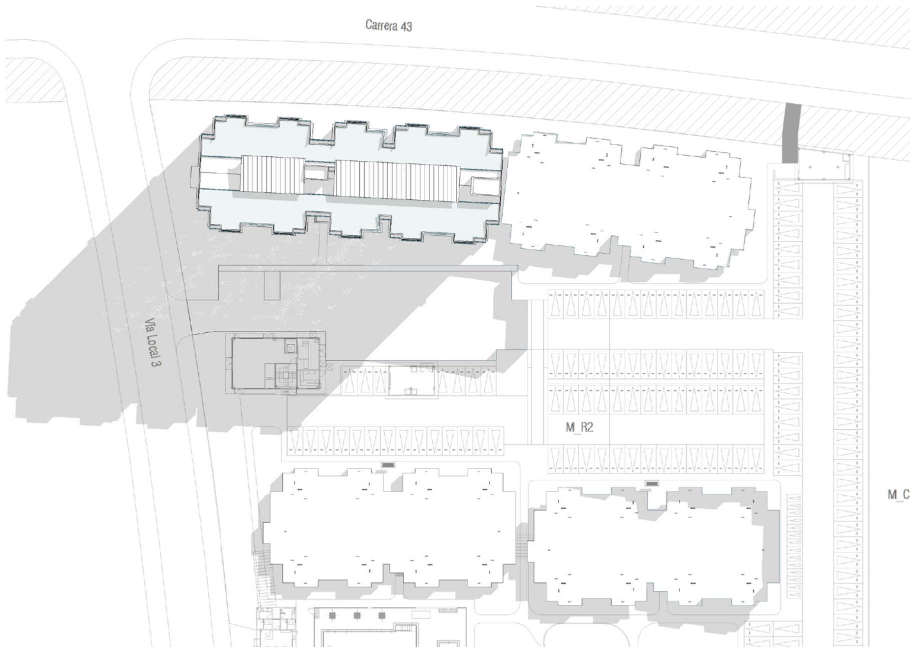


Illustration 22. Comfort hours increase in design options. Source: Author's elaboration.

Renovation approach

The renovation was developed just in the **Tower A**. It is characterised by having both main facades (south & north) exposed to the sun without representative shading produced by the context; hence it is a critical case of the entire housing complex. Besides, it was the focus of analysis in the thermal comfort survey. **The renovation process intends to enhance envelope performance by reducing heat gains and tolerate heat dissipation**, allowing the adaptation of the existing building to the local environmental conditions.



The proposal approaches the design based on the following measures, derived mainly from the cognitive process of Table 12 and the simulation results obtained in the Envelope section.

(1) Heat prevention:
- Operable shading devices in the living room façade; with 50% light permeability.
- Fixed balconies or overhangs with a depth between 0.4m to 1.5m.
- High performance glazing film with SHGC of 0.48.

(2) Heat management:
- High reflectance roof with a minimum solar reflective index (SRI) of 0.83.
- High reflectance wall with a minimum solar reflective index (SRI) of 0.83.
- Provide indirect natural lighting to the living room, even when the windows are open.

(3) Heat dissipation:
- Vents, lattices or openworks that allow continuous ventilation in spaces.
- Ventilate roof.
- Stack ventilation.

Renovation approach

Adaptation is understood as the action or process of adapting or being adapted[1], and it has become a critical element for taking action about future climate vulnerability. The analysis found that it was the immediate need that users look for, and the current building's architecture does not supply. Hence, three adaptation needs related to indoor space thermal performance, and people's indoor thermal comfort were identified: **(1) environmental adaptation**, the reduced building architecture adaptation to usual and extreme environmental events; **(2) cultural adaptation**, the absence of adaptation of vernacular materials and constructive techniques into contemporary architecture; **(3) Indoor-outdoor adaptation**, the deficient adaptation of the building to allow contact with the exterior environment and greenery. These are the three main concepts for the building envelope renovation; their cohesion will provide interior thermal comfort in the dwellings in compliance with the aim of this work.

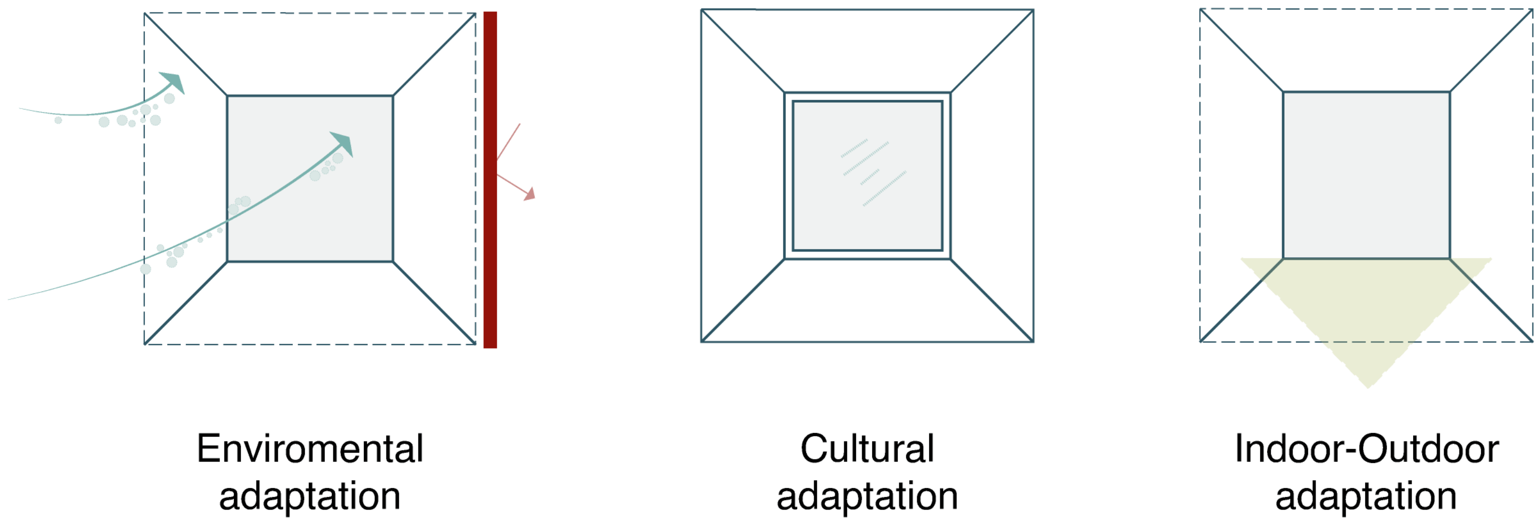


Illustration 23. Design concept. Source: Author's elaboration

1 Cambridge Dictionary.

Description envelope renovation measures

The envelope renovation is based on the previously highlighted approaches (heat prevention, heat management & heat dissipation). Even so, most measures are directed at heat prevention and management due to the Barranquilla climate and high solar incidence, which makes limiting or eliminating heat gains substantially essential. On the other hand, the difference in outdoor air temperature between day (7:00 - 19:00) and night (20:00 - 06:00) is approximately 6°C, so night ventilation is a relevant variable for thermal performance improvement. The bioclimatic proposal to optimise the VIS Perdiz project envelope is described below.

1. Operable shading devices:
A guadua mobile shading panel with 50% light permeability was selected to shade the living room glazing door. It is placed in front of the french balcony railing to protect the living room area. Along the guadua is a hygroscopic material which can absorb vapour water. Therefore, the exterior air could enter the space with less moisture improving the thermal sensation.

2. Overhangs:
The previous façade was characterized for the absence of horizontal shading elements letting the solar radiation go in and overheat the spaces. In the tropics, the horizontal shading is fundamental due to the sun's elevation angle, which is almost always closer to 60°. To counter the current overheating, a fixed overhang is implemented over the 4, 8 and 12-floor windows. The overhang will be in aluminium with a colourful finish remembering the colourful Barranquilla traditional architecture. Additionally, an aluminium plant pot over the overhang Is placed; its dimensions are 0.4m high and 0.3m wide.

3. Window box:
Following the previous statement, the traditional wood window box was reinterpreted. An aluminium overhang of 0.55m width was located over and below the secondary bedrooms' window. On the vertical side of the same window, an aluminium sidefin of 0.55m width was located, generating a closed box, "The window box". Furthermore, the box gives shade to the window in the story immediately down.

4. Opaque envelope optimization:
The opaque envelope optimization is divided into two main strategies. The first one is the implementation of a **ventilated roof that will dissipate the heat**, mainly for the dwellings on the top floor. This roof will have a white finish with an SRI greater or equal to 83%.

On the other hand, regarding the vertical envelope (exterior walls) in the west façade of tower A, a reflection coating will be applied to decrease the gains related to solar incidence.

5. High performance glazing:
The original windows of the building were kept, and their performance was improved through a window film with an SHGC of 0.48. Thereby, the heat gains from solar radiation are reduced.

Design process

CURRENTLY
FACADE STAGE

ADAPTATIVE
FACADE

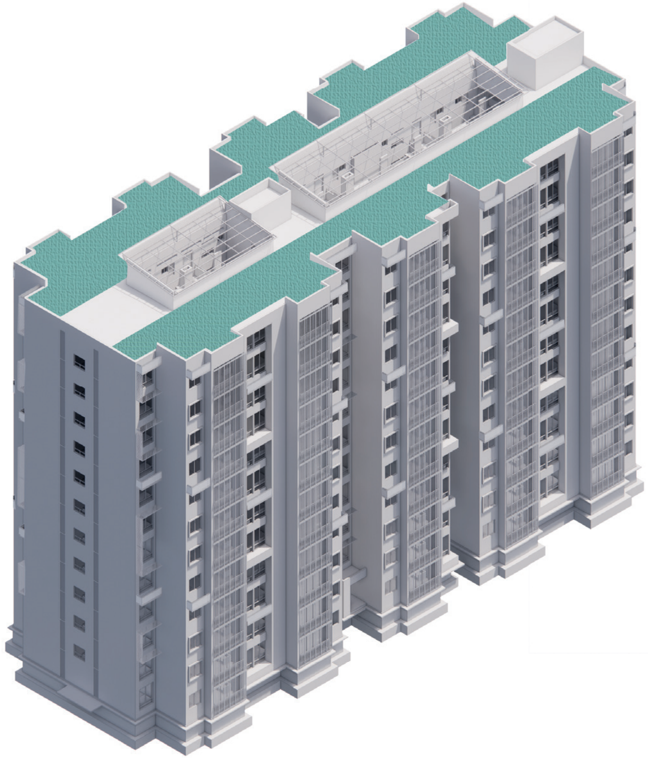
Implementing movable shading in the living room provides indirect natural light and sun protection. This is the space with the most significant window area.

FIXED
OVERHANGS

Implementation of fixed horizontal over-hangs, shading the flexible space window and the bedroom window. Besides the creation of vertical green areas.

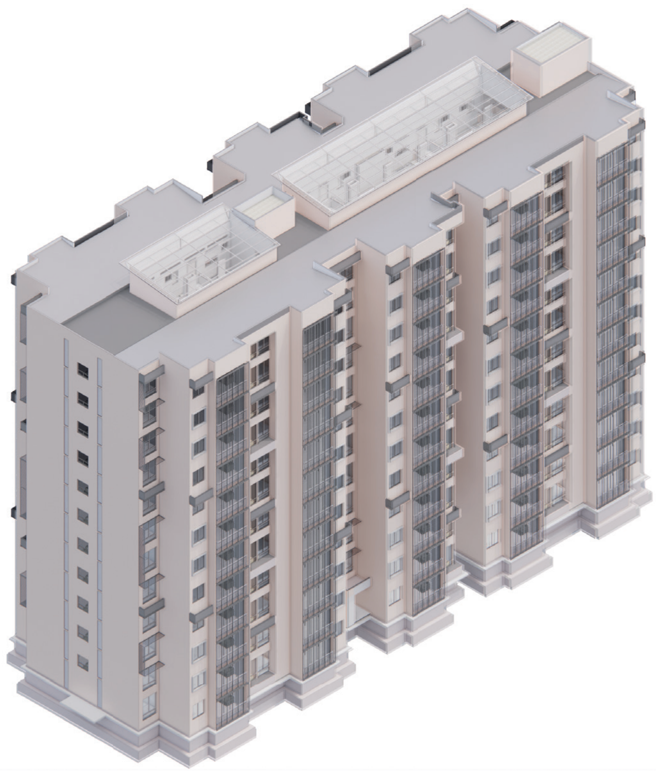
WINDOW BOX

Reinterpretation of vernacular window box. To provide shade in the bedroom area.



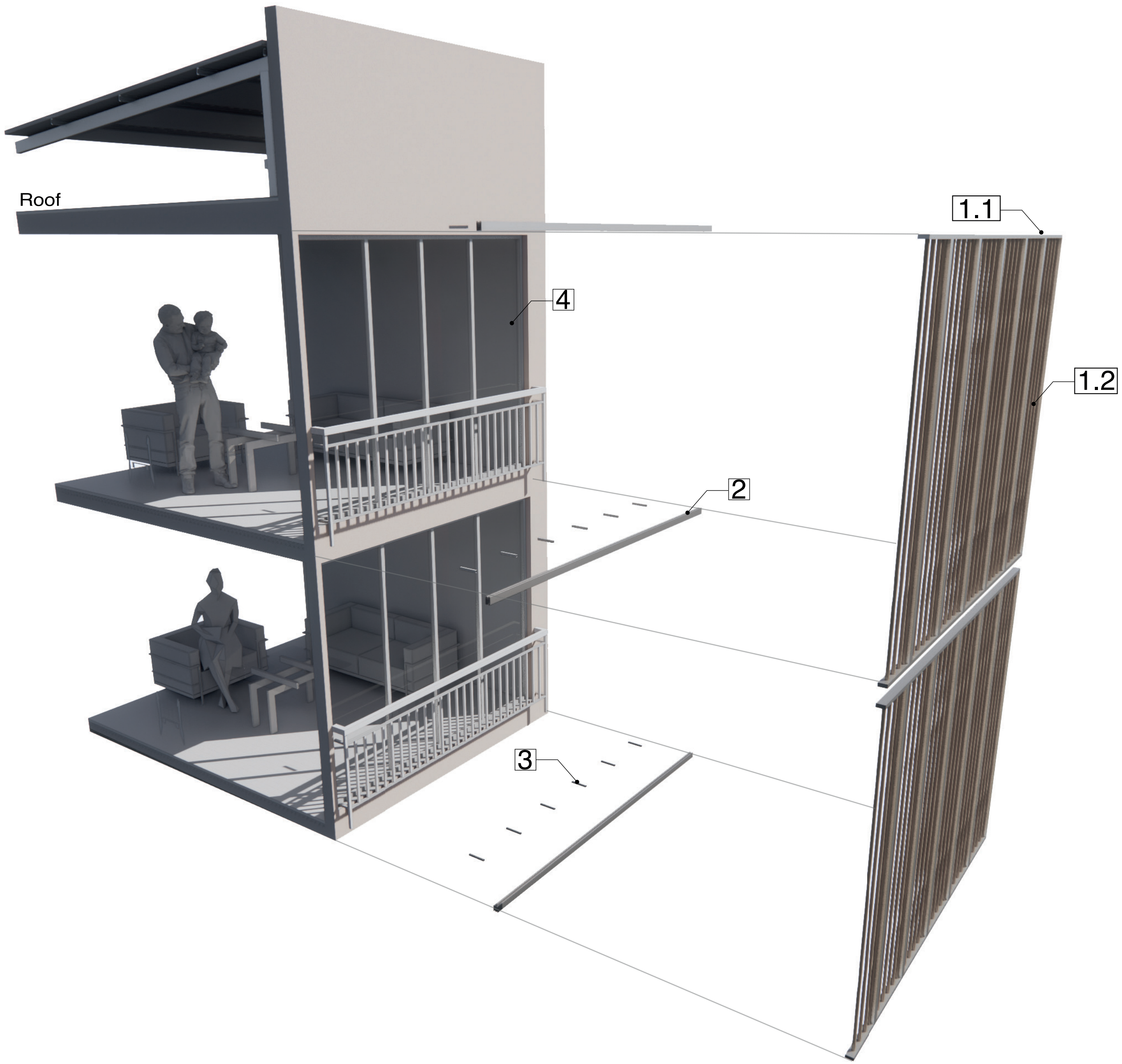
VENTILATED ROOF

The optimization of the ventilated roof allows for reducing heat gains on the upper floors and optimizing the natural ventilation system.



FINAL ENVELOPE OPTIMIZATION

Renovation measures assembly



1 Guadua Folding Panel

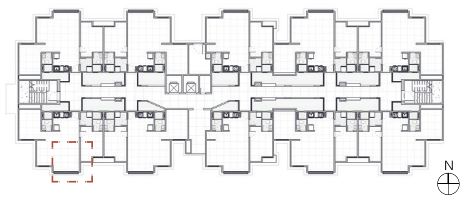
1.1 Marco metalico w - 4cm

1.2 Bamboo poles diameter 4 cm

2 Metal rail

3 Square hollow profiles anchored to the concrete structural slab

4 Glazing with internal film that provide of SHGC 0.48.



(1) Mobile shading assembly

PROPOSAL

Guadua folding panel

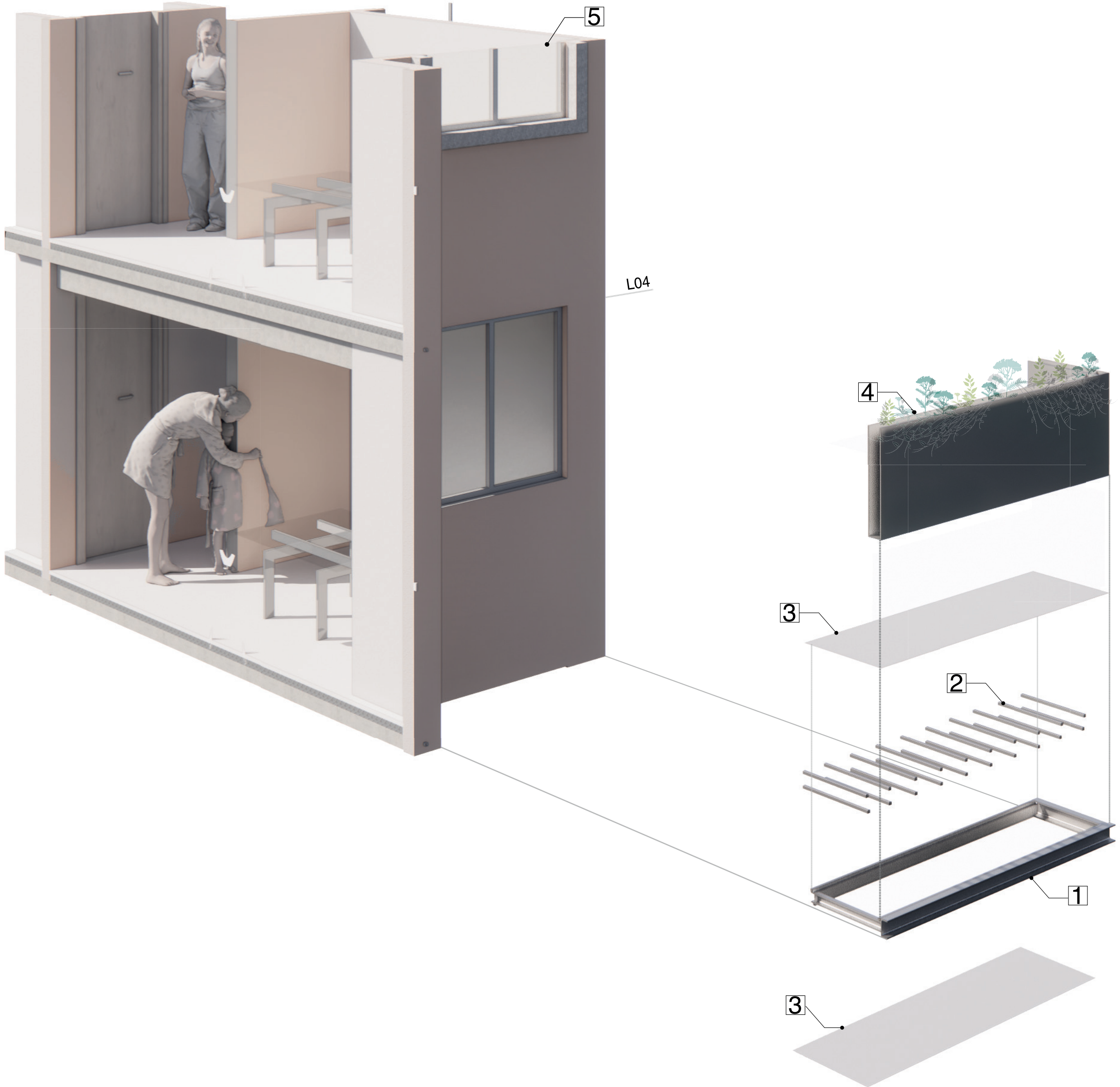
1 Perimetral C beam attached to the concrete slab

2 Hollow Square Profile Joists

3 Perforated sheet

4 Aluminium plant pot

5 Glazing with internal film that provide of SHGC 0.48.



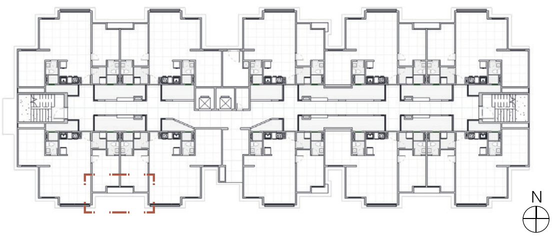
(2) Overhangs assembly
PROPOSAL

Metalic overhang with plant pot

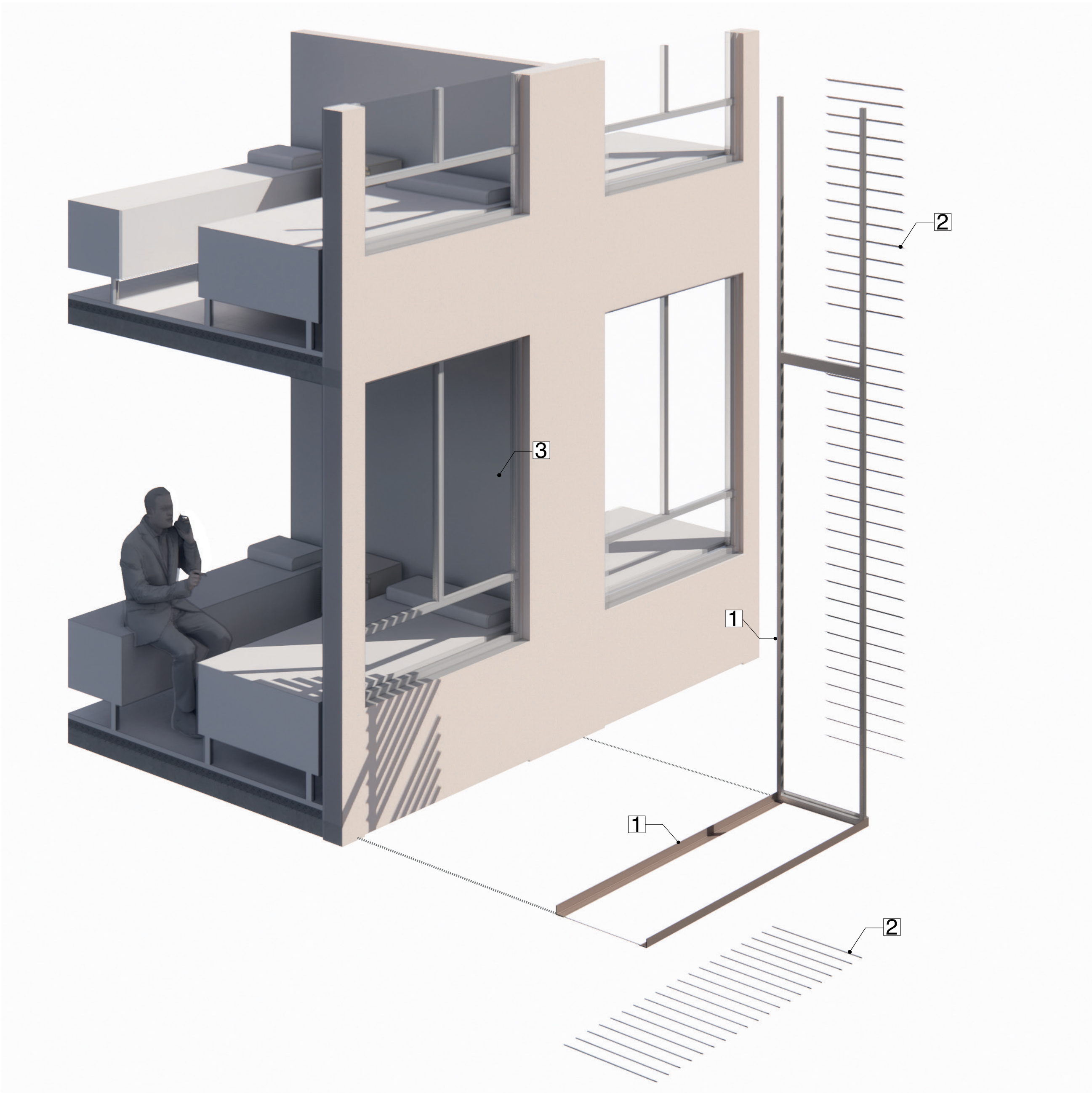
1 Perimetral L profiles attached to the concrete slab and wall

2 Hollow rectangular louvres attached to the L structure at 45° inclination

3 Glazing with internal film that provide of SHGC 0.48.



(3) Window box
PROPOSAL
Metalical louvre overhangs & sidefins

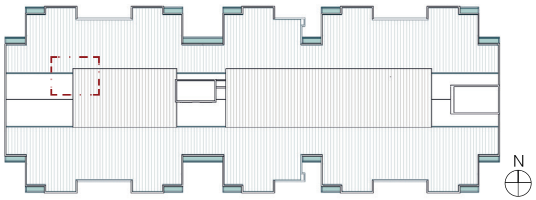


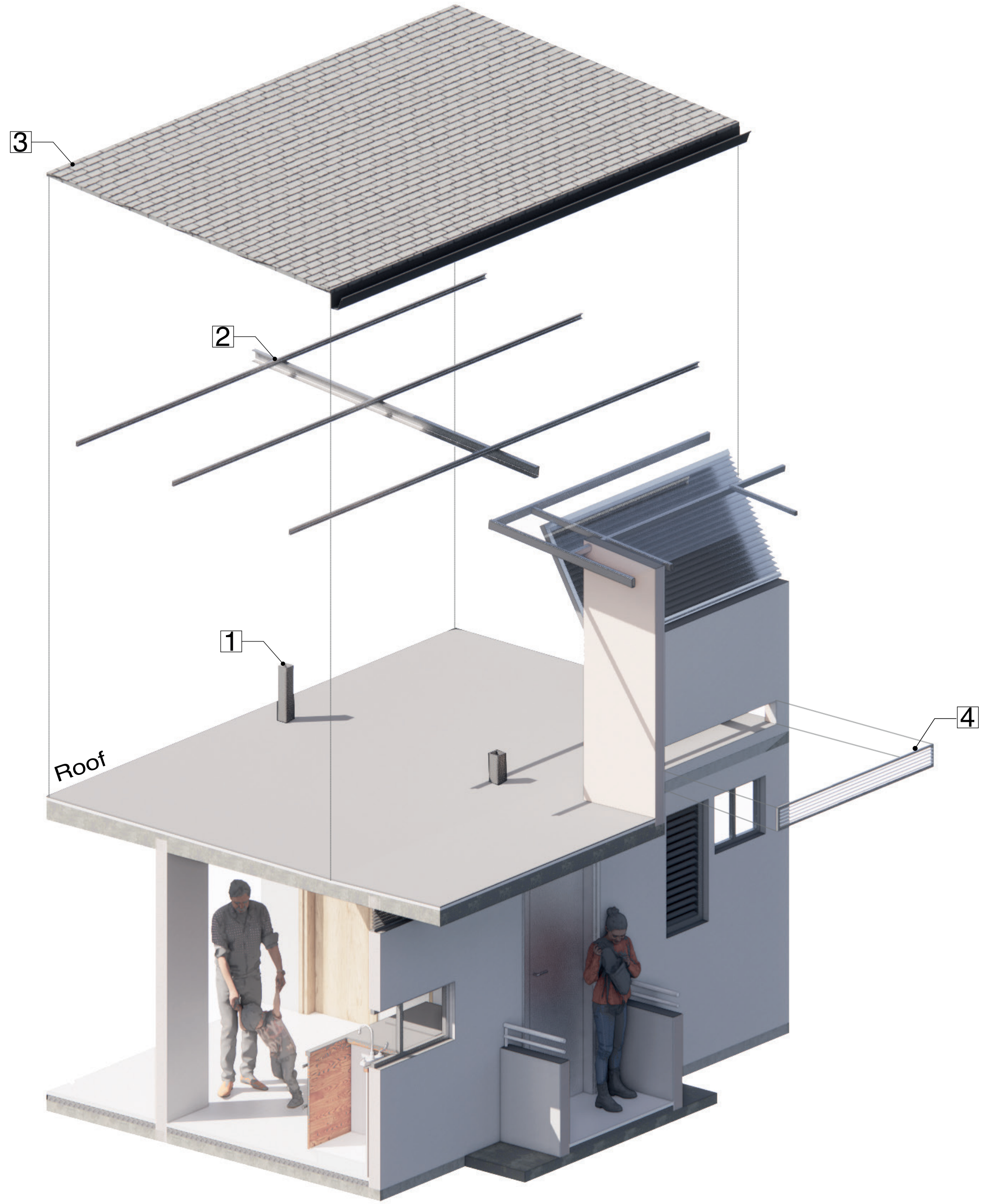
1 Metalic square hollow column

2 Ventilated roof structure with C profiles

3 White & aluminium thermo-acoustic roof

4 Vent that connects the ventilated roof with the stack hole—increasing the air flow.





(4) Opaque envelope optimization

PROPOSAL

Ventilated white aluminium roof

SOUTH FACADE

CURRENT Esc. 1:200

SOUTH FACADE

PROPOSAL Esc. 1:200

Proposal - Horizontal Overhangs

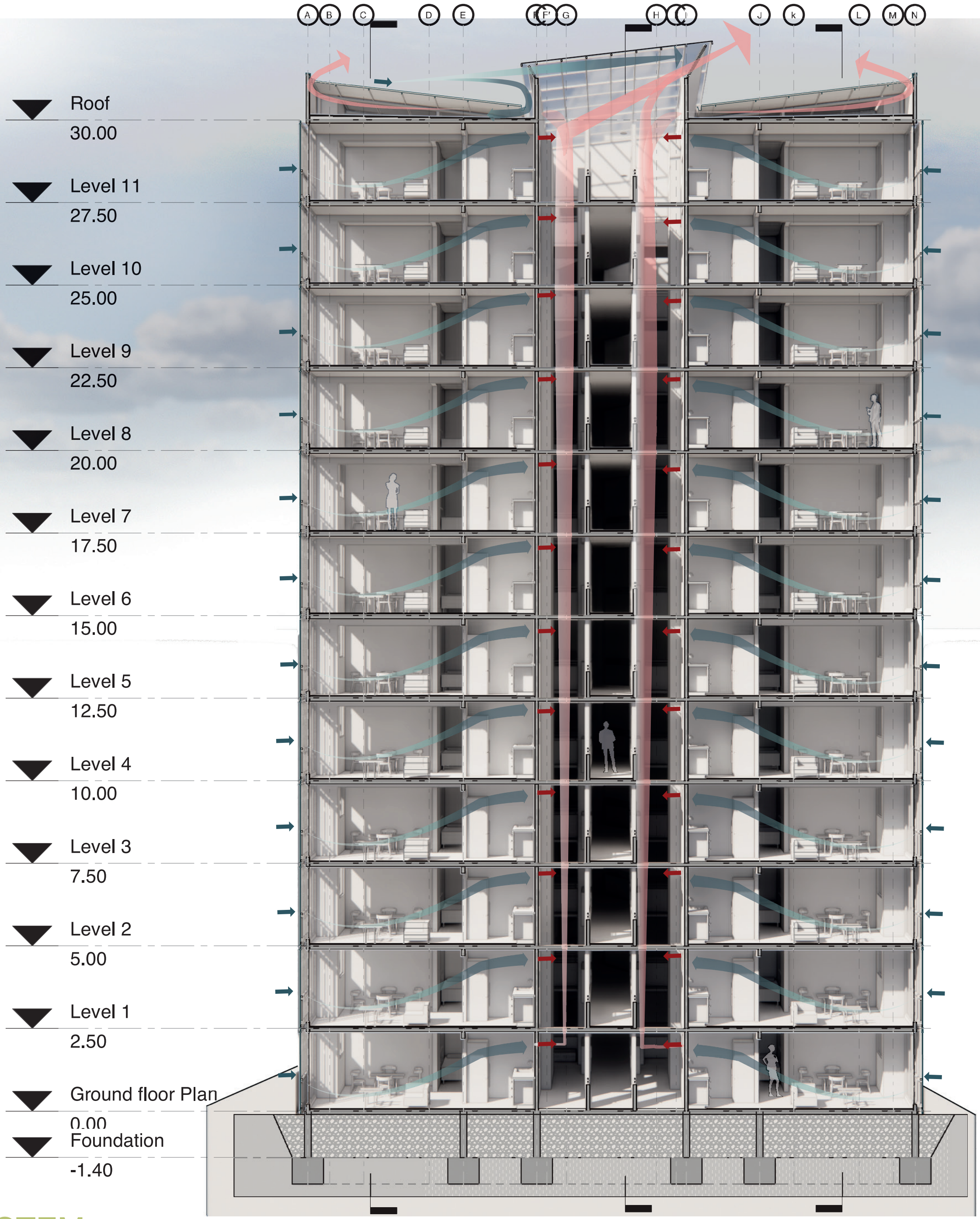
Proposal - Mobile shading

NORTH FACADE

CURRENT Esc. 1:200

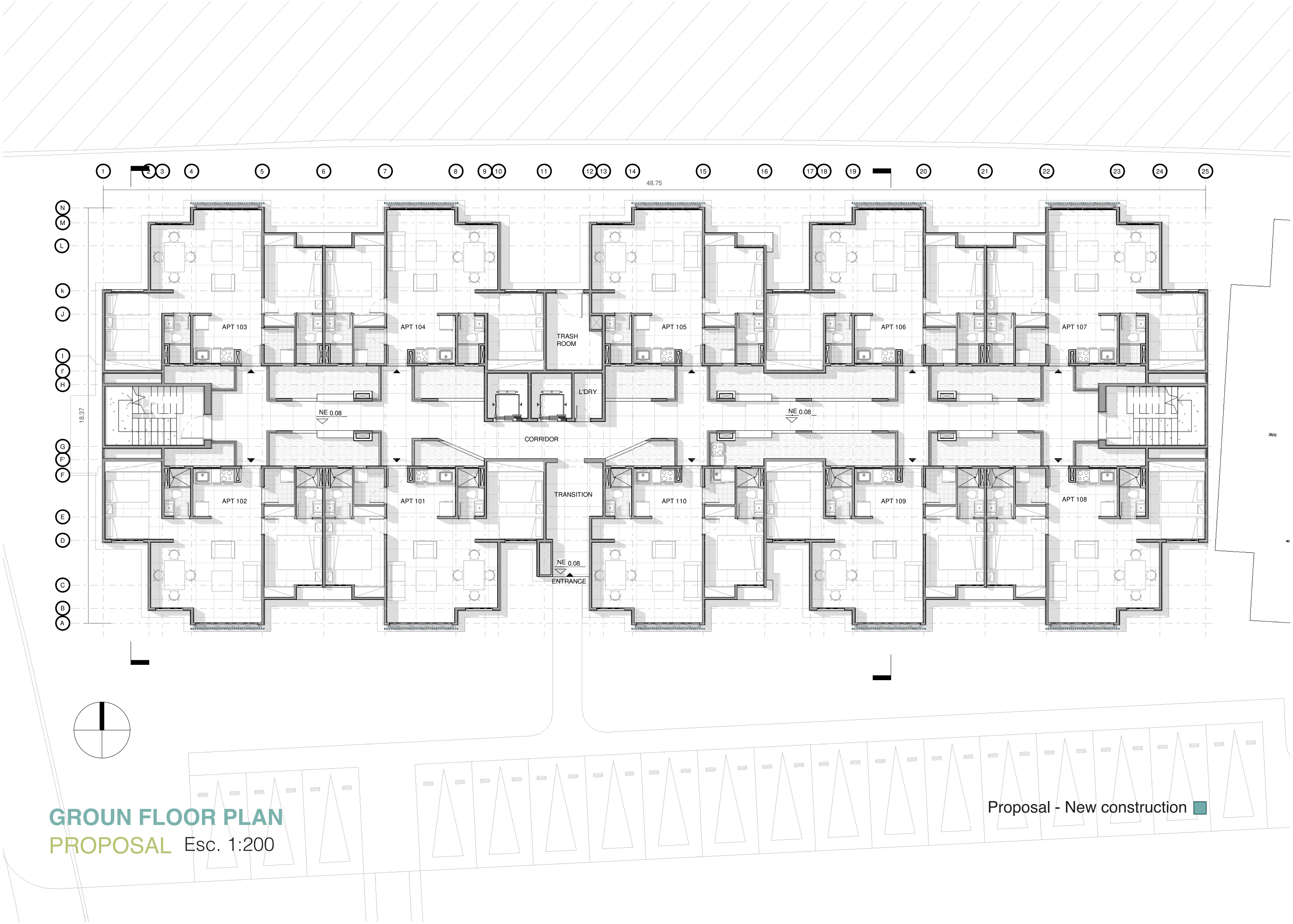
SOUTH FACADE

PROPOSAL Esc. 1:200



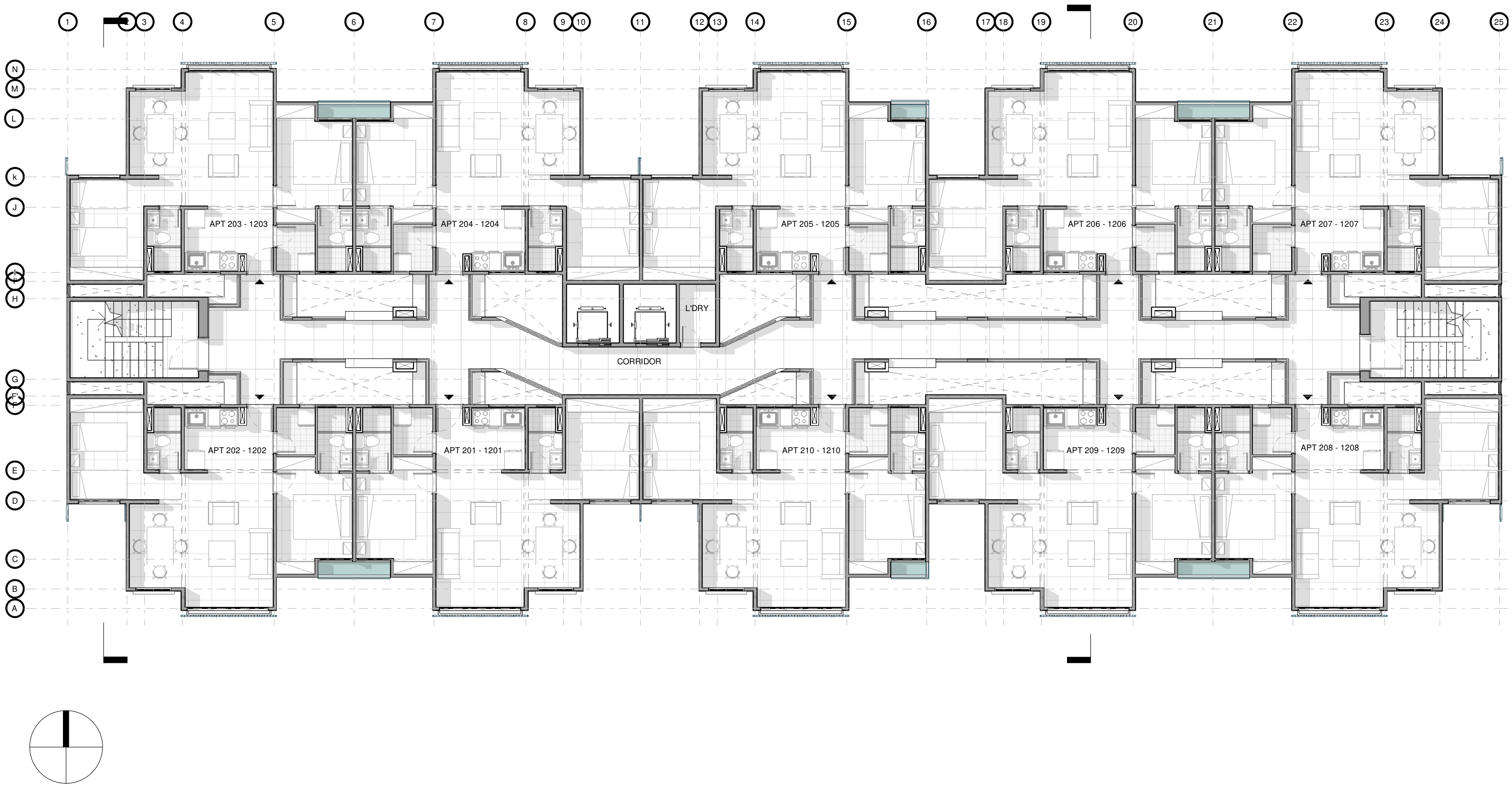
SECTION A-A'
VENTILATION SYSTEM

Esc. 1:200



GROUN FLOOR PLAN

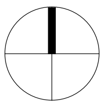
PROPOSAL Esc. 1:200



Proposal - New construction

FLOOR PLAN - TYPE 01

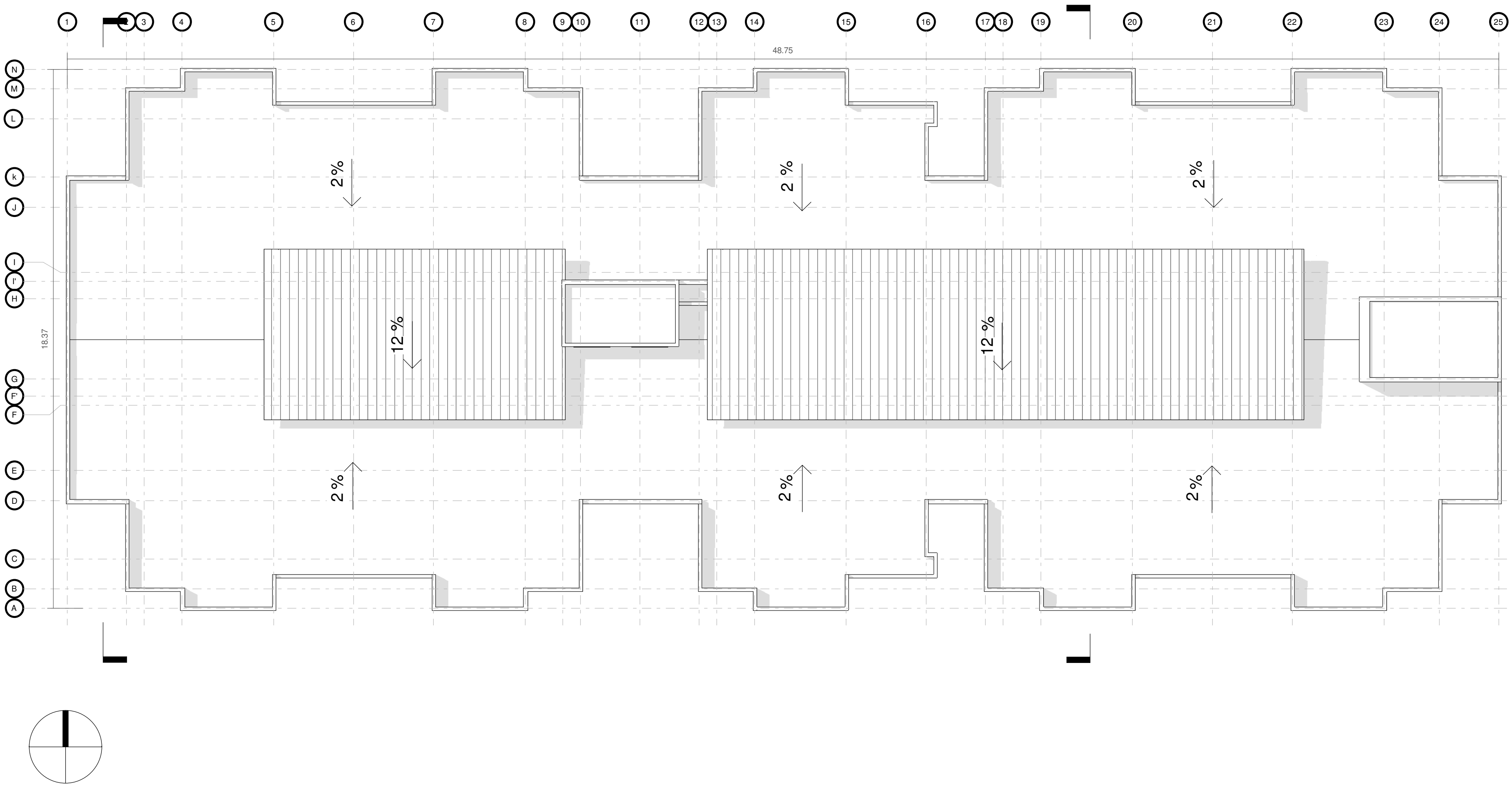
PROPOSAL Esc. 1:200



FLOOR PLAN - TYPE 02

PROPOSAL Esc. 1:200

Proposal - New construction

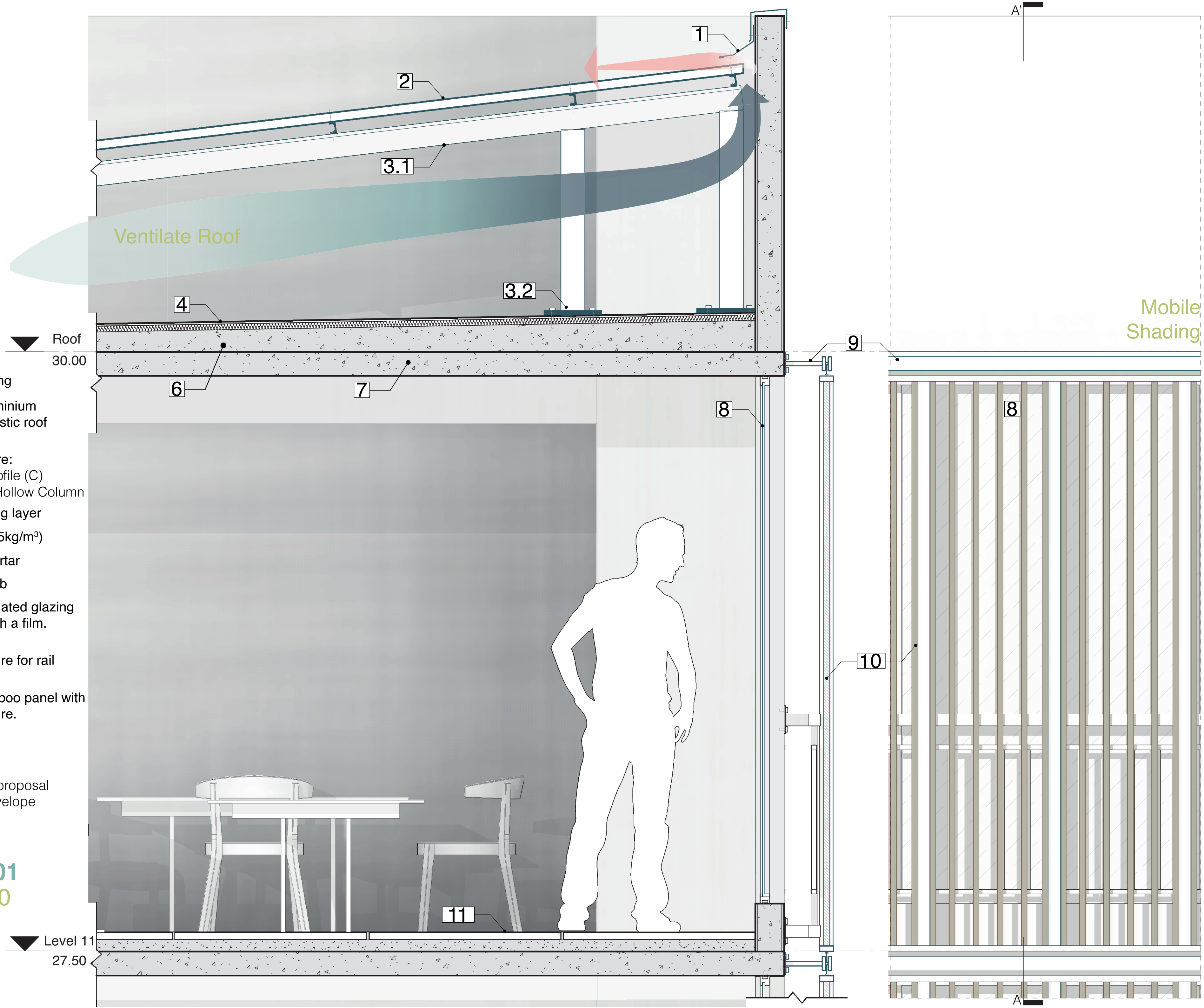


ROOF PLAN

CURRENT Esc. 1:200

Proposal - New construction

ROOF PLAN
PROPOSAL Esc. 1:200



1 Metal Flashing

2 White & aluminium thermo-acoustic roof
SRI 0.91

3 Roof structure:
3.1 Metal profile (C)
3.2 Square Hollow Column

4 Waterproofing layer

5 EPS E=1' (15kg/m³)

6 Levelling mortar

7 Concrete slab

8 Simple laminated glazing improved with a film.
SRI 0.48

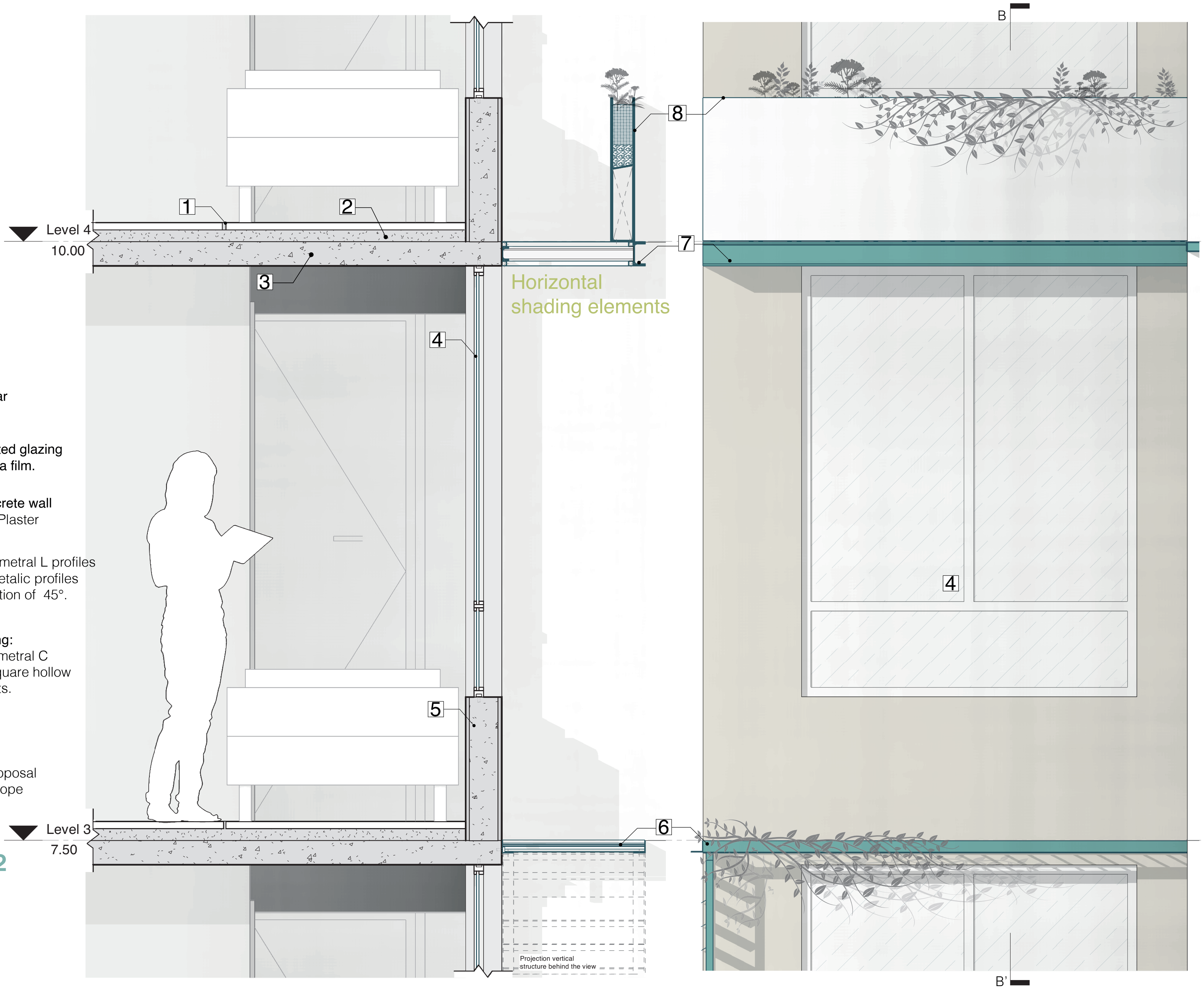
9 Metal structure for rail anchorage.

10 Folding bamboo panel with metal structure.

11 Ceramic tile

— Renovation proposal
— Previous envelope

DETAIL 01
ESC. 1:20



1 Ceramic tile

2 Levelling mortar

3 Concrete slab

4 Simple laminated glazing
improved with a film.
SRI 0.48

5 Structural concrete wall
10cm width + Plaster

6 Window box:
Structure: Perimetral L profiles
Overhangs: Metalic profiles
with an inclination of 45°.
Depth: 60cm

7 Green overhang:
Structure: Perimetral C
Profiles with square hollow
profiles as joists.
Depth: 60cm

8 Plan Pot

— Renovation proposal
— Previous envelope

DETAIL 02
ESC. 1:20

Proposal: Implementation phases

A construction process for the facade renewal is suggested in this section; the process has been divided into six steps.

1. INTERVENTION PLANNING

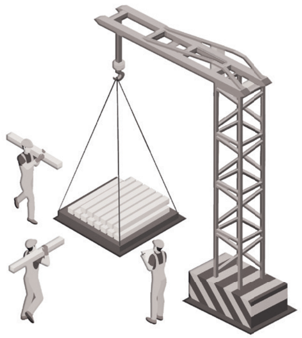
Delimitation of intervention order in 3 stages:

1. South facade: Because it is the most exposed facade.

2. North facade:
Because it is the least exposed façade and is oriented towards the interior of the residential complex.

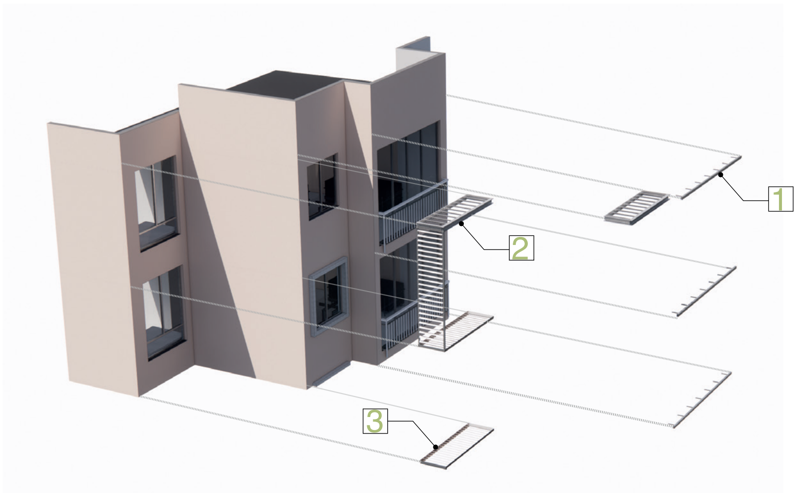
3. Roof:
More straightforward intervention and owners are less disturbed

Carry out interventions on the façade from top to bottom.



2. SCALFFOLDING SET UP

Use a certificated scaffolding structure and install the mandatory boundaries to avoid incidents.



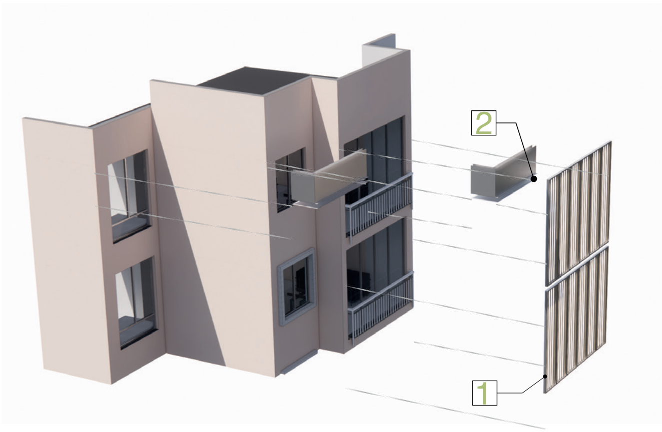
3. SHADING SYSTEMS STRUCTURE

Install the shade systems structure in the following order:

(1) Folding shading rails

(2) Aluminium overhangs structure

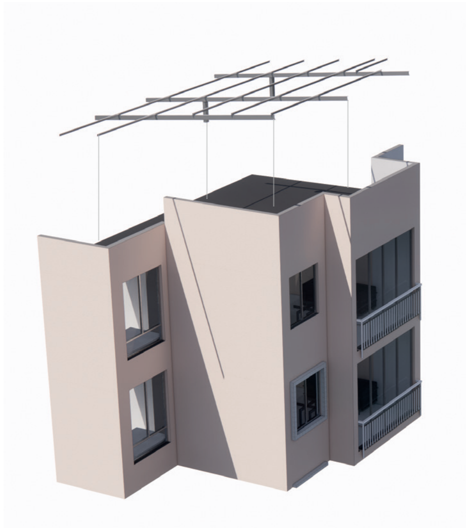
(3) Window boxes - aluminum panels



4. SHADING SYSTEM FINISHES

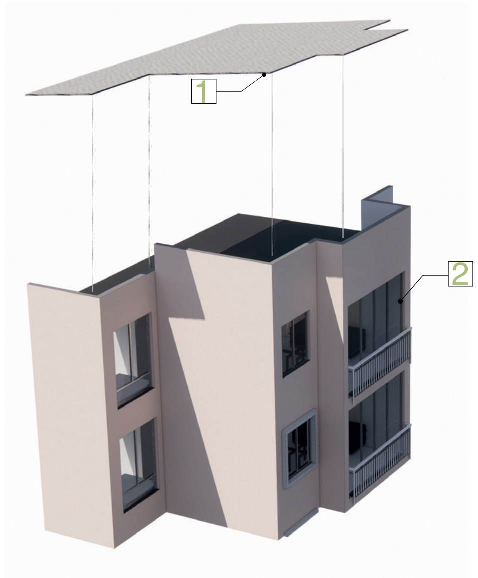
(1) Place the guadua folding panels.

(2) Place the stratum and plants on the overhang pots.



5. ROOF STRUCTURE

Clean the roof surface and install de ventilate roof structure.



6. ROOF FINISHING AND WINDOW FILM

(1) Place the roof finish

(2) Simultaneously, a designated crew places the films on each home's the inside side of the glass.

Final proposal evaluation

This section aims to check the renovation proposal's effectiveness in improving the dwellings' thermal performance. Therefore, as in the design options analysis, the annual operative temperature (To) and its behaviour concerning the comfort range are compared between the calibrated model with the house's current conditions and the model with the envelope renovation. This way, it could be identified if there is some enhancement in the space behaviour. The analysis is performed in the tower "A" apartments analysed in the Thermal comfort survey; target the following natural ventilate apartments: NA-507, SA-210, SA-608, SA-510, SA-108 & NA - 1204.

Model input data

Geometry

Illustration 24. axonometry of proposal building geometry. Source: Author's elaboration

- Climate data: Both scenarios were evaluated, the current scenario with the IDEAM et al. (2019) climate data of Barranquilla and the climate change scenario for 2050 RCP8.5 with the climate data modified following the morphing procedure.
- Simulation running time: 1-year period.
- Evaluate thermal zones: Main bedroom and Living room.
- Envelope: the building's base model opaque and transparent envelope was already described in Chapter 4:. For the proposed model, these are the main envelope changes:

  - Roof: Ventilated roof
  - Glass: window film with SHGC of 0.48
  - Shading:
  Folding panels with 50% of light permeability
  Horizontal Overhangs of 0.6 m

- Schedule: The dwellings schedule is variable. Generally, **the apartment is occupied for 24 hours**, but the schedule in each zone varies depending on the behaviour of each dweller
- System and load: The simulation is run with natural ventilation and the building stack system.
- Occupation: Each house occupation follows the dweller's behaviour.
- ASHRAE 55 Comfort range: Acceptability of 90% - 24.0°C to 29.0°C, and acceptability of 80% - 23.0°C to 30.0°C.

Thermal evaluation of the proposal

NA-507

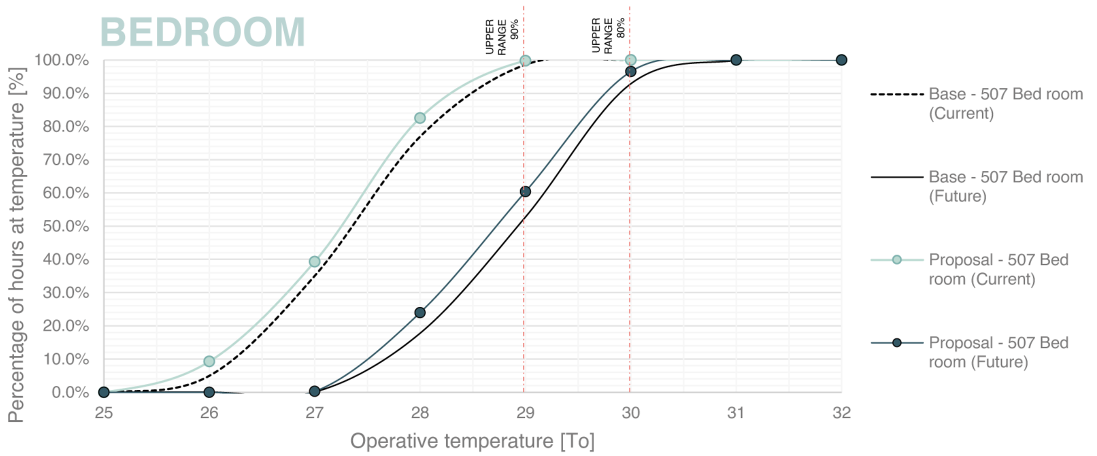
Comfort Range: 23°C - 30°C

Bedroom total Occupation hours/ year: **3650**

Living room total Occupation hours/ year: **5110**

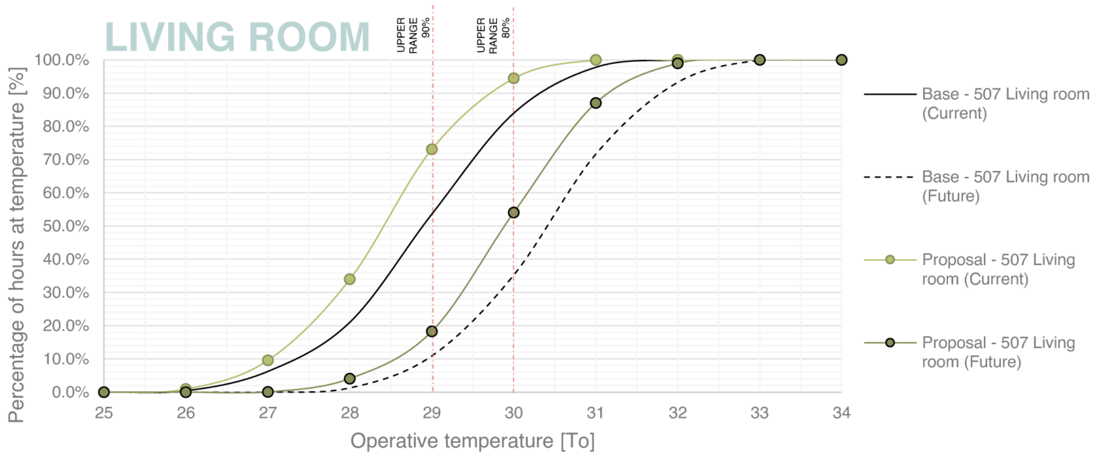
			Below 23 °C		Between		Above 30	
			Hours	%	Hours	%	Hours	%
Bedroom	**Current scenario**	Base	0	0%	3597	99%	53	1%
		Proposed	0	0%	3643	100%	7	0%
	Future scenario	Base	0	0%	1923	53%	1727	47%
		Proposed	0	0%	2203	60%	1447	40%

The room in the proposed case manages to reduce the hours of overheating by 1%, which allows around 100% of the occupied hours to be within the comfort range in the current scenario. A reduction of approximately 13% in overheating hours is presented for the future scenario.



			Below 23 °C		Between		Above 30	
			Hours	%	Hours	%	Hours	%
Living room	**Current scenario**	Base	0	0%	2737	54%	2373	46%
		Proposed	0	0%	3735	73%	1375	27%
	Future scenario	Base	0	0%	556	11%	4554	89%
		Proposed	0	0%	934	18%	4176	82%

Unlike the bedroom, in the proposed case, the living room goes from having 46% overheating hours to 27% in the current scenario. However, the proposal maintains the space at comfortable temperatures for 73% of the hours occupied. Reducing hours out of range in the future scenario corresponds to 7%.



SA-210

Comfort Range: 23°C - 30°C

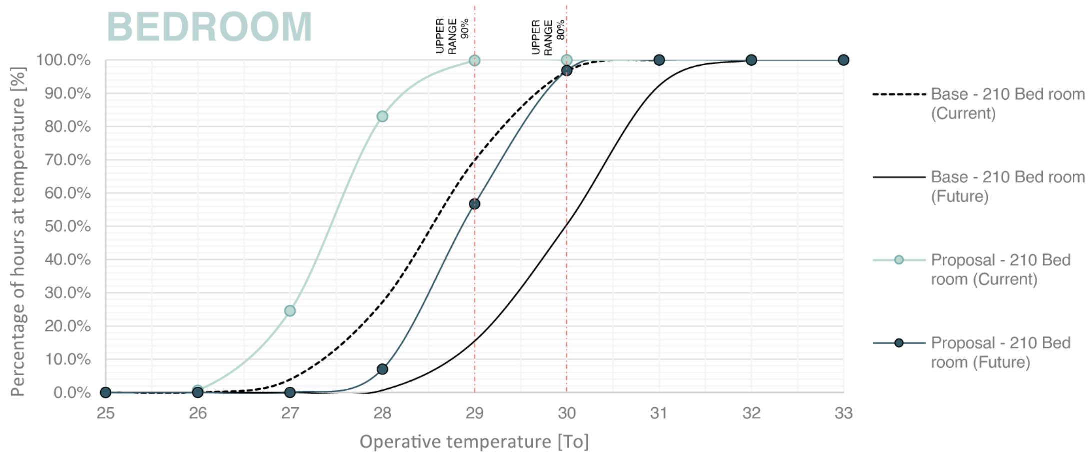
Bedroom total Occupation hours/ year: **3650**

Living room total Occupation hours/ year: **5110**

Bedroom

		Below 23 °C		Between		Above 30	
		Hours	%	Hours	%	Hours	%
Current scenario	Base	0	0%	2550	70%	1100	30%
	Proposed	0	0%	3646	100%	4	0%
Future scenario	Base	0	0%	565	15%	3085	85%
	Proposed	0	0%	2070	57%	1580	43%

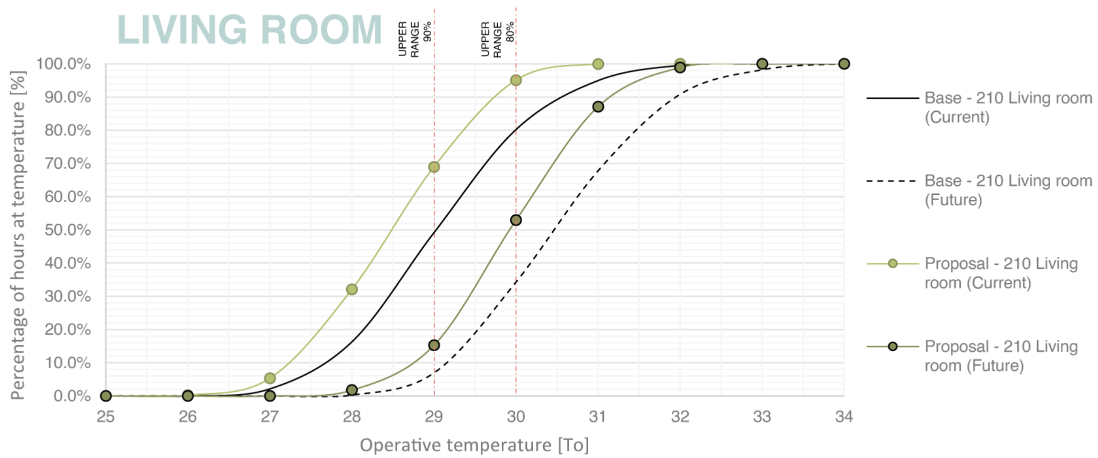
The bedroom goes from having 30% of its hours occupied in overheating to presenting a percentage that is less than zero in the proposed case. The reduction is also evident in the future scenario going from 85% to 43%, reducing almost half the time.



Living room

		Below 23 °C		Between		Above 30	
		Hours	%	Hours	%	Hours	%
Current scenario	Base	0	0%	2513	49%	2597	51%
	Proposed	0	0%	3524	69%	1587	31%
Future scenario	Base	0	0%	354	7%	4757	93%
	Proposed	0	0%	780	15%	4330	85%

The living room also presents better thermal performance. Although the reduction in hours of overheating in this space is less significant than in the bedroom, the space goes from having 51% to 31% of its occupied hours outside the comfort range. This reduction is only 8% of hours in the future scenario.



SA-608

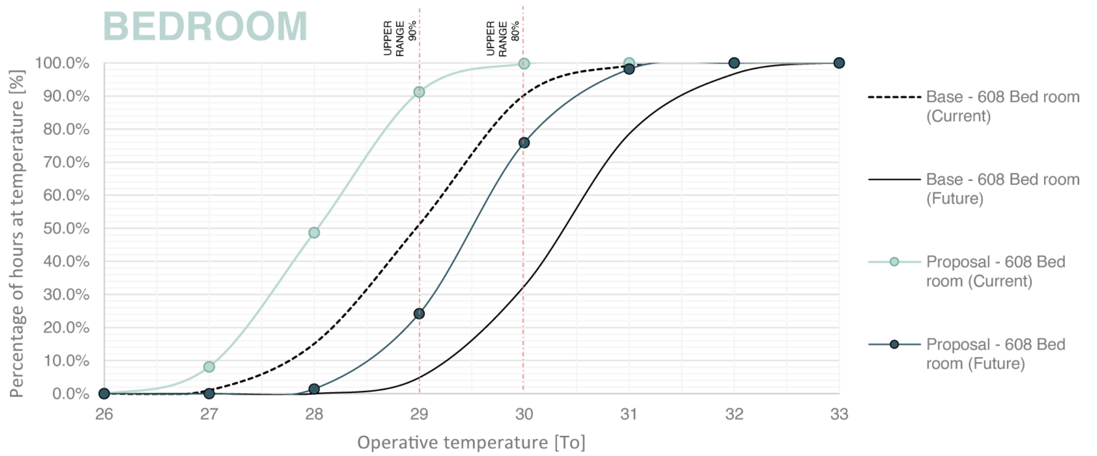
Comfort Range: 23°C - 30°C

Bedroom total Occupation hours/ year: **3650**

Living room total Occupation hours/ year: **5110**

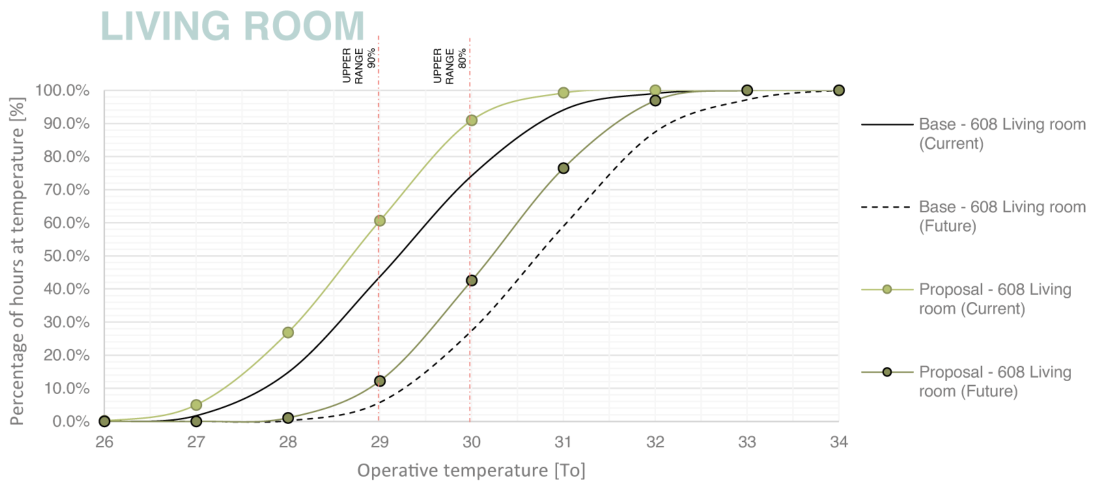
			Below 23 °C		Between		Above 30	
			Hours	%	Hours	%	Hours	%
Bedroom	**Current scenario**	Base	0	0%	1865	51%	1785	49%
		Proposed	0	0%	3330	91%	320	9%
	Future scenario	Base	0	0%	177	5%	3473	95%
		Proposed	0	0%	883	24%	2767	76%

The room in the proposed case manages to reduce the hours of overheating by 40%, which allows 91% of the occupied hours to be within the comfort range in the current scenario. A reduction of approximately 19% in overheating hours is presented for the future scenario.



			Below 23 °C		Between		Above 30	
			Hours	%	Hours	%	Hours	%
Living room	**Current scenario**	Base	0	0%	2234	44%	2877	56%
		Proposed	0	0%	3096	61%	2015	39%
	Future scenario	Base	0	0%	290	6%	4821	94%
		Proposed	0	0%	623	12%	4487	88%

The living room also presents better thermal performance. Although the reduction in hours of overheating in this space is less significant than in the bedroom, the space goes from having 56% to 39% of its occupied hours outside the comfort range. This reduction is only 6% of hours in the future scenario.



SA-510

Comfort Range: 23°C - 30°C

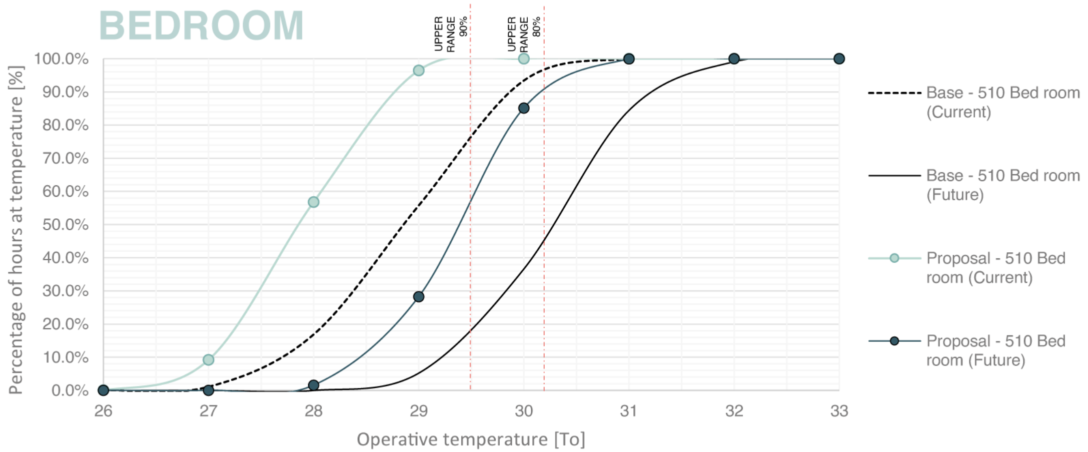
Bedroom total Occupation hours/ year: **3650**

Living room total Occupation hours/ year: **5110**

Bedroom

		Below 23 °C		Between		Above 30	
		Hours	%	Hours	%	Hours	%
Current scenario	Base	0	0%	2034	56%	1616	44%
	Proposed	0	0%	3521	96%	129	4%
Future scenario	Base	0	0%	191	5%	3459	95%
	Proposed	0	0%	1031	28%	2619	72%

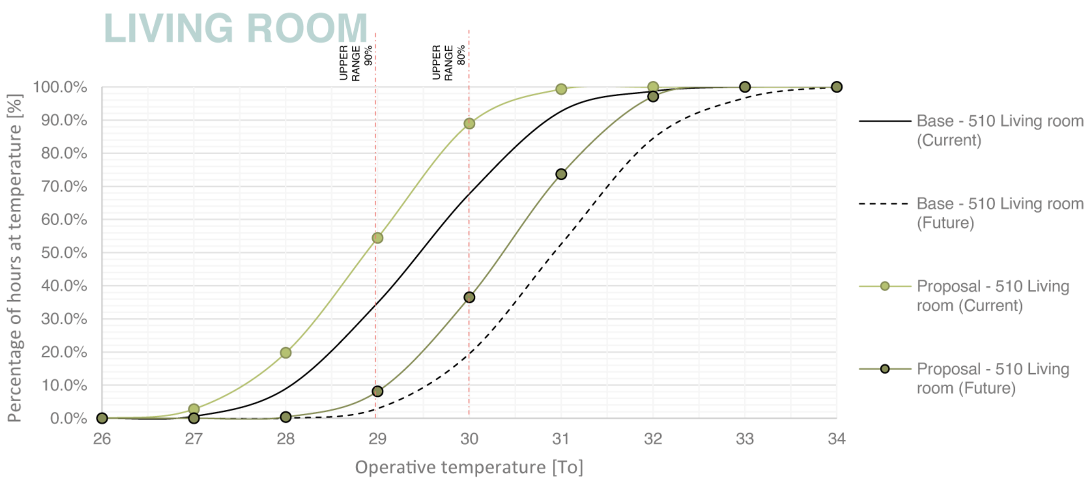
The bedroom goes from having 44% of its hours in overheating to presenting 4% in the proposed case. The reduction is also evident in the future scenario going from 95% to 72%, reducing almost 23% of the time.



Living room

		Below 23 °C		Between		Above 30	
		Hours	%	Hours	%	Hours	%
Current scenario	Base	0	0%	1780	35%	3331	65%
	Proposed	0	0%	2782	54%	2328	46%
Future scenario	Base	0	0%	149	3%	4961	97%
	Proposed	0	0%	414	8%	4697	92%

In the proposed case, the living room goes from having 65% overheating hours to 46% in the current scenario. The proposal maintains the space at comfortable temperatures for 54% of the hours occupied. Reducing hours out of range in the future scenario corresponds to 5%.



SA-108

Comfort Range: 23°C - 30°C

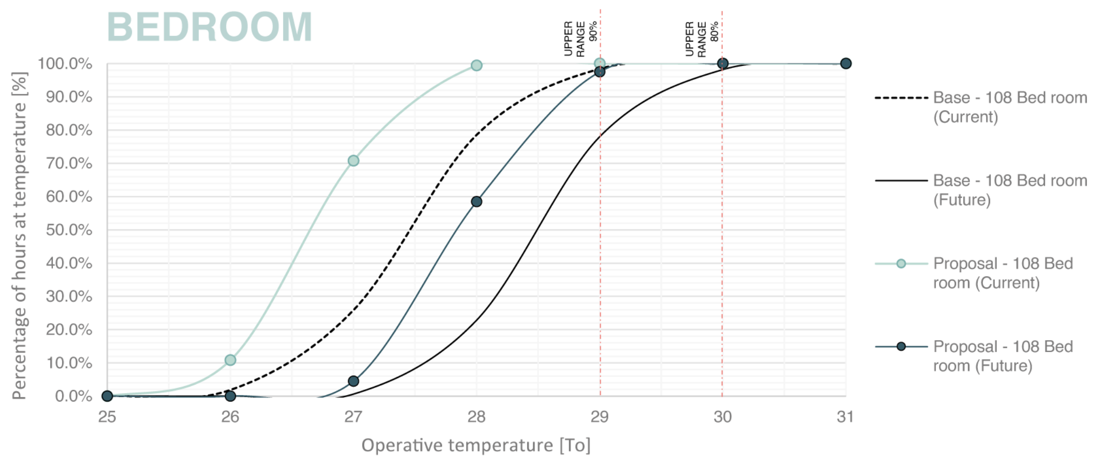
Bedroom total Occupation hours/ year: **3650**

Living room total Occupation hours/ year: **5110**

Bedroom

		Below 23 °C		Between		Above 30	
		Hours	%	Hours	%	Hours	%
Current scenario	Base	0	0%	3593	98%	57	2%
	Proposed	0	0%	3650	100%	0	0%
Future scenario	Base	0	0%	2847	78%	803	22%
	Proposed	0	0%	3559	98%	91	2%

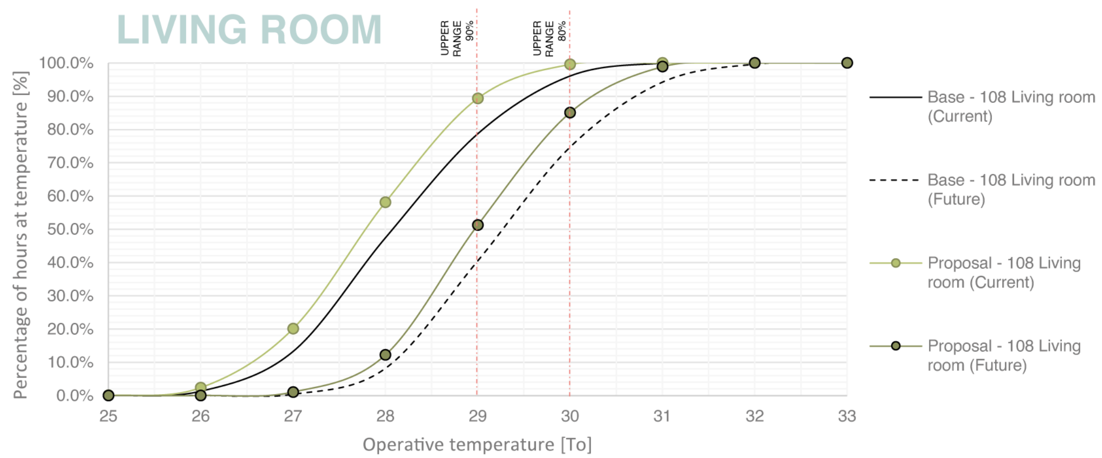
The room in the proposed case manages to reduce the hours of overheating by 0%, which allows 100% of the occupied hours to be within the comfort range in the current scenario. A reduction of approximately 20% in overheating hours is presented for the future scenario.



Living room

		Below 23 °C		Between		Above 30	
		Hours	%	Hours	%	Hours	%
Current scenario	Base	0	0%	4022	79%	1089	21%
	Proposed	0	0%	4566	89%	544	11%
Future scenario	Base	0	0%	2068	40%	3042	60%
	Proposed	0	0%	2619	51%	2491	49%

In the proposed case, the living room goes from having 21% overheating hours to 11% in the current scenario. The proposal maintains the space at comfortable temperatures for 89% of the hours occupied. Reducing hours out of range in the future scenario corresponds to 11%.



NA-1204

Comfort Range: 23°C - 30°C

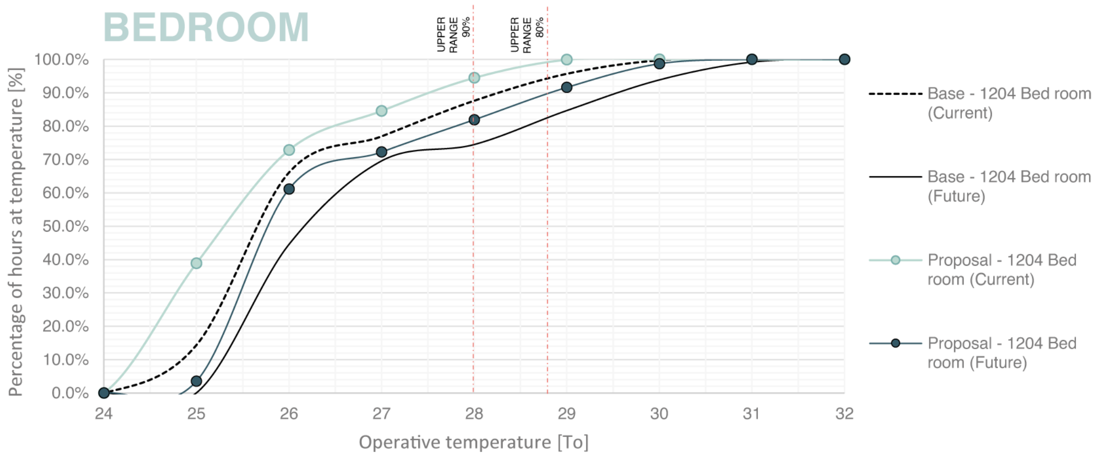
Bedroom total Occupation hours/ year: **3650**

Living room total Occupation hours/ year: **5110**

Bedroom

		Below 23 °C		Between		Above 30	
		Hours	%	Hours	%	Hours	%
Current scenario	Base	0	0%	3493	96%	157	4%
	Proposed	0	0%	3647	100%	4	0%
Future scenario	Base	0	0%	3091	85%	559	15%
	Proposed	0	0%	3343	92%	307	8%

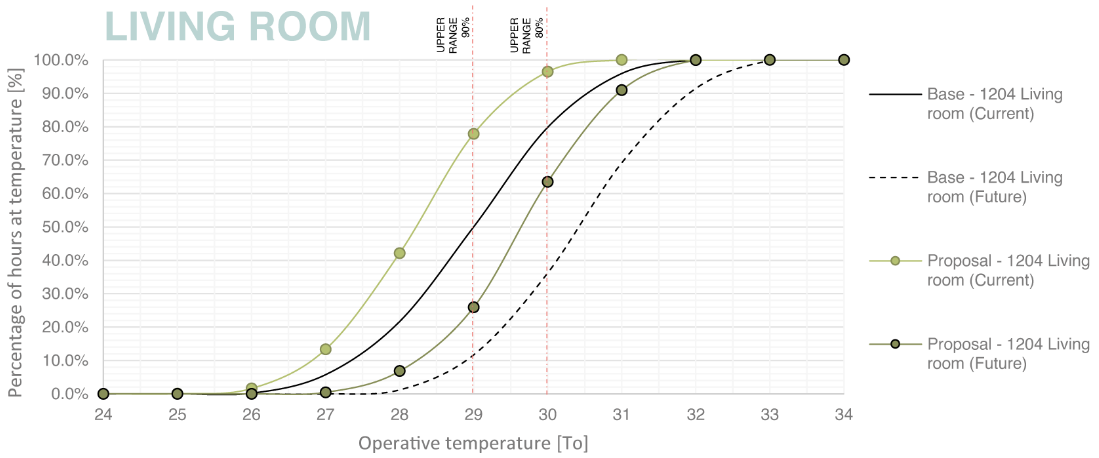
Regarding the bedroom in this apartment, it is essential to highlight that it has acooling system at night. However, a slight improvement of 4% is observed in the current scenario. In the future scenario, the improvement is 7%.



Living room

		Below 23 °C		Between		Above 30	
		Hours	%	Hours	%	Hours	%
Current scenario	Base	0	0%	2555	50%	2555	50%
	Proposed	0	0%	3978	78%	1132	22%
Future scenario	Base	0	0%	597	12%	4513	88%
	Proposed	0	0%	1324	26%	3786	74%

In the proposed case, the living room goes from having 50% overheating hours to 22% in the current scenario. The proposal maintains the space at comfortable temperatures for 78% of the hours occupied. Reducing hours out of range in the future scenario corresponds to 14%.



Final building evaluation conclusions

The results of the simulations show that the design strategies or design options applied to the building envelope demonstrate an improvement in the interior hydrothermal comfort. In the proposal, with the current climate scenario, the main bedroom has more hours inside the ASHRAE 55 comfort range (23°C - 30°C). Most bedrooms have 100% of their occupied hours within the comfort range (NA-1204, SA-108, SA-210 & NA-507). On the other hand, with the current climate scenario, the highest hours inside the ASHRAE 55 comfort range for the living room is 89% in the SA-108 apartment, and the lowest is 54% in the SA-510 apartment. The other living rooms' comfort hours range between 60% to 78% of the occupied hours. It could happen because the window film and shading devices have a more significant effect in the bedroom due to their window size, which is smaller than the living room window. **However, the optimization in the living room respecting the base model without folding panels is around 20%.**

As shown in Figure 30, in a **future climate scenario, the percentage of hours within the comfort range decreases for each apartment, both in the living rooms and the bedrooms.** This is normal due to climate change scenario in which the temperature increase and the air velocity have a reduction. However, **in both types of space, a trend exists in which when the apartment location increases in height, the among of comfort hours are reduced, the same trend as with the current scenario. Therefore, it could be inferred that more solar protection and active heating dissipation strategies are necessary for the upper floor to respond to the climate crisis.**

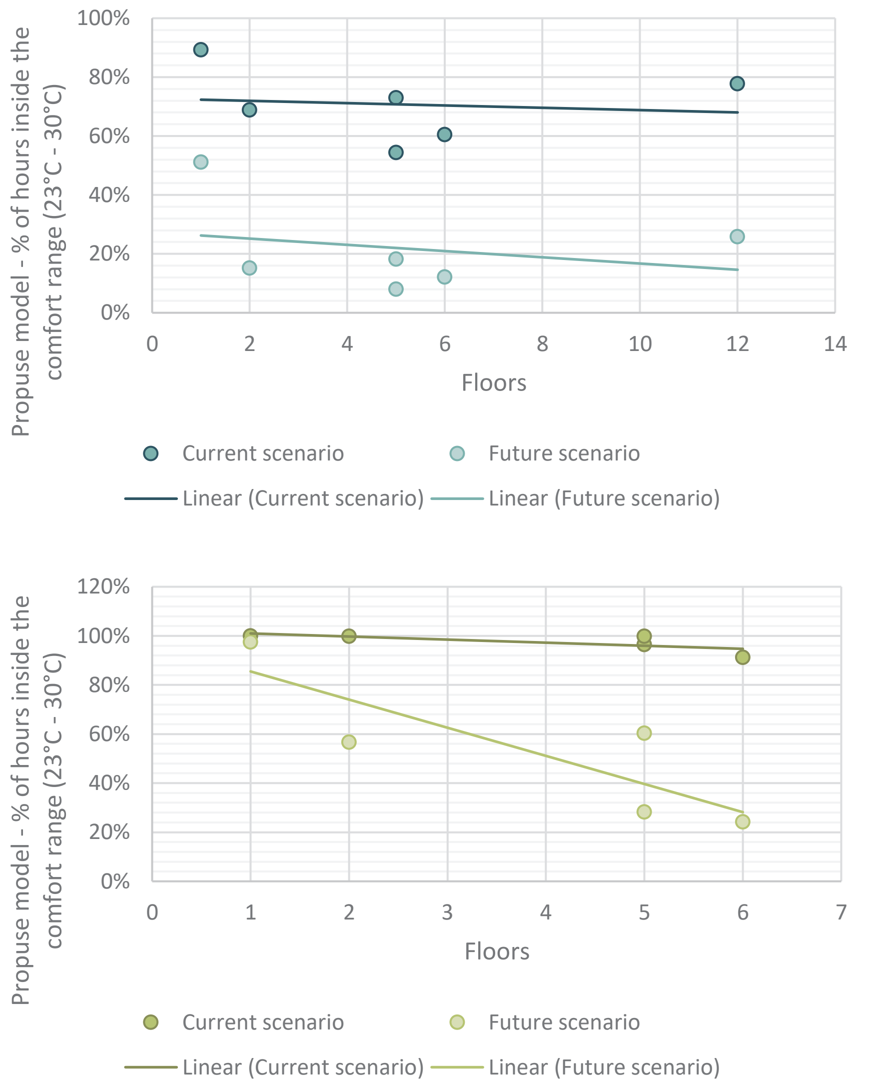
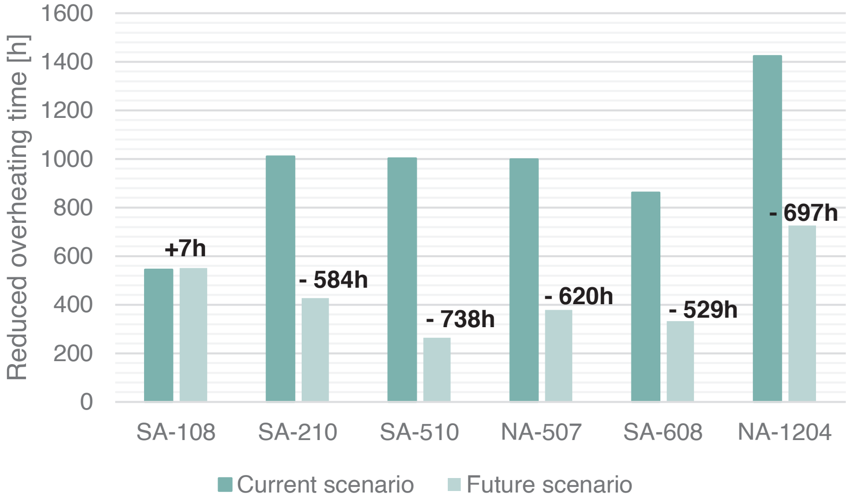


Figure 30. (1) Above proposed model living room % of hours inside the comfort range in current and future scenario. (2) below proposed model bedroom % of hours inside the comfort range in current and future scenario. Source: Author's elaboration.



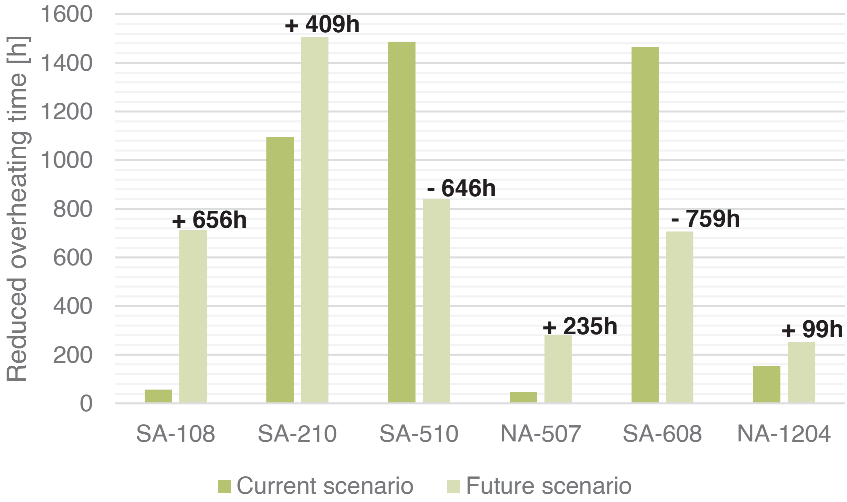


Figure 31. (Above) Proposed model- Living room reduce overheating time from the base case – current scenario & future scenario. (Below) Proposed model- Bedroom reduce overheating time from the base case – current scenario & future scenario. Source: Author's elaboration.

Figure 31 shows the reduced overheating hours of the proposed model concerning the base model in each climate scenario. **The highest reduction hours happen in the bedrooms; however, the reduction in the living room is also significant**. Further, the figure compares the overheating hours reduced in the current climate scenario vs the future climate scenario showing that on the first floor, the reduction of the climate change scenario is higher than in the current scenario in both spaces. Moreover, in four bedrooms, the overheating hours in the climate change scenario are higher than in the current scenario. This could happen due to the stack effect in which the thermosiphon roof temperature is higher than in the current scenario, pulling a significant amount of air and reducing hours of overheating concerning the base. **This shows that the building will respond better to climate change, although it may need mechanical conditioning support at certain times of the year.**

Conclusions

This renovation proposal aimed to improve the building design, making it more capable of responding to future climate change scenarios, focusing on its thermal performance. The proposal identifies and solves the building's weaknesses and recognizes its limitations and strengths. Hence, the measures applied are the most accurate to optimize the dwelling's thermal performance in the current and future climate scenarios. It also improves the dweller's habitability conditions, given that it considers the climatic impact and the social context of the building, designing towards greater feasibility.

The measures implementation is based on **(1)** heat prevention, **(2)** heat management, and **(3)** heat dissipation. The most relevant strategies seek to avoid heat gain through the windows due to their high heat transfer capability. These measures are the mobile shading, the overhangs, and the window film. On the other hand, heat dissipation is highly relevant in hot-humid climates. Hence the stack effect strategy already working in the building is improved by locating vents that join it with the newly ventilated roof, increasing the airflow.

Convincingly, the intervention promotes architectural adaptability related to the environment, traditional architecture and contact with the outside and nature as far as possible by implementing plant pots. Even though the reduction of air relative humidity is dealt with superficially through mobile shading materiality, in the future, it could consider implementing dehumidification systems in each apartment to improve the occupants' thermal sensation further.

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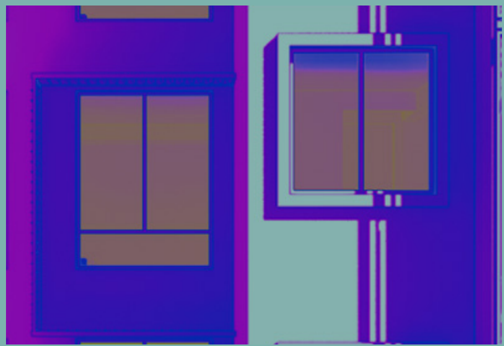

Lina María García Niño

Torino, February 2023