



Politecnico Di Torino

Department of Architecture and Design Master of Science in Architecture For Sustainability Master's Thesis
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Thermal Comfort and Energy Optimization of urban Social Housing for heat resilience in hot-dry climate.

The case of Cali, Colombia

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On a personal note, we are deeply grateful to our families for their unconditional love, endless patience, and unwavering belief in our potential. Their support has been our anchor during the most demanding phases of our academic journey. Lastly, we want to thank each other for the seamless collaboration, mutual motivation, and shared dedication that turned this challenging thesis project into an enriching and unforgettable experience, alongside all our friends and colleagues who offered kind words and support along the way.

ABSTRACT

EN.

Urban social housing in tropical cities faces increasing challenges related to thermal discomfort, energy inefficiency, and limited spatial adaptability. In Cali, Colombia, the standardisation of social housing design often overlooks local climatic conditions, resulting in dwellings that are highly exposed to solar radiation, dependent on insufficient natural ventilation, and vulnerable to overheating. This research aims to propose energy-spatial optimization strategies to improve thermal habitability and energy performance in urban social housing, using Cali as a case study.

The study adopts an applied and comparative methodology structured around climatic analysis, case study selection, archetype definition, environmental diagnosis, simulation, and strategy evaluation. First, the climatic conditions of Cali are characterised through key environmental variables such as air temperature, relative humidity, solar radiation, wind direction, and wind speed. Then, representative social housing projects are analysed and classified according to morphological, spatial, and constructive criteria, including block configuration, surface-to-volume ratio, orientation, structural system, envelope materiality, roof type, window-to-wall ratio, and internal layout. These variables are synthesised into analytical archetypes that serve as the basis for the simulation process.

The current performance of the selected archetypes is evaluated through thermal, energy, and spatial simulations, focusing on adaptive comfort, overheating, ventilation potential, daylighting, solar exposure, and cooling energy demand. Based on this diagnosis, passive retrofit strategies are formulated, including solar control, roof optimisation, envelope improvement, natural ventilation enhancement, material selection, and spatial reconfiguration. Finally, the proposed intervention scenarios are compared with the existing condition to assess their impact on comfort, energy demand reduction, and overall habitability.

The expected contribution of this research is to define design guidelines for the thermal comfort optimizing of urban social housing in Cali, offering a replicable methodological framework for improving the environmental performance of existing housing in similar tropical contexts.

ES.

La vivienda social urbana en ciudades tropicales enfrenta desafíos crecientes relacionados con el malestar térmico, la ineficiencia energética y la limitada adaptabilidad espacial. En Cali, Colombia, la estandarización del diseño de la vivienda social suele ignorar las condiciones climáticas locales, lo que da lugar a unidades habitacionales altamente expuestas a la radiación solar, con ventilación natural insuficiente y vulnerables al sobrecalentamiento. En este contexto, la presente investigación tiene como objetivo proponer estrategias de optimización energético-espacial orientadas a mejorar la habitabilidad térmica y el desempeño energético de la vivienda social urbana, tomando la ciudad de Cali como caso de estudio.

El estudio adopta una metodología aplicada y comparativa, estructurada en torno al análisis climático, la selección de casos de estudio, la definición de arquetipos, el diagnóstico ambiental, la simulación y la evaluación de estrategias. En primer lugar, se caracterizan las condiciones climáticas de Cali a partir de variables ambientales clave, como la temperatura del aire, la humedad relativa, la radiación solar, la dirección y velocidad del viento. Posteriormente, se analizan y clasifican proyectos representativos de vivienda social según criterios morfológicos, espaciales y constructivos, incluyendo la configuración del bloque, la relación superficie-volumen, la orientación, el sistema estructural, la materialidad de la

envolvente, el tipo de cubierta, la relación ventana-muro y la distribución interna. Estas variables se sintetizan en arquetipos analíticos, los cuales sirven como base para el proceso de simulación.

El desempeño actual de los arquetipos seleccionados se evalúa mediante simulaciones térmicas, energéticas y espaciales, con énfasis en el confort adaptativo, el riesgo de sobrecalentamiento, el potencial de ventilación natural, la iluminación natural, la exposición solar y la demanda energética asociada a la refrigeración. A partir de este diagnóstico, se formulan estrategias de rehabilitación pasiva, entre las que se incluyen el control solar, la optimización de la cubierta, la mejora de la envolvente, el incremento de la ventilación natural, la selección de materiales y la reconfiguración espacial. Finalmente, los escenarios de intervención propuestos se comparan con la situación actual, con el fin de evaluar su impacto en el confort térmico, la reducción de la demanda energética y la mejora de la habitabilidad general.

La contribución esperada de esta investigación consiste en definir directrices de diseño para la optimización del confort térmico en la vivienda social urbana de Cali, ofreciendo un marco metodológico replicable para mejorar el desempeño ambiental de la vivienda existente en contextos tropicales similares.



introduces the issue of thermal comfort in social housing under warm-humid climatic conditions, explains the relevance of Cali as a case study in the context of climate change, and defines the research questions, objectives, and scope of the thesis. It concludes by outlining the structure of the document.

INTRODUCTION

Social Housing (Vivienda de Interés Social – VIS) has become the primary instrument of the Colombian State to guarantee the fundamental right to adequate housing for low-income populations. Over time, the participation of the private sector in the development of these projects has been promoted, resulting in mass-produced housing characterized by a high degree of standardization in both spatial and structural design.

However, in response to the housing needs of millions of Colombians, a predominantly quantitative approach has been prioritized over a qualitative one, favoring the number of housing units delivered rather than their quality. Consequently, Social Housing has increasingly become an industrialized consumer product that is initially low-cost but often disregards the specific environmental and climatic conditions of the territories in which it is built.

In a country such as Colombia, located in the tropics and characterized by a wide diversity of climatic zones, it is essential to consider local contextual conditions in order to design housing that responds adequately to its environment.

This lack of contextualization has direct implications for fundamental aspects such as thermal comfort and environmental impact, which are frequently neglected, negatively affecting



the quality of habitability and generating long-term problems for the health of the inhabitants.

In an effort to move toward more climate-responsible construction practices, the Colombian State issued Resolution 0549 in 2015, within the framework of the Paris Agreement, establishing the Sustainable Construction Regulation. This regulation, mandatory since 2016 for all new buildings, aims to reduce wa-

gas emissions through energy efficiency measures and passive climate design strategies. Nevertheless, its application remains optional for Social Housing projects, a paradox considering that this housing typology represented 62.13% of the total housing projects initiated in Colombia in recent years, according to the National Administrative Department of Statistics (DANE, 2025).



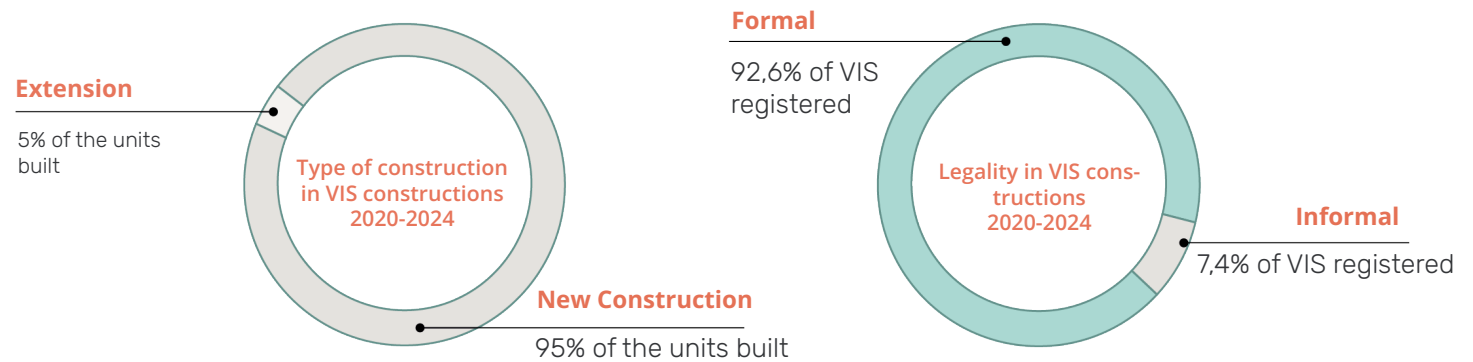
Within this context, the city of Cali, located in southwestern Colombia and characterized by a hot-dry climate, represents a particularly critical case for analyzing habitability in Social Housing due to high average temperatures, high relative humidity, and intense exposure to direct solar radiation. Several studies have documented significant thermal deficiencies in Social Housing developments in Cali and its metropolitan area. Research conducted in single-family dwellings in Candelaria and Jamundí indicates that the most common construction systems, structural masonry with fired clay blocks and solid reinforced concrete walls, do not provide sufficient thermal insulation, resulting in indoor thermal sensations described as “very hot” and dissatisfaction levels exceeding 90% (Barona, 2012). Additionally, surface temperatures of up to 49°C have been recorded on roofs and façades (Gamboa et al., 2011), along with widespread reliance on mechanical cooling systems due to the absence of cross-ventilation and the low thermal resistance of construction materials (Iturre Campiño, 2013).

These conditions highlight the need to establish a stronger connection between Social Housing and sustainability, recognizing that improving habitability responds not only to a social imperative but also to an environmental one. In urban contexts such as Cali, where qualitative housing deficits manifest through thermal discomfort, excessive energy consumption, and inadequate material use, rethinking the architectural design approach of Social Housing represents an opportunity to positively impact the lives of thousands of families currently facing conditions of vulnerability.

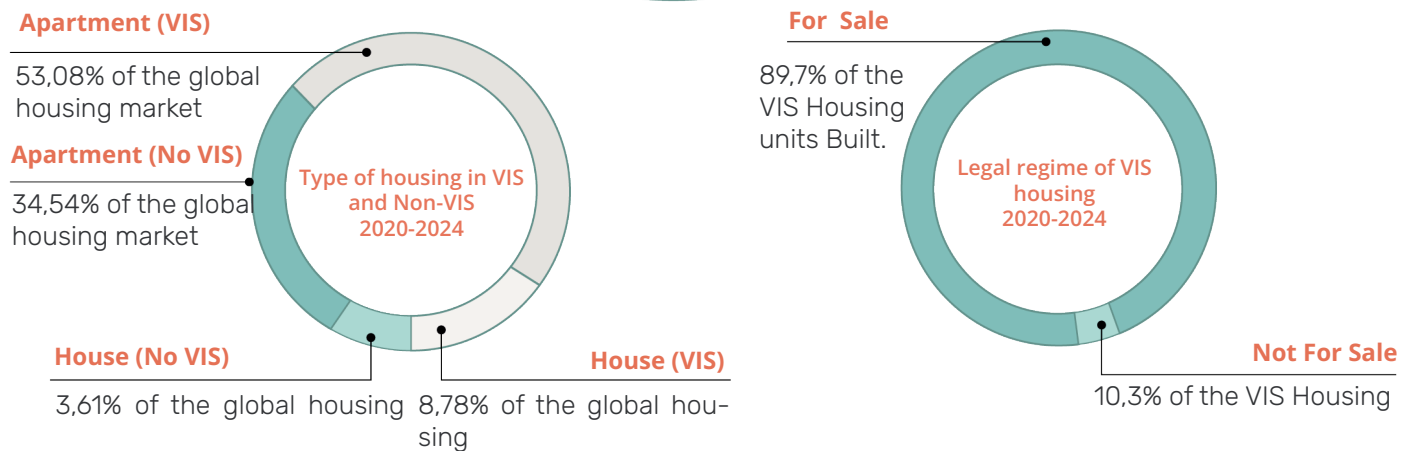
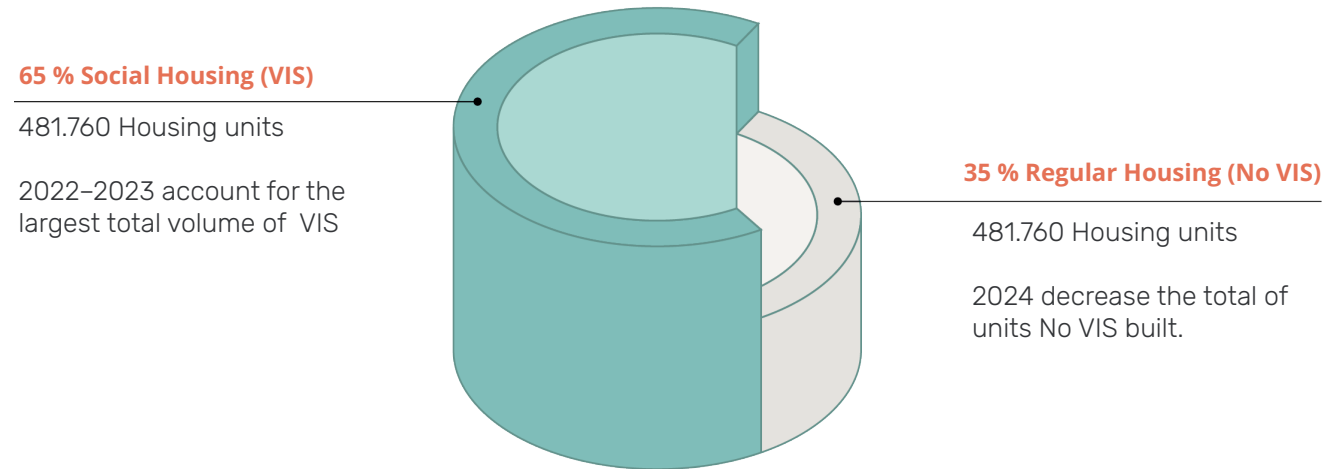
By developing cost-efficient solutions that reduce dependence on mechanical cooling systems, a more equitable, resilient, and climate-responsive housing model can be promoted, contributing to the achievement of national and international sustainability goals. Consequently, this research emphasizes the urgent need for habitability requalification of urban Social Housing in Colombia, with particular attention to hot-dry climatic contexts

This process must incorporate passive design principles, appropriate material selection, optimization of natural ventilation, and the integration of sustainability principles as fundamental pillars to ensure more equitable, resilient, and dignified housing for all.

Rather than addressing these deficiencies through isolated measures, this research argues that the thermal habitability of VIS in Cali must be improved by combining complementary passive strategies into coherent renovation packages, calibrated to the constructive logic and local supply chains of each housing type. Existing archetypes are therefore used as an evidence base: their simulated behaviour is not an end in itself, but the basis for deriving transferable passive design principles that inform a new, climate-responsive VIS proposal.



Units built in Colombia between 2020 and 2024 by type of housing: VIS and Non-VIS



*Source: DANE Censo de Edificaciones -CEED
DANE Technical Bulletin February 21, 2025

RESEARCH GOALS

GENERAL OBJECTIVE

to derive transferable passive design principles for urban social housing (VIS) in Cali's climatic scenario, by simulating representative existing archetypes, evaluating renovation packages that combine passive measures adapted to each archetype and to local construction practices and supply methods, and translating the resulting evidence into a projective architectural proposal aimed at impro-

SPECIFIC OBJECTIVES

- 1.** To analyse the current state of habitability in urban social housing in Cali, considering variables related to thermal comfort.
- 2.** To characterise the climatic conditions of Cali, with particular emphasis on the environmental variables that influence the thermal performance of housing, s(air temperature, relative humidity, solar radiation, wind direction and speed), and its projected evolution.
- 3.** To identify, classify, and define representative archetypes of urban social housing in Cali based on morphological, spatial, and constructive criteria, in order to establish a typological basis for the subsequent environmental diagnosis and simulation process.

4. To define and document a building energy simulation methodology specifying the software environment, modelling scale, evaluation KPIs, and underlying assumptions, in order to establish the base-case thermal and energy performance of each representative housing archetype.

5. To conduct a sensitivity analysis of passive design variables, supported by performance diagnostics, including thermal load balance by floor and heat source, overheating degree-hours, and incident solar radiation, in order to rank the most influential design levers for each representative archetype.

6. To define and simulate progressive renovation packages that integrate passive design measures adapted to each housing archetype, local construction practices, and available supply methods, including operable openings and natural cross-ventilation strategies, in order to evaluate their impact on cooling demand and adaptive thermal comfort.

7. To synthesise the simulation results into transferable passive design principles and a projective VIS proposal, validating its thermal and energy performance against the base-case scenario.

HYPOTESIS

The thermal habitability of VIS in Cali can be significantly improved through passive design strategies. By combining envelope enhancement, solar shading, and natural ventilation measures into archetype-specific renovation packages, calibrated to local construction practices and supply methods, is expected to reduce annual cooling demand and increase the share of passively comfortable hours compared to the base-case scenario. The effectiveness and priority of each measure are expected to vary according to the constructive, spatial, and morphological characteristics of each archetype.

RESEARCH QUESTIONS

- Which passive design variables have the greatest influence on cooling demand and overheating risk in VIS archetypes under Cali's warm-humid climate?
- How can these variables be combined into archetype-specific renovation packages, adapted to local construction practices and supply methods, and structured according to different levels of intervention?

METHODOLOGY

The methodological process combines documentary analysis, climatic characterisation, typological assessment, building-energy simulation, and projective design, structured in seven phases.

Phase 1 | Conceptual and Climatic Framework.

Establishes the theoretical basis and characterises Cali's climate scenario, including current conditions and projected (2050) trends.

Phase 2 | Case-Study Selection and Archetype Definition.

Representative VIS projects are selected and synthesised into analytical archetypes according to morphological, spatial and constructive variables.

Phase 3 | Simulation Methodology and Base-Case Modelling.

Defines the simulation workflow, the model scale and thermal zoning, the construction and operational assumptions, and the evaluation KPIs (cooling demand under ideal loads; free-floating adaptive comfort, ASHRAE 55). archetype.

Establishes the base-case performance of each.

Phase 4 | Sensitivity Analysis and Performance Diagnostics.

A sensitivity analysis of passive variables, complemented by thermal load balance, overheating degree-hours and incident-radiation diagnostics, to identify and rank the most influential levers per archetype.

Phase 5 | Renovation Packages: Definition and Combined Simulation.

The analyse measures are combined into renovation packages adapted to each archetype and to local construction practices and supply methods. Including operable openings and cross-ventilation strategies, the packages are simulated to quantify their impact on the KPIs.

Phase 6 | Design Proposal and Verification.

The best-performing principles are translated into a new VIS architectural proposal, whose performance is verified against the base case.

Phase 7 | Synthesis, Conclusions and Future Work.

Consolidates the transferable passive design principles and states limitations and future work.



This chapter presents the problem of thermal comfort in social housing under warm-humid climatic conditions, explains the relevance of Cali in relation to climate change, and defines the research questions, objectives, scope, and structure of the thesis.

SOCIAL HOUSING IN COLOMBIA

At the beginning of the twentieth century, Colombia was undergoing profound political, economic, and social transformations. The process of industrialization, together with massive rural-to-urban migration, accelerated urban expansion in the country's main cities. However, public service infrastructure, such as potable water supply, sewerage systems, and urban transportation, was still at an incipient stage and, in many cases, failed to adequately respond to rapid demographic growth. This situation contributed to the consolidation of precarious urban conditions, particularly among lower-income sectors.

The process of urbanization was largely shaped by the subdivision of large landed estates carried out by private developers, who played a central role in the production of urban land. In the case of low-income populations, these developers frequently operated outside the formal banking system, offering direct financing mechanisms characterized by high costs and unfavorable conditions to families who lacked access to institutional credit.

This dynamic not only limited the State's capacity to guide and regulate urban development but also encouraged a fragmented, dispersed, and weakly planned pattern of urban growth.

As a consequence, real estate speculation and the progressive social stratification of urban space became increasingly evident, giving rise to the formation of a dual city. On the one hand, self-built, informally developed working-class neighborhoods emerged, often lacking adequate services and dignified living conditions; on the other, exclusive residential sectors consolidated, better equipped with infrastructure and services, reinforcing the socio-spatial inequalities that have historically characterized urban development in Colombia.



Social housing Mirador del Aguacatal II

*Photographed by Carmeneliza
Guzmán, 2016*

'39 Creation of the Territorial Credit Institute (TIC)

The State assumes an active role as "builder"

'18 Law 46 on Workers' Housing

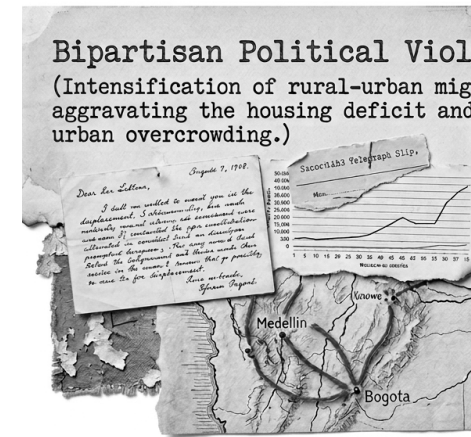
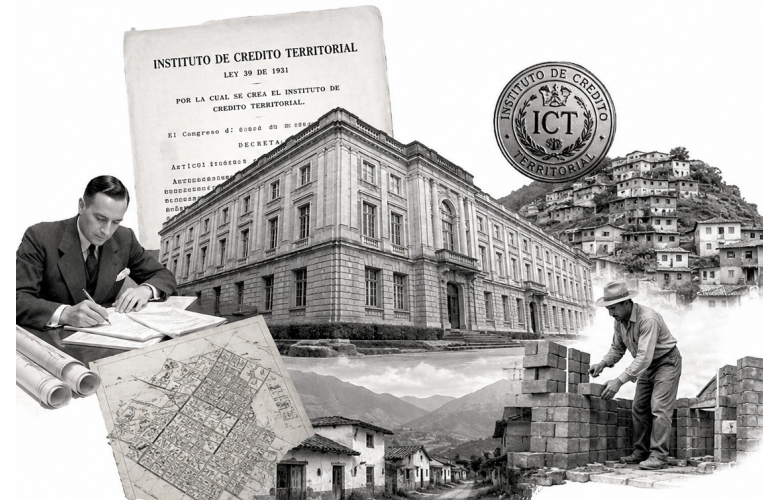
Housing is addressed as a public health problem under a hygienist logic.

'40 Creation of the Popular Housing Fund (CVP)

Housing policy is institutionalized and the provision of affordable housing is expanded.

'47 Transition to formal urban housing

State action is shifting from rural material improvement to the construction of urban neighborhoods.



PHASE I : THE HYGIENIST AND RURAL APPROACH

*In Cali: From Haciendas to Neighborhoods

Urban growth was constrained by extensive sugarcane haciendas and communal lands (ejidos). National hygienist policies were locally reflected in concerns over working-class neighborhoods emerging near the city center and the Cali River. Despite this, the city retained a semi-rural character, with limited state intervention and low-income populations largely dependent on overcrowded rental housing in the historic center.

During the first decades of the twentieth century, housing was understood primarily as a public health issue rather than as a social right, within a context in which the State assumed the role of a "Sanitary Guard." Under the hygienist approach, formalized through Law 46 of 1918, the first legislation addressing workers' housing, the main concern was not homeownership but sanitary conditions, aiming to prevent the

epidemics from working-class areas to higher-income sectors. The creation of the Territorial Credit Institute (ICT) in 1939 and the Popular Housing Fund (CVP) marked the beginning of a more active role of the State in housing provision. During this stage, the State adopted the role of a "Rural Builder," focusing on the production of single-family housing for working-class and peasant populations and



Housing types in the Centenario neighborhood

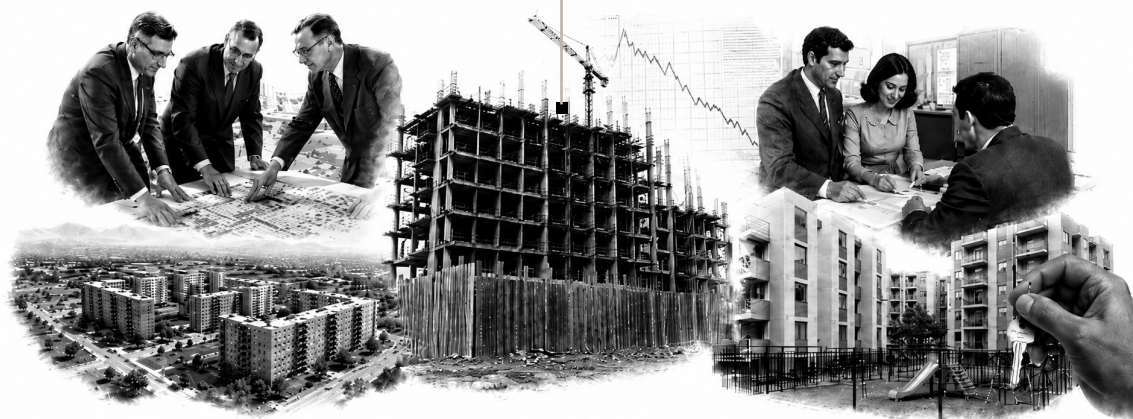
Brunner, K. (1939). Manual de Urbanismo Tomo II. Bogotá



on improving the material conditions of rural dwellings. At this time, the housing deficit was predominantly qualitative, and significant conflicts over urban land had not yet emerged, before state action shifted toward the development of formalized and affordable urban neighborhoods.

Bipartisan Political Violence

Intensification of rural-urban migration, aggravating the housing deficit and urban overcrowding.



PHASE II : THE "GOLDEN AGE" AND STATE PLANNING

Massive rural-to-urban migration, driven by historical periods of bipartisan political violence, intensified housing shortages and urban overcrowding, compelling the State and the Instituto de Crédito Territorial (ICT) to assume the role of an "Urban Builder," albeit with limited capacity. Within this context, "pirate urban developers" proliferated, subdividing peripheral land without basic services and offering usurious credit to low-income populations, thereby consolidating

The State as "Urban Builder "

- Proliferation of "pirate developers" and consolidation of self-built neighborhoods without services or technical planning.
- The State and the ICT as an "Urban Builder", although with insufficient capacity to meet demand.

URESAs in Cali and Kennedy in Bogotá, where comprehensive neighborhoods with collective facilities were developed to address the quantitative housing deficit while maintaining high standards of quality. Although financially unsustainable, this model represented the peak of state-led urban planning by prioritizing quality of life over the quantity of housing produced.

Cali experienced a major urban transformation during the preparation for the 1971 Pan American Games. The ICT developed the Unidad Residencial Santiago de Cali (URESAs), exemplifying the “State as Builder” through well-ventilated housing, ample green areas, and strategic siting. At the same time, growing migration from the Pacific region surpassed state capacity, leading to informal settlement in the city’s eastern lowlands.

***In Cali:
The “Urban Showcase” (1960s)**

The state-led housing construction model collapsed financially during the 1970s. With the introduction of the UPAC system to mobilize private savings and the progressive decapitalization of the Instituto de Crédito Territorial (ICT), housing standards were significantly reduced. In order to expand coverage with limited resources, “basic solutions” such as serviced plots and minimal sanitary units were promoted, institutionalizing progressive housing.

PHASE III : FINANCIAL CRISIS



“Alliance for Progress” policy

‘61

- Articulation of international housing and urban development policies as neighborhood units and the superblocks
- The State assumes the role of “Urban Planner”



**MDU Nariño Centre,
Bogotá**

Brunner, K. (1939). Manual de Urbanismo Tomo II. Bogotá

‘70 Financial Crisis

Financial collapse of the state-run housing construction model.

‘72 Creation of the UPAC (Purchasing Power Unit) system.

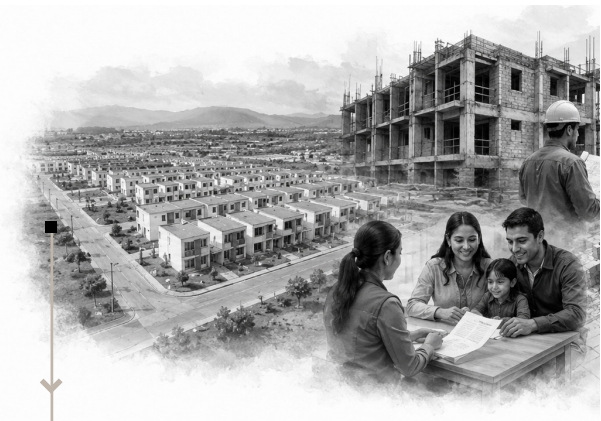
Creation of the IUPAC for the collection of private savings for housing acquisition.

This approach transferred the responsibility for completing dwellings to low-income households, resulting in unfinished neighborhoods, uncontrolled densification, and the deepening of the qualitative housing deficit and socio-spatial segregation. This period also marked a shift toward private-sector participation in housing production through National Development Plans aimed at addressing housing shortages among low-income populations. Later, Law 9 of

1989 (Urban Reform Law) represented a milestone by recognizing land management for housing within a free-market economy, although it led both to the consolidation of overcrowded areas and to market-driven urban expansion.

The Law 3 of 1991 consolidated the neoliberal shift in Colombia's housing policy. With the liquidation of the Instituto de Crédito Territorial (ICT), the State withdrew from housing provision and adopted a demand-side subsidy model, assuming the role of a "Facilitator" and transferring housing production to the private sector. Under profit-driven market logics, development prioritized low-cost peripheral land, reinforcing dispersed urban expansion

SOCIAL CRISIS AND THE RETURN OF SELF-CONSTRUCTION



'80 Reduction of housing standards

Decreased housing quality and institutionalization of progressive housing through serviced lots.

'89 Law 9 of 1989 (Urban Reform Law)

Regulating urban land management in a free market economy.

*In Cali:

The Eastern Expansion and the Aguablanca District (1970s–1980s)

As the ICT declined, Cali responded to land scarcity through formal and informal expansion into drained wetlands toward the Cauca River. Neighborhoods such as El Vallado and the Aguablanca District emerged through state-led projects and self-construction, consolidating a segregated eastern periphery physically and socially detached from traditional Cali.

'91 Political Constitution of Colombia (1991)

- Establishes the institutional framework for the State's new role as a "facilitator" rather than a direct housing provider.
- Law 3 of 1991
Marks the neoliberal shift in housing policy; the State withdraws from housing production, liquidates the ICT, and adopts a demand-side subsidy model.

Law 388 (Land-Use Planning Law)

'97

Reintroduces the public function of urban planning through municipal land-use regulation, with limited impact on land speculation and housing quality standards.



Housing types in the Centenario neighborhood

Brunner, K. (1939). Manual de Urbanismo Tomo II. Bogotá

'15 Resolution 0549 of 2015

Establishing the Sustainable Construction Regulation within the framework of the Paris Agreement.

'12 Free Housing Program

Marking the beginning of large-scale, state-led industrialized housing production.



PHASE IV : THE "GOLDEN AGE" AND STATE PLANNING

and the spatial segregation of low-income populations away from employment centers. While this model reduced the quantitative housing deficit, it generated new urban challenges, including disconnected dormitory cities and increased mobility costs. Housing policy primarily benefited middle-income groups, while lower-income households were relegated to minimal housing solutions and self-construction, effectively turning social housing into a

driver of the real estate and mortgage markets.

Law 388 of 1997 partially reintroduced the public function of urban planning through municipal land-use regulation; however, its impact remained limited in controlling land speculation and ensuring minimum housing quality standards, despite promoting a mixed low-rise and higher-density housing supply.

***In Cali:**

Cali-Jamundí Conurbation (1990s–2000s)

Following Law 3 of 1991 and the exhaustion of developable land within Cali, private developers expanded southward toward Jamundí. Subsidized social housing (VIS) fueled the emergence of dormitory neighborhoods such as El Rodeo and Terranova, intensifying daily commuting and generating severe mobility pressures along the Cañasgordas Avenue and the Pan-American Highway, as employment remained concentrated in northern Cali..

'16 Creation of the Territorial Credit Institute (TIC)

The State assumes an active role as "builder"

'17 Consolidation of "Mi Casa Ya" Program

As the main national housing subsidy program, reinforcing demand-side incentives and private-sector leadership.

TD Recognition of the "external habitability crisis" in social housing developments

The standardized use of concrete wall systems in Cali's expansion areas, designed for colder climates, has caused severe thermal discomfort. High solar radiation turns VIS housing into heat-retaining structures, increasing dependence on air conditioning and exacerbating energy poverty.

***In Cali:**
The Concrete "Heat Trap" in the Geographic Valley (2012–Present)

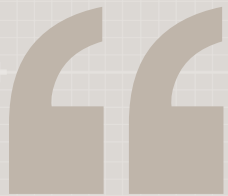


PHASE V : INDUSTRIALIZED MASS HOUSING AND THE COMFORT CRISIS

Since 2012, the Colombian State has assumed a "Mixed Promoter" role, promoting large-scale housing production through programs such as Free Housing and Mi Casa Ya. These initiatives significantly accelerated the reduction of the quantitative housing deficit by expanding access to homeownership for low- and middle-income households. However, they also reinforced socio-spatial segregation by prioritizing peripheral

land where costs are lower and market profitability is higher. The current challenge is defined by a structural paradox: although newly built housing units generally comply with acceptable internal construction standards, they are frequently located in urban contexts characterized by deficits in public infrastructure, services, public space, and transportation connectivity.

As a result, housing provision has increasingly failed to guarantee adequate living conditions beyond the dwelling itself, a condition widely recognized in academic literature as a crisis of external habitability.



The current regulatory framework for social interest housing prioritizes minimal legal and economic compliance, reducing housing to a standardized market object while systematically neglecting essential conditions of habitability, health, and everyday living.

SOCIAL HOUSING FRAMEWORK

Currently, social housing (VIS) is structured within a regulatory framework that prioritizes the control of minimal legal, economic, and urban planning variables, aimed at guaranteeing formal access to housing for low-income households. This model is primarily regulated by Decree 1467 of 2019, in coordination with the Territorial Planning Plans (POT) and the NSR-10 Seismic-Resistant Standard, which define the basic conditions for the conception, design, and commercialization of VIS projects in Colombia.

In practice, VIS is governed by a limited set of minimal requirements, revealing a regulatory structure that is deeply unbalanced, prioritizing compliance with legal, economic, and structural parameters while neglecting fundamental aspects necessary to ensure adequate habitability. This normative hierarchy reduces social housing to a standardized, quantifiable object, regulated primarily from a market logic, without fully considering the real dynamics of everyday habitat.

VIS regulations mandate variables such as minimum built area, maximum sale price, location according to the POT, and compliance with NSR-10. While necessary, these conditions function solely as legal thresholds that guarantee the formal viability of a project, but do not ensure truly habitable housing. Implicitly, compliance with these requirements is assumed sufficient to guarantee “decent housing,” without questioning how such housing is effectively inhabited.

This minimal conception is particularly evident in the regulation of built area, which is defined as a fixed figure independent of the number of occupants, spatial organization, or daily activities. Several studies have indicated that the relationship between area, occupancy density, and well-being is a critical factor for the physical and mental health of residents, particularly in social housing contexts (UN-Habitat, 2015; WHO, 2018). However, VIS regulations do not include indicators to assess spatial adequacy based on habitation, consolidating an abstract and decontextualized understanding of housing.

The maximum sale price, set at 150 current legal minimum monthly wage (SMMLV), oscillating in 2025 to 48.417€, becomes the structuring variable of the VIS model. While it serves a redistributive function, it also subordinates all other design decisions to compliance with the economic limit. In the absence of normative requirements regarding thermal comfort, energy efficiency, or indoor environmental quality, these dimensions are considered secondary to cost control. This approach has been widely criticized by organizations such as the Inter-American Development Bank, which note that reducing initial costs often results in higher operational expenses and poorer long-term living conditions for low-income households (BID, 2012).

It is particularly contradictory that Colombia has regulations such as Resolution 0549 of 2015 on sustainable construction, stemming from the 2015 Paris Agreements, which establish guidelines to optimize energy consumption, improve ventilation, natural lighting, and thermal comfort.

However, these variables are not mandatory within the VIS framework and appear fragmented across parallel regulations, lacking clear articulation or specific application to social housing. This regulatory fragmentation creates an operational gap in which essential aspects of well-being are left to voluntary decisions by developers, reinforcing structural inequality in access to healthy living conditions.

International literature has consistently shown that poor ventilation, insufficient lighting, extreme temperatures, and limited space are associated with higher rates of respiratory illnesses, stress, mental health problems, and overall deterioration of well-being (WHO, 2018; Marmot et al., 2020). Nevertheless, these findings are not reflected in VIS regulatory requirements, calling into question the State's capacity to effectively guarantee the right to decent housing beyond its legal dimension.

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VIS MAIN RULE CHARACTERS

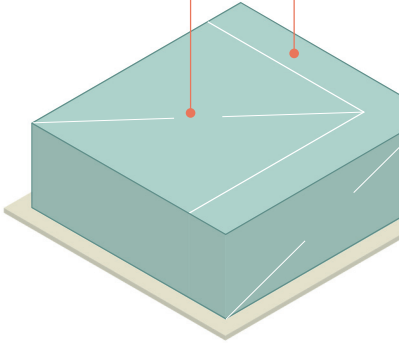
As such, the buildable area constitutes one of the primary mechanisms for cost control employed by private developers.

Regular Buidable
 Area in Cali
 42 - 55m²

Regular Buidable
 Area in Colombia
 36 - 48 m²

The buildable area is determined by the land-use or territorial planning regulations (POT) of each city and may therefore vary.

Buildable Area 

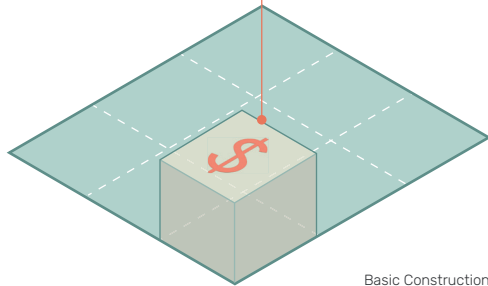


Cost per m² 2026

■ € 274,16 EUR

✠ € 648,32 EUR

Cali has one of the most affordable prices per square meter compared to other major cities.



Basic Construction ■
Construction with Finishes ✠

150 SMMLV

\$ 262.635.750 COP

€ 60003,60 EUR

According to Decree 1467 of 2019, the maximum price of VIS is set at 135 current legal monthly minimum wages (SMMLV), with an exceptional increase to 150 SMMLV in cities with more than one million inhabitants, as established by CONPES 3819 of 2014. This value encompasses all project-related costs, including construction, urban development, design, permits, and the developer's profit.

The location of Social Interest Housing (VIS) projects is determined by each city's Land-Use or Territorial Planning Plan, which defines permitted land uses, maximum densities, and allowable building heights. These projects are generally required to be developed on urban, urban expansion land or urban areas that can be fully consolidated with residential use.

Location



Sale Price



The sale price constitutes one of the most restrictive criteria in Social Interest Housing (VIS), as it imposes extremely limited budgets per square meter and directly conditions both design and construction decisions. This economic constraint translates into strict control over structural typologies, construction systems, and finishes, favoring highly standardized processes and the repetition of housing units.

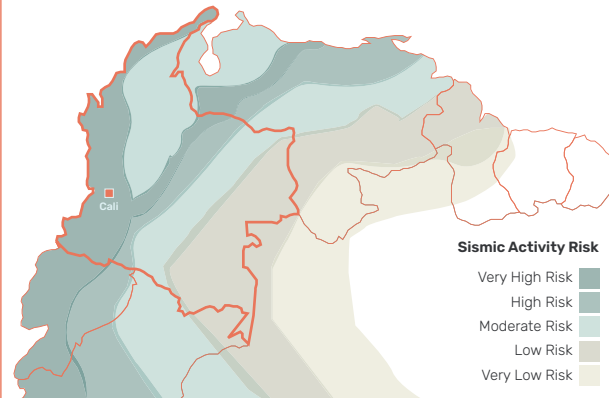
However, budgetary constraints related to land values tend to push VIS developments toward peripheral areas or zones with low levels of service consolidation, where land prices are lower. This spatial pattern negatively affects accessibility and proximity to urban services, thereby reinforcing processes of socio-spatial segregation.



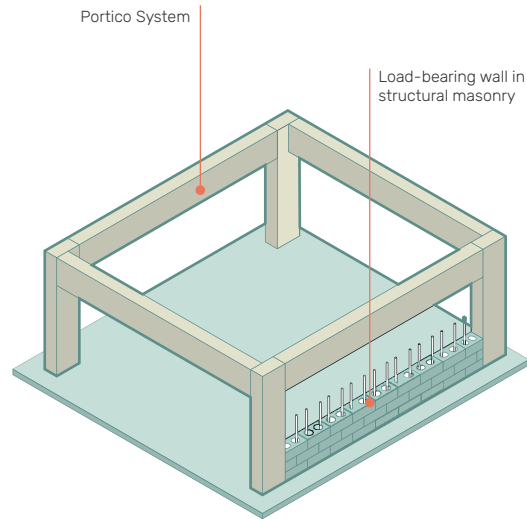
NSR-10 Compliance

Compliance with Colombia's Seismic-Resistant Technical Standard (NSR-10) is mandatory for all construction, requiring adherence to structural seismic safety criteria. In Social Interest Housing (VIS), the primary permitted construction systems are reinforced concrete frames and load-bearing walls, either in concrete or structural masonry. Economic considerations also influence the application of these standards, aiming to ensure

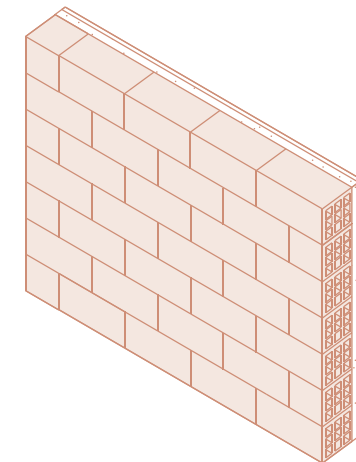
seismic safety efficiently without generating excessive costs. This results in limitations on large spans and cantilevers and promotes a regular, structurally rigid spatial layout.



reinforced concrete and structural masonry, with enclosures made of brick or concrete blocks and minimal finishes, since most projects are delivered in a gray-shell condition. Consequently, materiality is conceived mainly from a functional perspective, with its qualitative dimension often relegated. At the architectural level, spatial quality is typically understood to depend more on factors such as lighting, ventilation, and dimensions than on materiality itself, an assumption that will be critically examined later by highlighting the role of materials in shaping habitability.

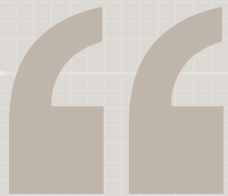


Material selection in Social Interest Housing (VIS) is unrestricted provided it complies with the technical and quality standards established by NSR-10. Within this framework, materiality is not the result of an aesthetic decision but rather a consequence of technical and economic constraints. Predominant criteria include low initial cost, ease of maintenance, durability, local availability, and the use of familiar labor. As a result, structural systems are primarily resolved through



Materials





The current regulatory framework for social interest housing prioritizes minimal legal and economic compliance, reducing housing to a standardized market object while systematically neglecting essential conditions of habitability, health, and everyday living.

Another key factor is the population's access to housing, which is currently mediated through the subsidy system. These subsidies emerged as a response to the persistence of a significant housing deficit, both quantitative and qualitative, that primarily affects the most vulnerable populations. As the real estate market has been unable to provide affordable housing solutions for low-income households, the State has implemented public policies aimed at guaranteeing access to adequate housing as a basic right.

As previously noted, housing public policies have been formulated since 1918 to address this issue. Initially, these policies responded to concerns related to public health and habitability, particularly in urban and rural contexts, and were oriented toward the mass provision of housing. During the institutional period (1942–1964), the State assumed the role of promoter, builder, and financier, establishing entities responsible for developing housing programs for low-income households.

Subsequently, between 1990 and 2009, the subsidy-based approach was consolidated through the introduction of Social Interest Housing and the strengthening of state support mechanisms, a process that intensified following the 1991 Constitution. This constitutional framework recognized adequate housing as a fundamental right and redefined the role of the State, which ceased to act as a direct builder and promoter and instead delegated these functions to the private sector. Since then, the State's role has focused on setting the maximum price for Social Interest Housing and providing subsidies to eligible households in order to facilitate financial closure and ensure access to housing.

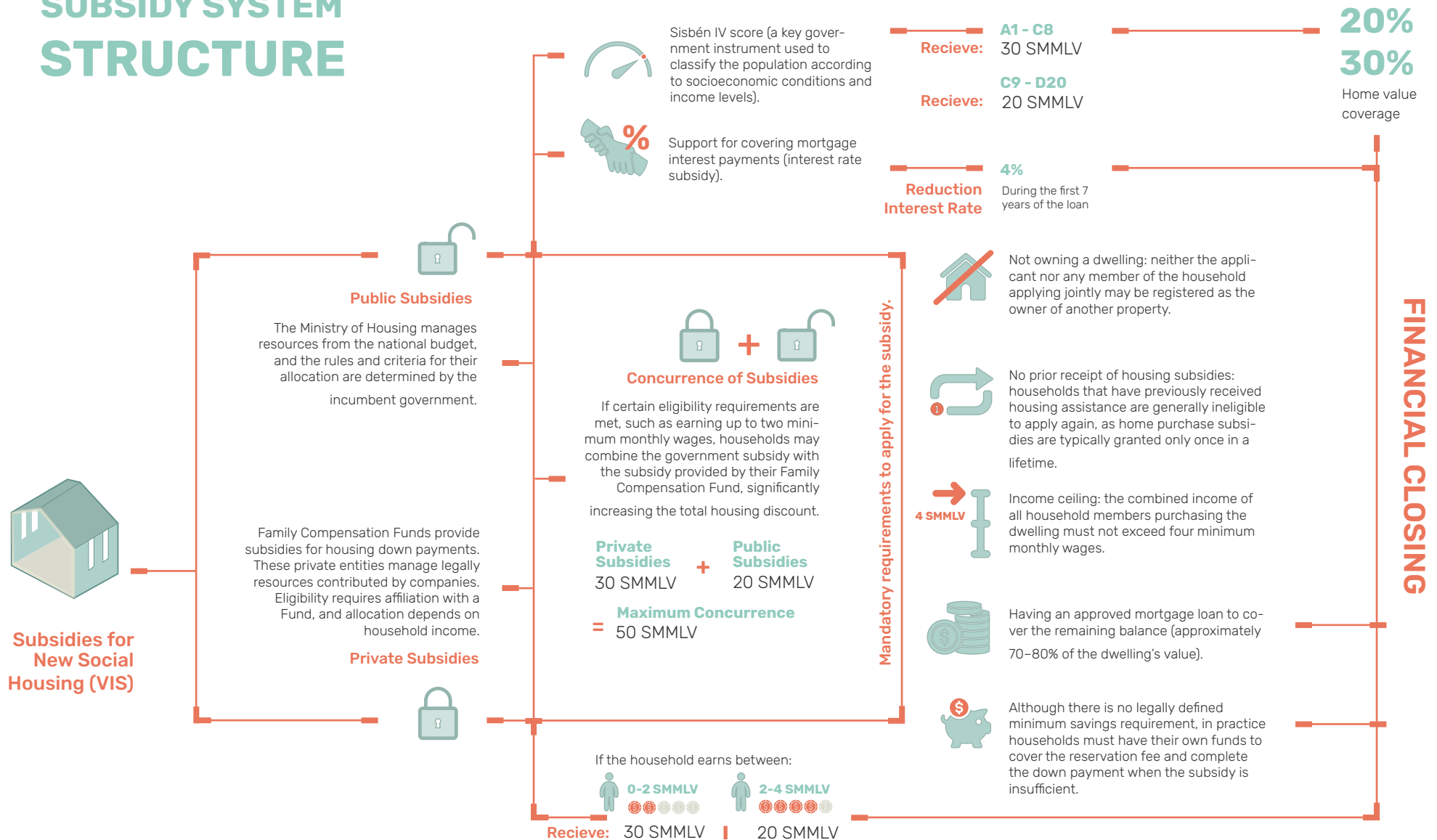
Today, the subsidy system is regulated based on the values assigned to VIS and Priority Interest Housing (VIP), expressed in Current Legal Monthly Minimum Wages (SMMLV), rather than fixed prices or fixed monetary amounts. Consequently, both housing prices and subsidy values increase annually in line with the

government-decreed adjustment of the minimum wage, which is influenced by factors such as inflation, economic growth, productivity, and cost of living.

Within this framework, the subsidy system is structured around two main components. On the one hand, public subsidies are granted by the national government through the Ministry of Housing. Their primary objective is to finance a portion of the down payment and, in some cases, to cover mortgage interest during the initial years of the loan. Eligibility and allocation are determined mainly by the household's classification within the Sisbén IV system (A1–D20).

On the other hand, private or parafiscal subsidies are administered by Family Compensation Funds and financed through mandatory employer contributions. These subsidies are targeted at affiliated households within specific income ranges and are also intended to support the down payment, with their value varying according to household income level.

SUBSIDY SYSTEM STRUCTURE



The concurrence of subsidies allows households with incomes of up to two current legal monthly minimum wages (SMMLV) to combine both public and parafiscal contributions, reaching total assistance of up to 50 SMMLV. This significantly reduces the amount that must be financed through mortgage credit.

Requirements and limitations:

Access to these subsidies requires that households not own a dwelling, have not previously received housing assistance, maintain incomes within the established thresholds (a maximum of 4 SMMLV), and meet the corresponding Sisbén IV classification criteria. In addition, households must demonstrate financial closure capacity, meaning they must secure a combination of subsidies, personal savings, and an approved mortgage loan.

At this point, a structural tension emerges: households that meet the low-income criteria

necessary to qualify for concurrent subsidies often face difficulties in obtaining sufficient credit, as the debt capacity required by financial institutions may exceed their income levels. This paradox limits the real impact of subsidies and reveals the system's vulnerabilities when confronted with market-based financing logics.

Financing and Down Payment:

Housing subsidies typically cover only between 20% and 30% of the total value of the dwelling, requiring households to finance the remaining share through mortgage credit. Loan terms generally range from 20 to 30 years, with interest rates partially subsidized by the government through the FRECH program during the first seven years. However, the need to demonstrate effective savings and to comply with banking requirements limits many households' ability to access housing in practice, even when they qualify for subsidies.

Mortgage credit is therefore mandatory, as it is almost always required to cover the remaining 70–80% of the housing cost. Although there is no legally defined minimum savings requirement to apply for a subsidy, in practice households must have available funds to cover the reservation fee (approximately COP 500,000 to 2,000,000) and to complete the down payment when the subsidy is insufficient.

This situation gives rise to a paradox: households that meet the low-income requirements to qualify for subsidies often face difficulties in obtaining the necessary mortgage credit, as their borrowing capacity does not meet financial institutions' lending criteria.

Scope in Relation to the Housing Deficit:

Colombia's housing deficit affects approximately 5.1 million households, of which 1.3 million require new housing. The number of subsidies available each year (between 50,000 and 75,000) covers less than 5% of total demand,

highlighting both the intense competition for access and the structural limitations of the system. Factors such as application withdrawals, changes in Sisbén classification, and mortgage credit denials further reduce its overall effectiveness.

While public policy has succeeded in articulating innovative mechanisms, such as the concurrence of subsidies and interest rate coverage, it continues to face tensions between social objectives and the economic constraints imposed by the housing market. The emphasis on addressing the quantitative housing deficit and the use of price caps for VIS and VIP housing have led to a form of housing production that, although formally affordable, often compromises construction quality and urban conditions. Moreover, policy interventions have not comprehensively addressed the qualitative housing deficit: many dwellings, despite being accessible, exhibit limitations in space, durability and habitability.

HABITABILITY AND HEALTH

The regulatory scenario in which current Social Interest Housing (VIS) policies in Colombia are framed raises a central question:



What happens to habitability, space, and health when social housing is conceived and regulated exclusively from compliance with legal minimums?



The gap between what the regulations require and what daily life demands highlights the need to shift the analysis from housing understood as a normative product to housing as a lived space.

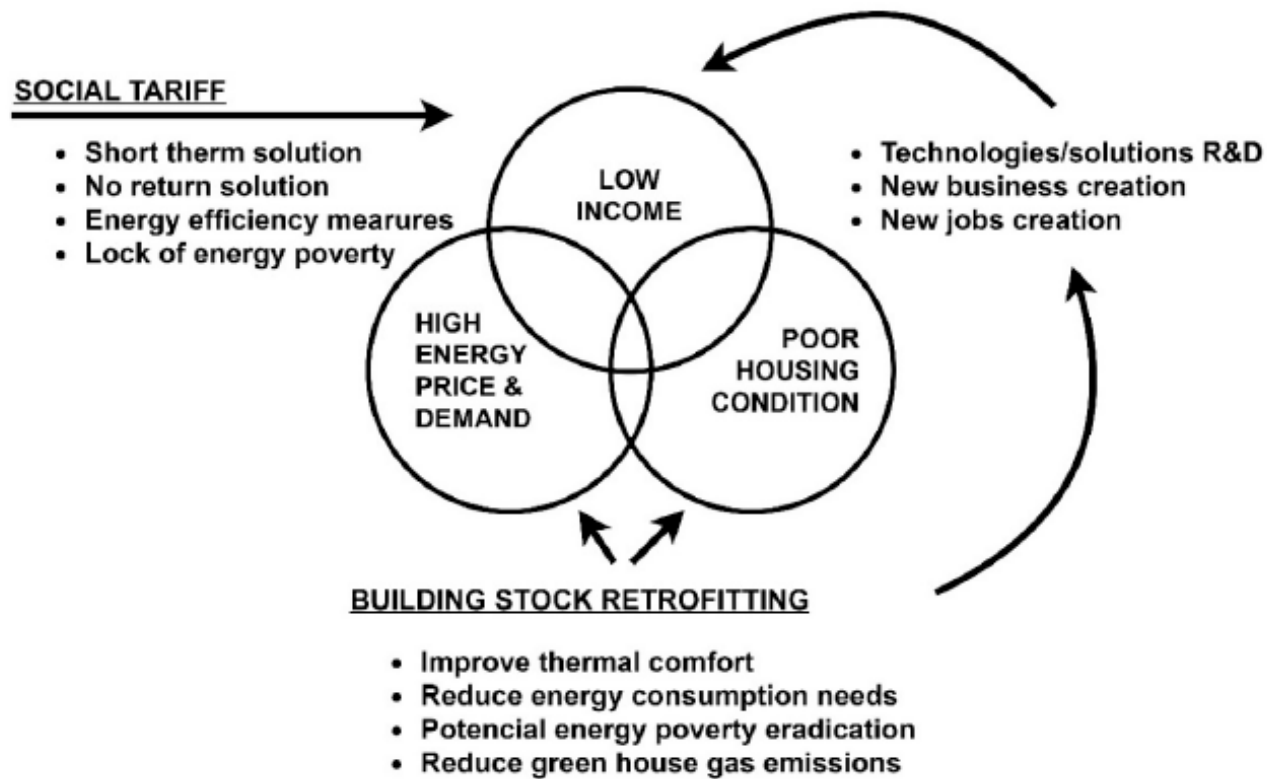
It starts from the premise that housing does not constitute a static object, but a dynamic system in which physical, social, and environmental factors interact. Depending on their configuration, these factors can act as protectors of health or, on the contrary, become structural sources of risk.

In a country characterized by accelerated urbanization processes, high housing densities, and deep socioeconomic inequalities, the quality of the inhabited space acquires a central relevance as a public health issue. In this sense, habitability is not approached as an additional or desirable attribute, but as an essential condition to understand the real impact of the VIS on the quality of life and health of its inhabitants.

The production of the VIS is today at a historical crossroads where the climate crisis, social inequity, and the persistent challenges of public health converge.

Traditionally, housing policy has been evaluated using quantitative indicators aimed at reducing the housing deficit, celebrating the delivery of residential units as the main indicator of success. However, a deeper qualitative analysis reveals that the massification of housing, disconnected from climatic considerations and real habitability, has contributed to the generation of a new form of social vulnerability: structural energy poverty.

Energy Poverty Vectors



ENERGY POVERTY VECTORS

Housing as a social determinant of health.

Nowdays, the understanding of the relationship between housing and health has moved beyond the traditional medical approach, positioning housing as one of the most critical social determinants of morbidity and mortality profiles. Housing does not function as a passive container for domestic life, but rather as an active membrane that regulates the indoor climate, air quality, hygiene, privacy, security, and social interaction, structurally influencing the physical and mental health of the population.

From this perspective, variables such as ventilation, building materials, indoor temperature, accessibility, and urban location directly affect disease transmission, environmental stress, and the overall well-being of households. Empirical evidence demonstrates that deficiencies in these conditions are associated with higher rates of respiratory, cardiovascular, and infectious diseases, as well as significant impacts on mental health.

The World Health Organization (WHO, 2018) guidelines establish that factors such as thermal comfort, physical safety, accessibility, and indoor air quality constitute minimum conditions that housing must guarantee to avoid posing a health risk. It also points out that excessively high or low indoor temperatures increase the risk of respiratory and cardiovascular diseases and heat-related events, an aspect that is especially relevant in hot climates such as those of many Colombian cities.

Energy Poverty from a Habitability perspective.

Energy Poverty from a Habitability Perspective To comprehensively address the relationship between housing, health, and energy poverty, the conceptual and operational model for assessing housing quality in low-income sectors developed by Tarchópulos and Ceballos (2003) is adopted ¹. This model establishes that habitability comprises physical and non-physical dimensions that, together, must guarantee human life in dignified conditions.

The physical dimension encompasses both the urban and architectural scales. At the urban scale, the location of the dwelling within the city, neighborhood, and zone is considered, recognizing that housing does not exist in isolation. Its capacity to promote health depends on the quality of the surroundings, access to services, the physical environment, and exposure to pollutants. Several studies have demonstrated that living in marginalized urban areas is associated with worse health indicators, including higher infant mortality rates.¹

The architectural scale focuses on the dwelling unit and analyzes aspects such as hygiene, protection, privacy, and comfort. Problems such as dampness, overcrowding, and physical deterioration of buildings are not merely structural deficiencies, but rather factors directly related to respiratory illnesses, infections, and domestic accidents. The persistent presence of dampness and mold, for example, has been consistently associated with asthma, rhinitis, and pneumonia, even when controlling for socioeconomic variables.¹

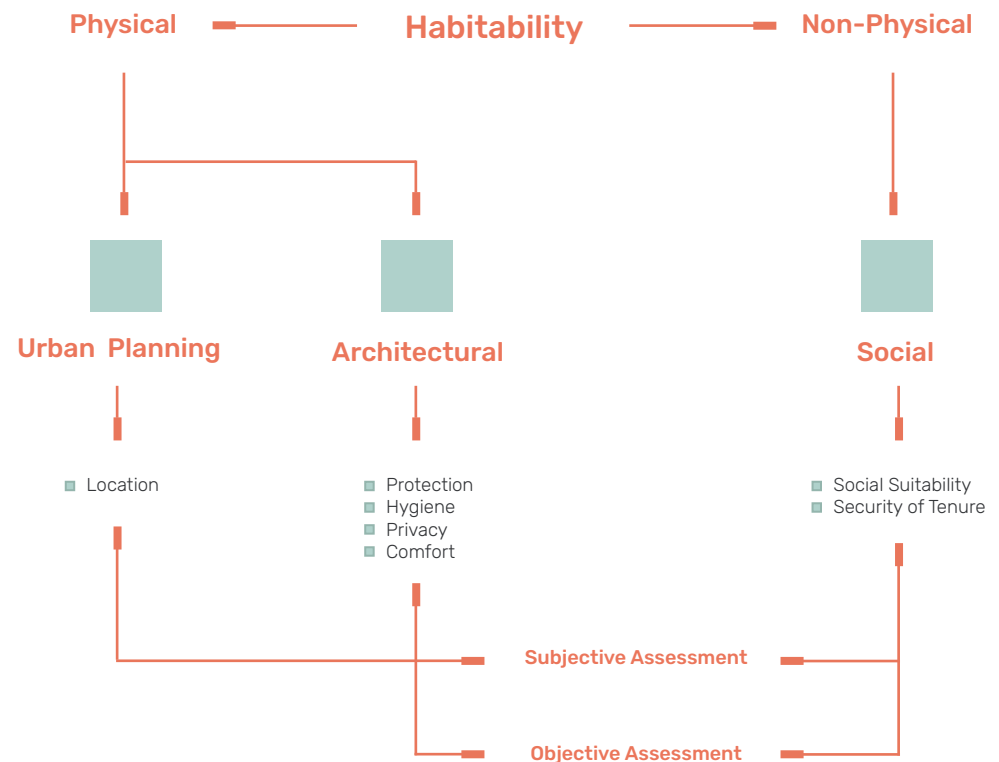
1. Ceballos Ramos, O. & Tarchópulos, D. 2003. Calidad de la vivienda dirigida a sectores de bajos ingresos en Bogotá.

1. Ramos, O. L. C. 2006, Política habitacional y calidad de la vivienda: Reflexiones sobre la habitabilidad de la vivienda bajo costo en Bogotá.

HOUSING QUALITY

Figure X

Model for evaluating housing quality according to habitability conditions. Source: Tarchópulos and Ceballos (2003).



The non-physical dimension introduces the social component of habitability. Factors such as security of tenure and the social adequacy of housing profoundly influence mental health. Uncertainty regarding one's continued residence generates chronic stress and affects emotional stability. Similarly, when housing does not meet the cultural, functional, or productive needs of households, conflicts, functional overcrowding, and a decline in psychological well-being arise.¹

1. Ceballos-Ramos, O. L. & Vega-Romero, R. 2015. La habitabilidad y la salud en Colombia. Una propuesta metodológica para su análisis.

In the Latin American context, and specifically in the Colombian tropics, energy poverty cannot be understood solely through the European lens focused on winter heating. In cities like Cali, this condition manifests itself in the inability of households to mitigate high temperatures, ensure adequate food preservation through refrigeration, and guarantee effective ventilation that does not compromise the physical or respiratory safety of their occupants. This form of energy poverty, frequently invisible in official electricity coverage statistics, constitutes a significant epidemiological burden.

From Ceballos methodology perspective, energy poverty ceases to be solely a cost issue and reveals itself as a direct consequence of the qualitative decline in low-cost housing.¹ A poorly designed dwelling, with highly heat-conducting materials, inadequate ventilation, and insufficient solar protection, condemns its inhabitants to constant energy consumption to achieve minimum living conditions—consumption that is often economically unattainable.

Studies based on this methodology demonstrate that improvements in living conditions significantly reduce the likelihood that people perceive their health as poor. This confirms that when these conditions are combined in contexts of urban poverty, housing ceases to be a space of protection and becomes an amplifier of inequalities.

Thermal Performance of Social Housing in Cali and its Health Effects

In some regions of Colombia, the analysis of energy poverty reveals a paradox between coverage and quality. The Valle del Cauca, where Cali is located, appears in official reports as a case of favorable performance, with an energy poverty rate of 3.2% in 2022 according to multidimensional index of energy poverty (IMPE) coverage metrics.¹

Although electrical infrastructure reaches most households, the quality of service and its affordability are deficient. The IMPE (2023)

The physical dimension encompasses both the urban and architectural scales. At the urban scale, the location of the dwelling within the city, neighborhood, and zone is considered, recognizing that housing does not exist in isolation. Its capacity to promote health depends on the quality of the surroundings, access to services, the physical environment, and exposure to pollutants. Several studies have demonstrated that living in marginalized urban areas is associated with worse health indicators, including higher infant mortality rates.¹

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1. Ramos, O. L. C. 2006, Política habitacional y calidad de la vivienda: Reflexiones sobre la habitabilidad de la vivienda bajo costo en Bogotá.

1. Análisis del Índice Multidimensional de Pobreza Energética (IMPE). 2025

1. Giraldo Castañeda, W. 2018. Optimización del confort térmico en clima ecuatorial con tecnologías pasivas en fachadas: el caso de las viviendas de interés social de Cali.

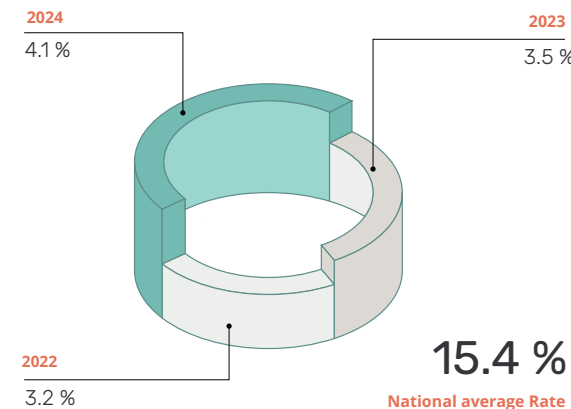
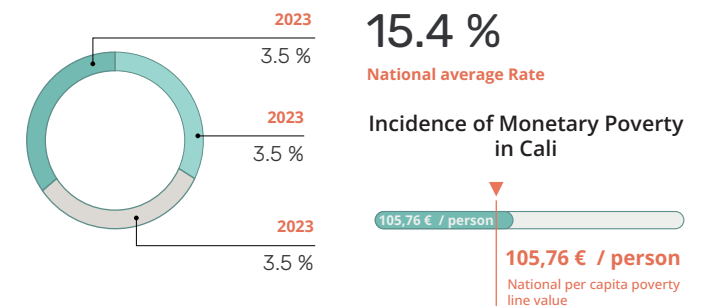
Several academic studies have highlighted the predominant use of poured concrete and brick construction systems without thermal insulation, resulting in high thermal inertia. ¹ The walls absorb heat during the day and release it back into the interior at night, preventing the nighttime cooling necessary for rest. This is compounded by the absence of sun protection devices, the small size of the dwellings, and the lack of cross-ventilation, creating homes that function as veritable heat traps.

Evaluations using the Predicted Mean Vote (PMV) and Percentage of Dissatisfied Persons (PPD) models indicate thermal sensations of “very hot” inside social housing, with dissatisfaction levels approaching 100% during daylight hours. From a habitability perspective, these homes do not act as shelters from the elements, but rather as amplifiers of heat stress, shifting an architectural design problem into the realm of domestic energy consumption.

Finally, energy poverty directly impacts mental health. Living in overcrowded conditions, with persistent heat and economic uncertainty

related to paying for utilities, generates chronic stress, irritability, and anxiety. It also limits opportunities for learning, communication, and leisure by restricting access to adequate lighting and the use of electronic devices, deepening social and health inequalities.

Monetary poverty Index in Cali over the National Rate

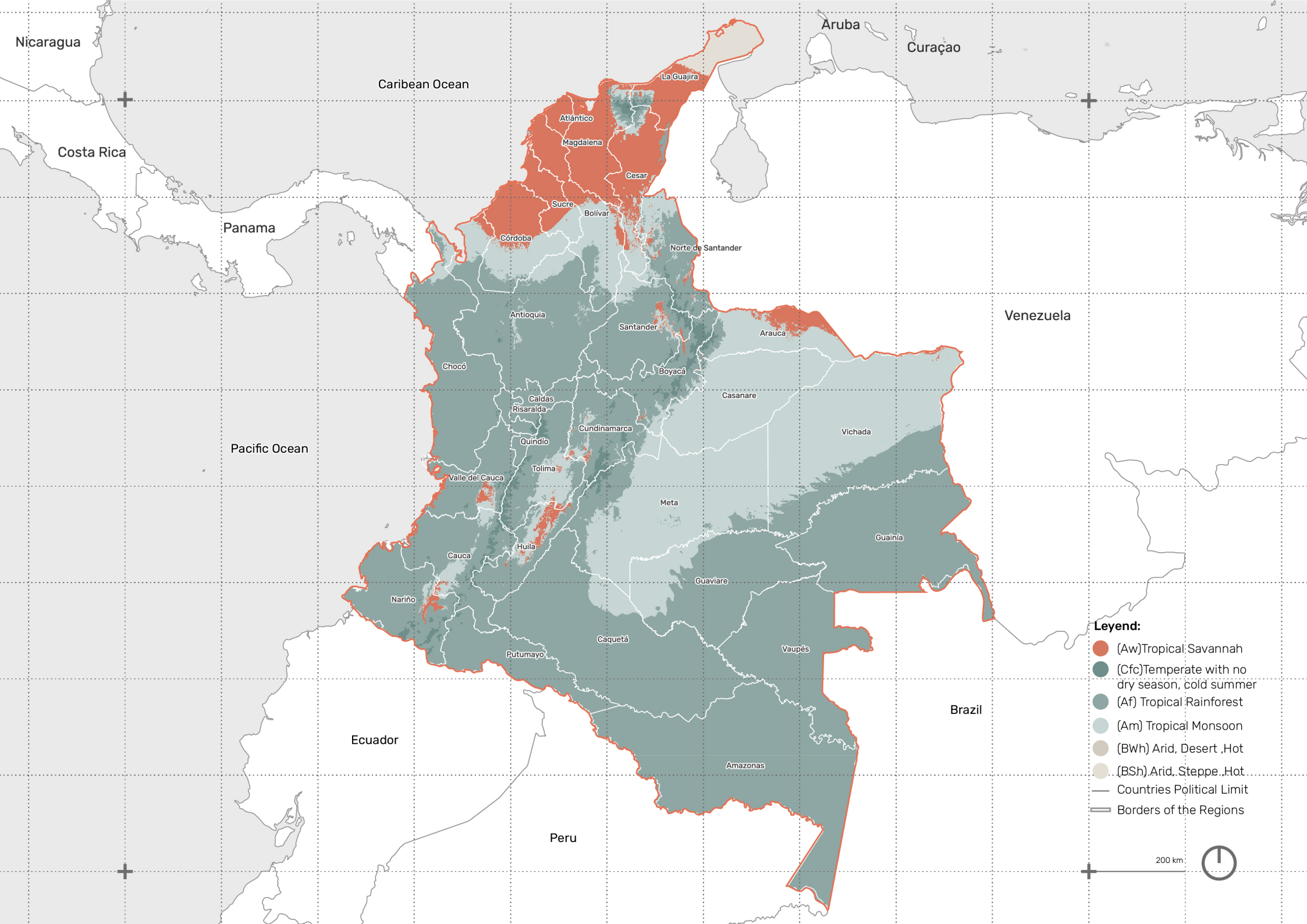


Multidimensional Energy Poverty Index in Cali over the National Rate

1. Giraldo Castañeda, W. 2018. Optimización del confort térmico en clima ecuatorial con tecnologías pasivas en fachadas: el caso de las viviendas de interés social de Cali.



This chapter combines the climatic and housing context of the research. It characterises Cali's climate, including its Köppen Aw classification, future climate projections, and the EPW morphing process toward the 2050 scenario under SSP2-4.5 and MIROC6. It also presents the framework of social housing in Colombia, with attention to VIS policy, construction systems, urban production, and the multifamily housing stock built in Cali between 1990 and 2015.



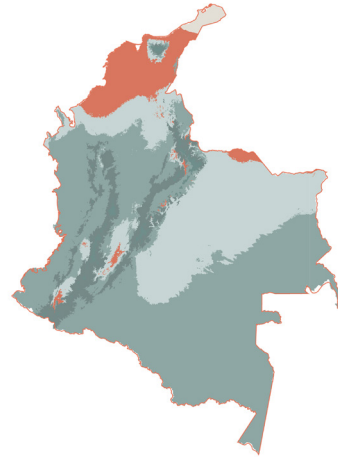
CLIMATE IN COLOMBIA

Colombia is located in the tropical region near the equator, where seasonal temperature variations are minimal throughout the year. Instead of pronounced seasonal changes, climatic conditions are mainly influenced by the country's complex topography and the presence of the Andes mountain range, which divides the territory into several geographic regions with distinct environmental characteristics. As a result, Colombia exhibits a wide range of climatic conditions, from humid tropical lowlands to cooler mountain environments. A key concept used to explain this variation is the system of thermal floors, which classifies climate according to altitude above sea level. As elevation increases, air temperature gradually decreases, generating different climatic zones that influence ecosystems, settlement patterns, and environmental conditions. Consequently, altitude becomes a primary factor in determining local temperature, humidity, and solar exposure, all of which play an important role in shaping architectural responses and building performance.

City Location Accordign to Thermal Floors

> 4000 m.a.sl | < 6°C 1000 m.a.sl | 17°C - 25°C
 3000 m.a.sl | 6°C - 12°C 0 m.a.sl | > 25°C
 2000 m.a.sl | 12°C - 17°C

Projected future conditions 2041 - 2070 under climate change

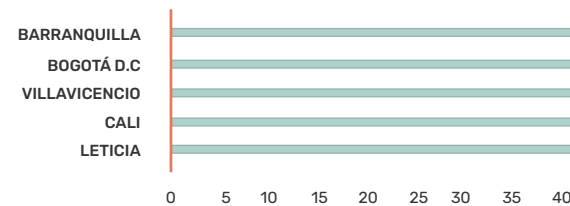


Greater regions in Colombia

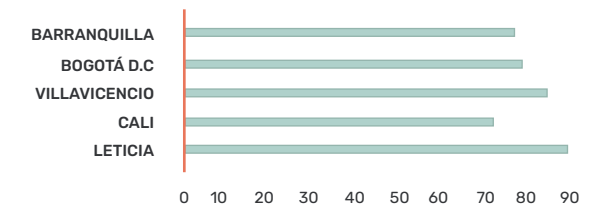


Climate data for greater cities of Colombia per year / average

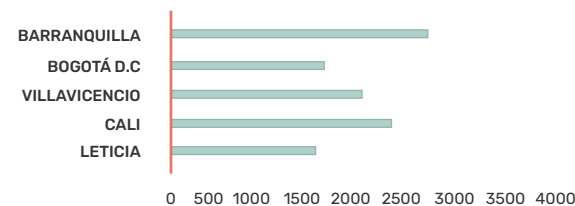
Average Temperature (°C)



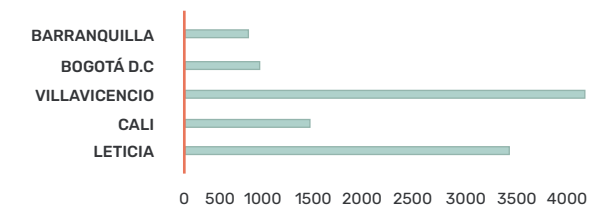
Humidity (%)



Sunshine Hours



Precipitation (mm)



(96 m.a.s.l) LETICIA

(2640 m.a.s.l) BOGOTÁ D.C

(1018 m.a.s.l) CALI

(18 m.a.s.l) BARRANQUILLA

(467 m.a.s.l) VILLAVICENCIO

PACIFIC REGION
CAUCA VALLEY DEPARTMENT

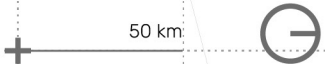
General Information:

Location: Pacific Region
Territory: 619 km ²
Population: 2 234 400 (2023)

Housing: Cali produce the 38% of the total
VIS social housing in Colombia (2023)
Communes: 22



- Legend:**
- Urban city Subdivision into Communes
 - Rural Borders
 - Roads
 - Rivers
 - Green Open Space
 - Social housing Concentration



CLIMATE SCENARIO IN CALI

Cali is located in southwestern Colombia, in the Cauca River valley between the Western and Central branches of the Andes. This geographic position plays an important role in shaping the city's climate. The surrounding mountain ranges create a valley condition that influences solar exposure, wind circulation, and the accumulation of heat within the urban area. At the same time, Cali's elevation of around 1,000 meters above sea level places it within Colombia's temperate thermal floor, where temperatures remain relatively stable throughout the year despite the country's tropical latitude.

Cali is the third largest city in Colombia and a major urban center in the Pacific region. Rapid urban growth and expansion across the valley floor have intensified environmental pressures, particularly those related to heat exposure and urban thermal comfort. In addition, the city's proximity to the Pacific region contributes to high atmospheric humidity and influences regional climatic patterns.

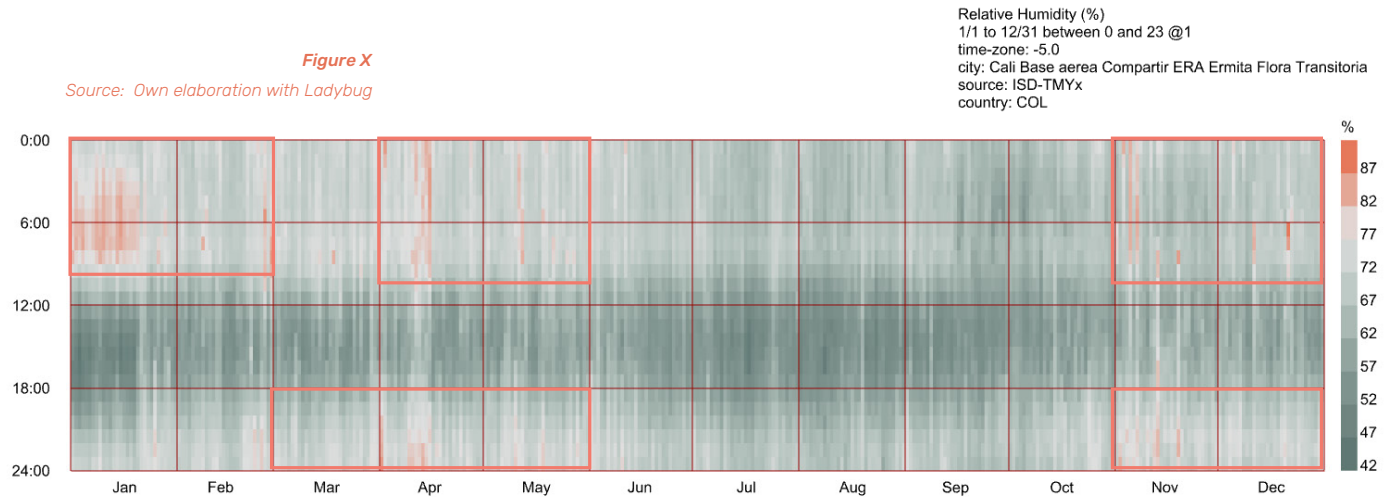
Together, these geographic conditions define the macroclimatic context of the city and provide the basis for understanding the main climate variables analyzed in the following sections.

1 | Relative Humidity

Cali exhibits consistently high relative humidity throughout the year, with nighttime values ranging between 75–85% and daytime values between 50–65%, indicating that the diurnal cycle is more influential than seasonal variation. This pattern is driven by the thermodynamic mechanisms characteristic of tropical climates: nocturnal cooling increases relative humidity, while daytime heating reduces it. At the annual scale, two periods of slightly higher humidity can be identified, coinciding with the rainy seasons (March–May and October–November), although the amplitude of this variation remains moderate compared to the daily fluctuation.

From a bioclimatic perspective, sustained high humidity has direct implications for architectural design: as it reduces the effectiveness of evaporative cooling, indoor spaces may be perceived as thermally warmer even under moderate temperatures. Therefore, the primary design response should not be limited to providing shading, but should also prioritize the active promotion of air movement through ventilation strategies.

Figure X
Source: Own elaboration with Ladybug

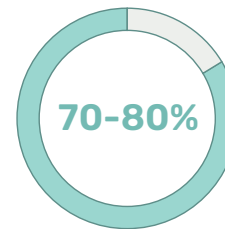


 Humidity variation periods



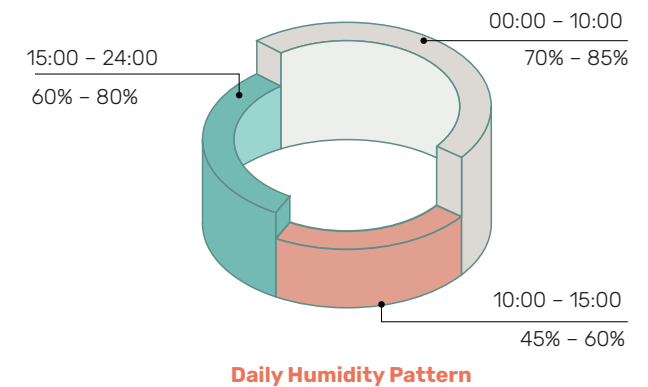
Low Humidity Periods

June - September
December - February



High Humidity Periods

March- May
November - December



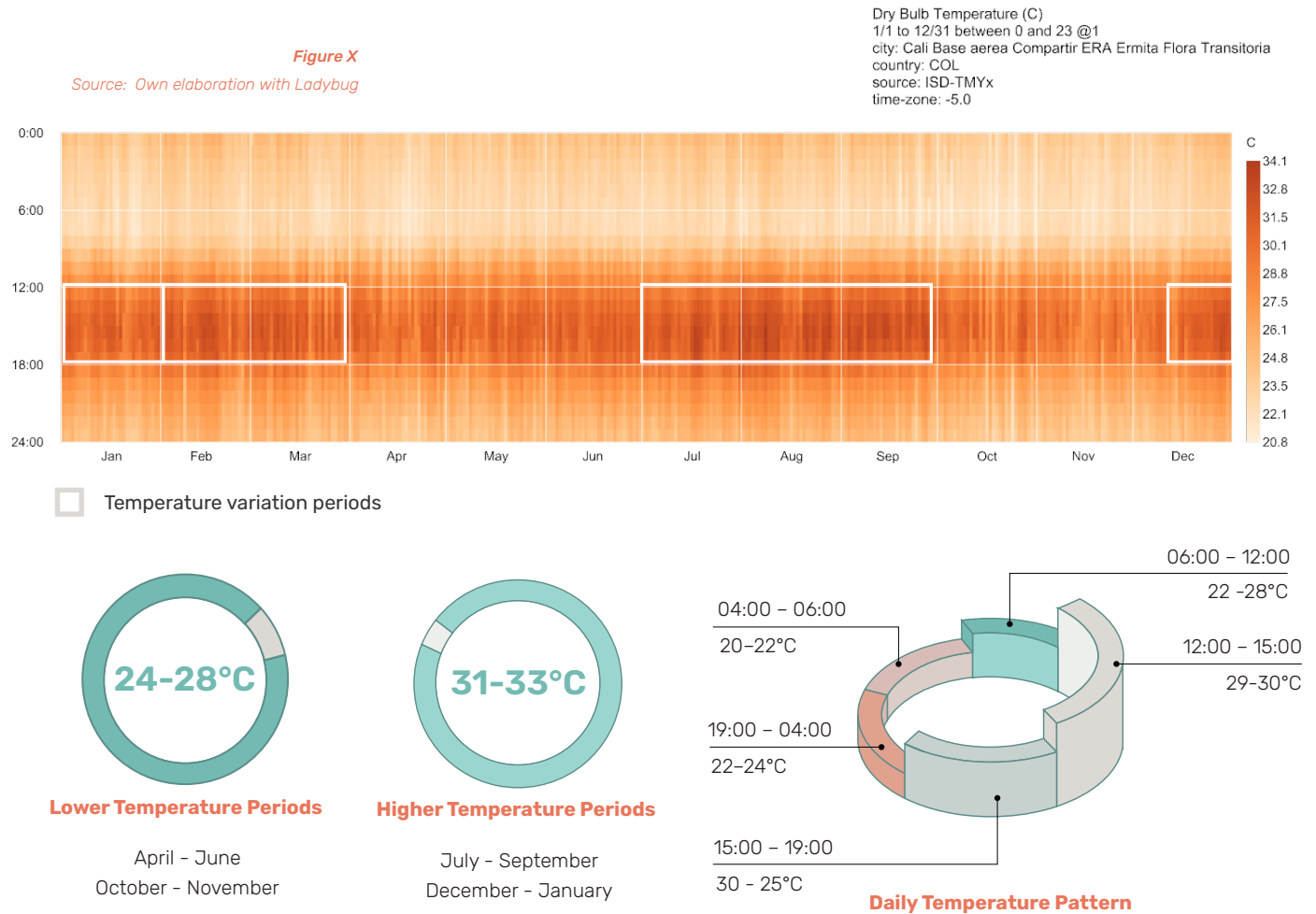
"Nocturnal cooling increases relative humidity by reducing the air's capacity to hold water vapor, whereas daytime heating decreases it by enhancing that capacity".

2 | Dry Bulb Temperature

Cali's dry-bulb temperature profile confirms a highly stable equatorial macroclimate, defined not by seasonal extremes but by a dominant and repetitive diurnal cycle. Annual thermal amplitude is remarkably narrow, approximately 2–3°C, with peak daytime temperatures of 31–32°C occurring between July and September and minimum early morning values of 20–21°C registered during April–June and October–December. This near-absence of seasonal differentiation contrasts sharply with a daily swing of 8–10°C, driven by consistent solar radiation patterns, which constitutes the primary thermal driver at the macroclimatic scale.

From a bioclimatic standpoint, this pattern carries a direct design implication: since seasonal adaptation is climatically irrelevant in Cali, architectural strategies must instead respond to the diurnal cycle, prioritizing nocturnal cooling, thermal mass calibration, and solar control during peak afternoon hours as the operative levers for achieving thermal comfort.

Figure X
Source: Own elaboration with Ladybug



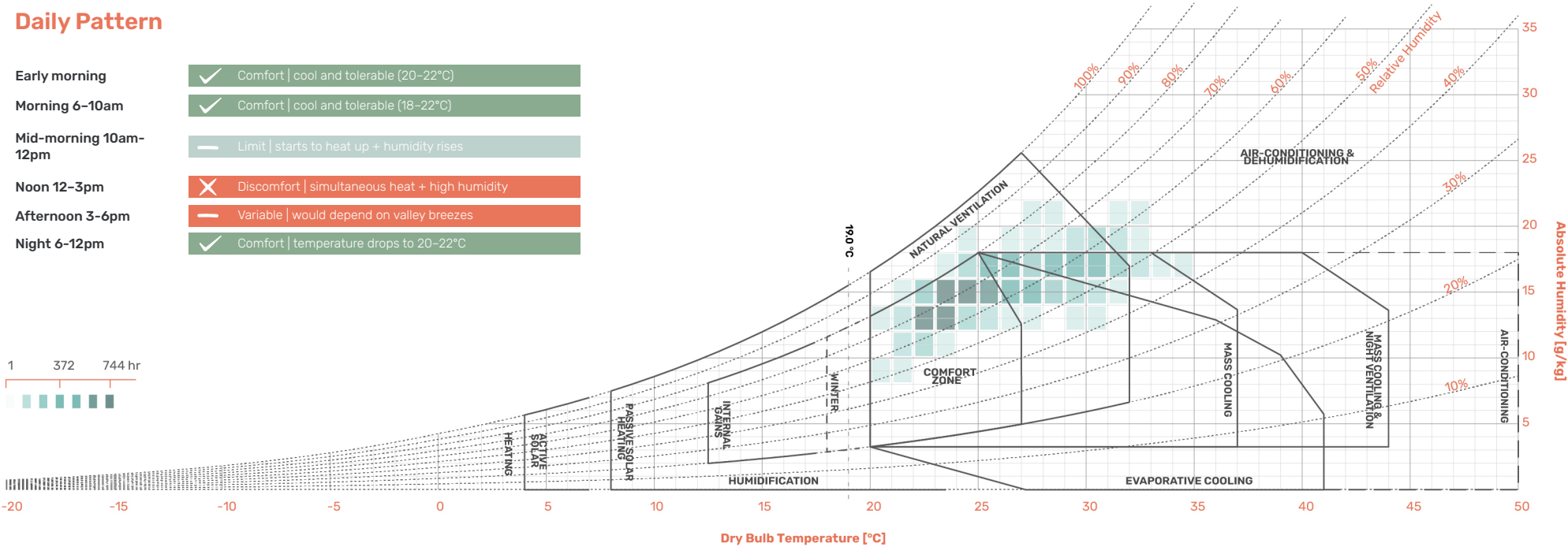
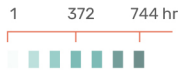
PSHYCHROMETRIC CHART

Figure X

Source: Own elaboration - ClimateStudio

Daily Pattern

Early morning	✓ Comfort cool and tolerable (20–22°C)
Morning 6–10am	✓ Comfort cool and tolerable (18–22°C)
Mid-morning 10am–12pm	— Limit starts to heat up + humidity rises
Noon 12–3pm	✗ Discomfort simultaneous heat + high humidity
Afternoon 3–6pm	— Variable would depend on valley breezes
Night 6–12pm	✓ Comfort temperature drops to 20–22°C



44.46%

Percentage in Comfort

25%

Recoverable with Natural Ventilation

20%

Recoverable with thermal mass

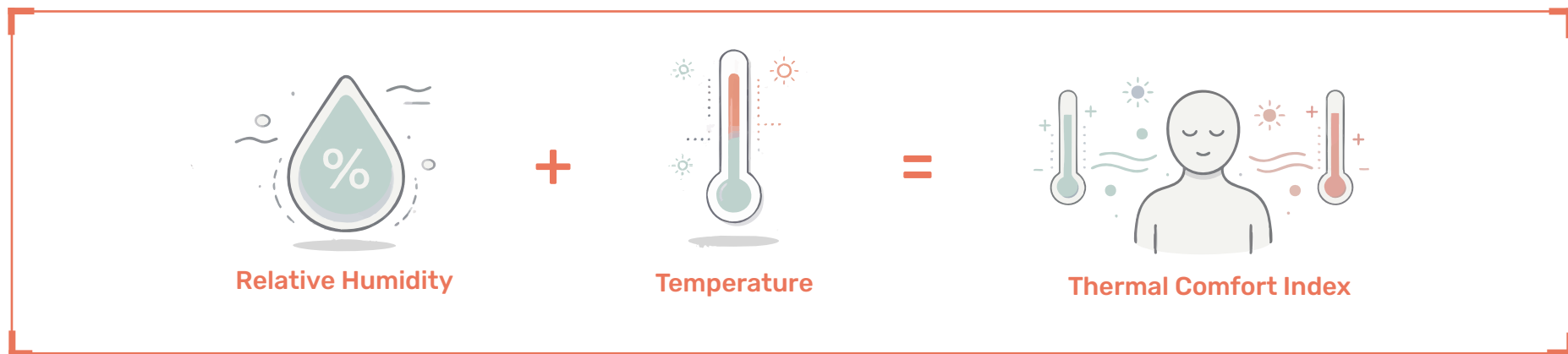
11%

Requires A/C

3895/8760

hrs/year

Total Annual Hours In Comfort



Cali has a tropical savanna climate (Köppen Aw), with temperatures ranging between 23°C and 33°C, moderated by its elevation of approximately 1,000 meters above sea level. Relative humidity remains between 70% and 80% throughout the year, increasing the perceived temperature by approximately 5°C to 8°C above the actual air temperature. This condition makes humidity, rather than temperature, the primary driver of thermal discomfort in residential environments.

Givoni's psychrometric chart indicates that only 44.46% of the annual hours fall within the natural thermal comfort zone, defined by a dry-bulb temperature range of 18°C to 26°C and a relative humidity between 30% and 70%. This percentage indicates that, for more than

half of the time, the building requires some form of active or passive strategy to ensure adequate habitability conditions.

This proportion of thermal comfort can be primarily attributed to the combination of high temperatures and elevated relative humidity significantly reduces the human body's ability to dissipate heat through sweat evaporation. Under conditions approaching 80% relative humidity, the air becomes nearly saturated with water vapor, restricting this physiological cooling mechanism and increasing the perceived operative temperature to values ranging from 35°C to 38°C during midday hours. The psychrometric analysis demonstrates that thermal discomfort in residential buildings is not driven by extreme temperatures but rather

by the simultaneous interaction of moderately high temperatures and elevated relative humidity levels. This condition increases the perceived thermal sensation by approximately 5°C to 8°C above the actual measured air temperature.

However, the implementation of passive design strategies can significantly improve comfort conditions. In particular, a dwelling that incorporates effective cross-ventilation, solar control on the most exposed façades, and appropriately dimensioned thermal mass can achieve between 65% and 70% of annual hours within the natural thermal comfort range. Consequently, reliance on mechanical air conditioning can be reduced to approximately 11% of the time, resulting in substantial benefits in terms of energy efficiency.

3 | Solar Radiation

Solar radiation is a constant and dominant climatic factor, with high levels of global radiation throughout the year and little seasonal variation. Peak values reach up to 983 W/m², supported by both strong direct radiation and a significant diffuse component, meaning that even shaded areas remain exposed to solar energy. While peak radiation occurs around midday, when solar angles are high (60°–90°) and can be more easily controlled through horizontal shading (optimal angles), the most critical conditions occur at low solar angles between 10° and 35°, during early morning and late afternoon. At these angles, solar radiation penetrates deeply into buildings and urban spaces, especially on east and west façades, and becomes much harder to control.

As a result, design strategies must address both conditions by combining effective shading, proper orientation, and urban forms that reduce heat gain and support thermal dissipation.

**1,572 kWh/m²
year**

Total annual radiation

179.4 W/m²

Average annual radiation

331.2 W/m²

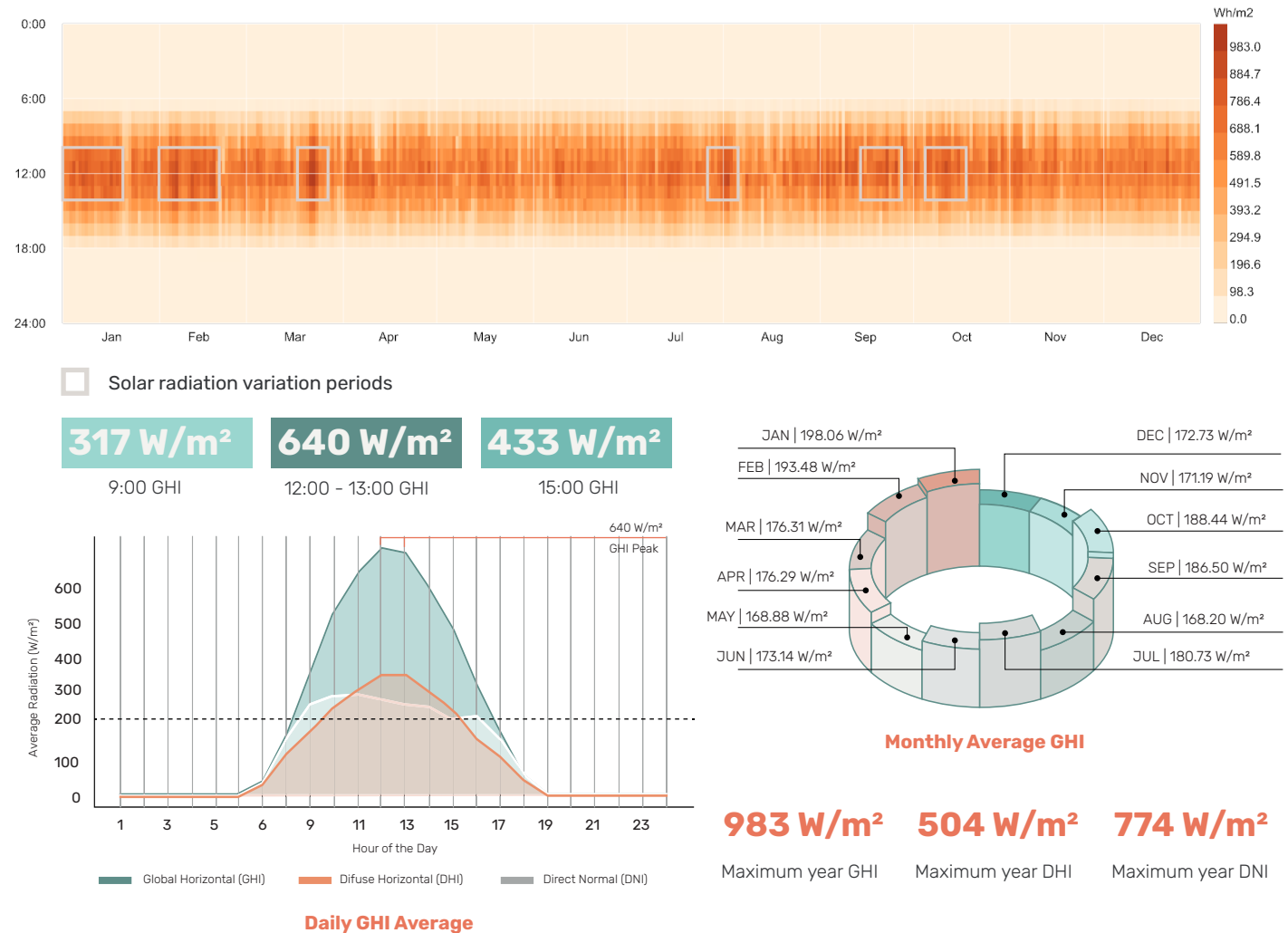
Average daytime radiation
(6am–6pm)

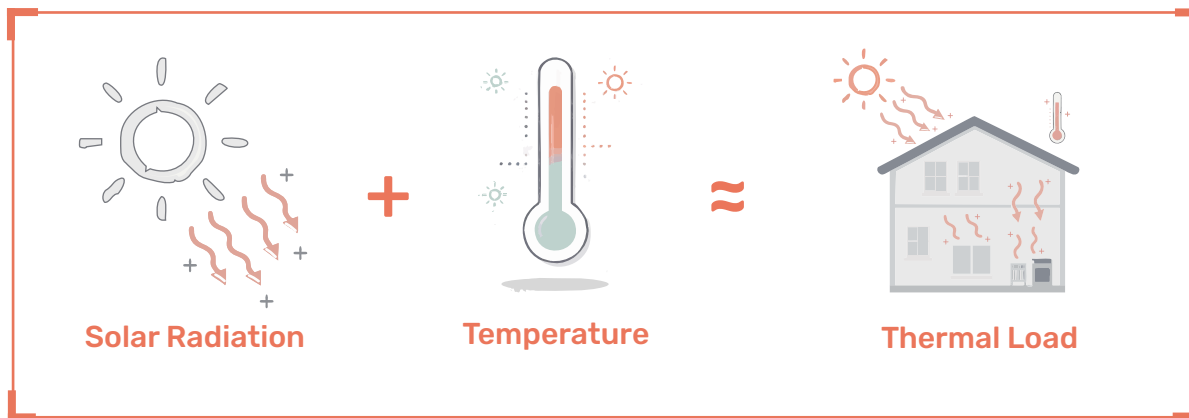
983 W/m²

Maximum Radiation

Figure X

Source: Own elaboration with Ladybug

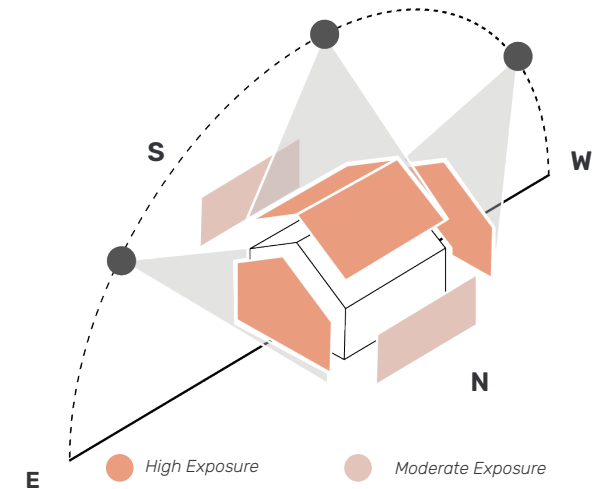




In a climate such as Cali's, thermal load does not depend on a single variable but rather on the synchronization between solar radiation and air temperature, where radiation acts as the primary source of heat gain while ambient temperature limits the capacity for heat dissipation. This interaction produces a cumulative effect that intensifies overheating, particularly during the hours following midday, when stored heat continues to affect the built environment even as solar radiation begins to decrease. In warm climates, the combination of high solar radiation and elevated air temperatures significantly contributes to heat accumulation and increased thermal stress in urban environments (IPCC, 2021; IPCC, 2022). Within this framework, two radiation thresholds can be identified to interpret their impact on thermal comfort: a lower threshold of approximately 200 W/m², at which solar radiation becomes thermally relevant, and an upper threshold of around 400 W/m², which indicates conditions

of significant thermal stress and potential overheating.

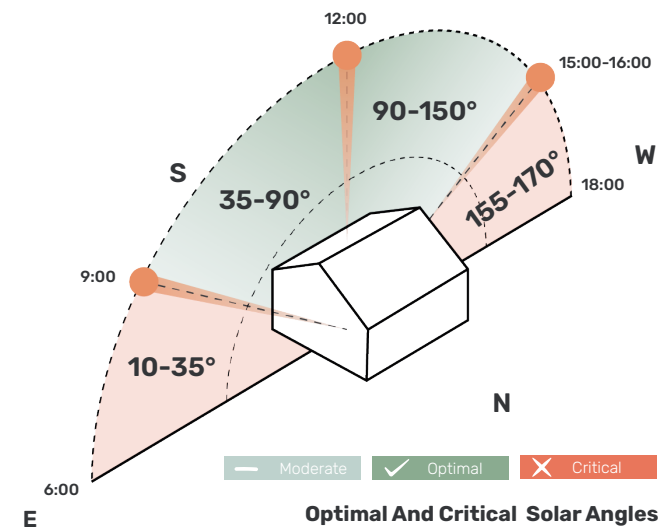
While the former marks the onset of solar gains affecting the building, the latter defines the point at which these gains become critical for thermal comfort. In the case of Cali, radiation values frequently exceed this upper threshold during daytime hours, demonstrating that thermal overload is not an occasional condition but a recurrent one. Thus, rather than analyzing solar radiation as an isolated variable, this approach frames thermal load as a persistent microclimatic condition, where ranges of 0–200 W/m² correspond to low impact, 200–400 W/m² to moderate impact, and values above 400 W/m² to critical thermal overload, reinforcing the need for architectural strategies based on continuous solar control, effective ventilation, and the reduction of thermal exposure.



Facade Exposition to Solar Radiation

Figure X

Source: Own elaboration - ClimateStudio



Optimal And Critical Solar Angles

Figure X

Source: Own elaboration - ClimateStudio

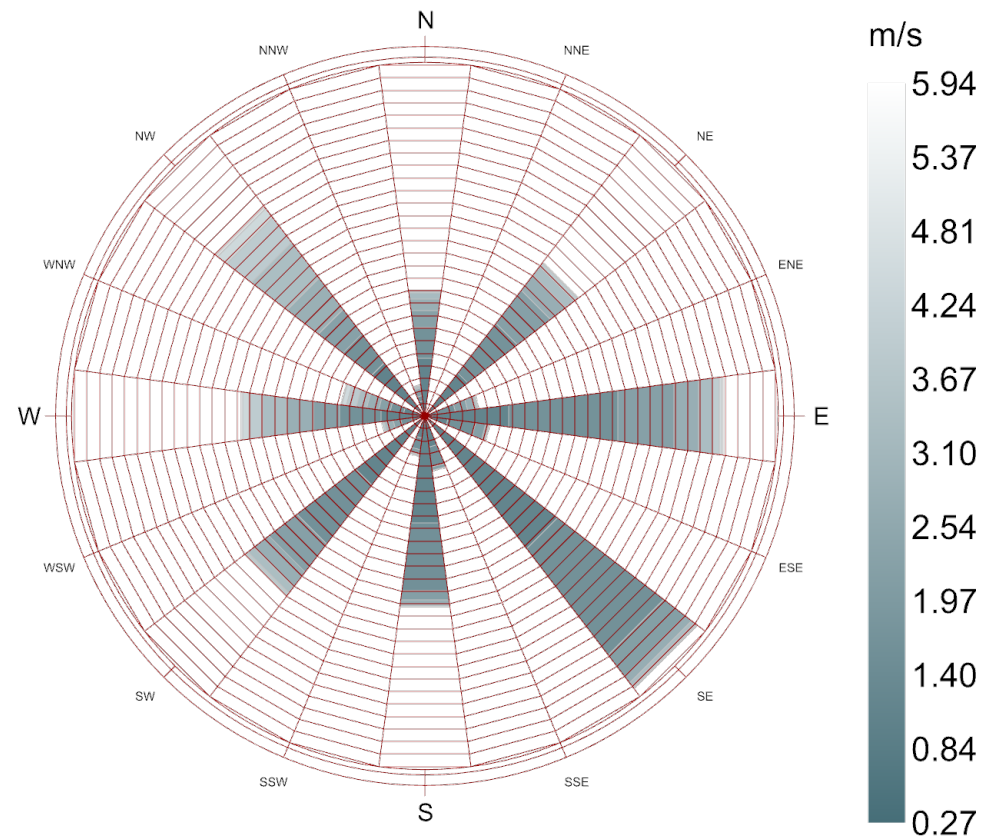
4 | Wind

The wind regime in Cali is strongly influenced by the Cauca River valley, resulting in a clear and consistent directional pattern rather than random airflow. The dominant winds come from the north-northwest (N-NNW), with a secondary flow from the east (E), southeast (SE). Together, these directions form a longitudinal airflow corridor aligned with the valley, shaped by both regional Pacific air movements and local valley-mountain dynamics.

Wind speeds are generally moderate, 2–4 m/s, which are suitable for natural ventilation. However, periods of calm conditions can reduce airflow and limit the dispersion of heat and pollutants. Therefore, the effectiveness of ventilation in the city depends more on urban form than on wind intensity.

From a design perspective, urban and architectural layouts that align with prevailing winds can significantly improve thermal comfort, which is essential in a warm-humid climate such as Cali. More permeable and elongated buildings, allow for more effective ventilation than compact forms, which tend to trap heat.

Wind Speed (m/s)
country: COL
source: ISD-TMYx
city: Cali Base aerea Compartir ERA Ermita Flora Transitoria
time-zone: -5.0
period: 1/1 to 12/31 between 0 and 23 @1
Calm for 0.0% of the time = 0 hours.
Each closed polyline shows frequency of 0.6% = 50 hours.



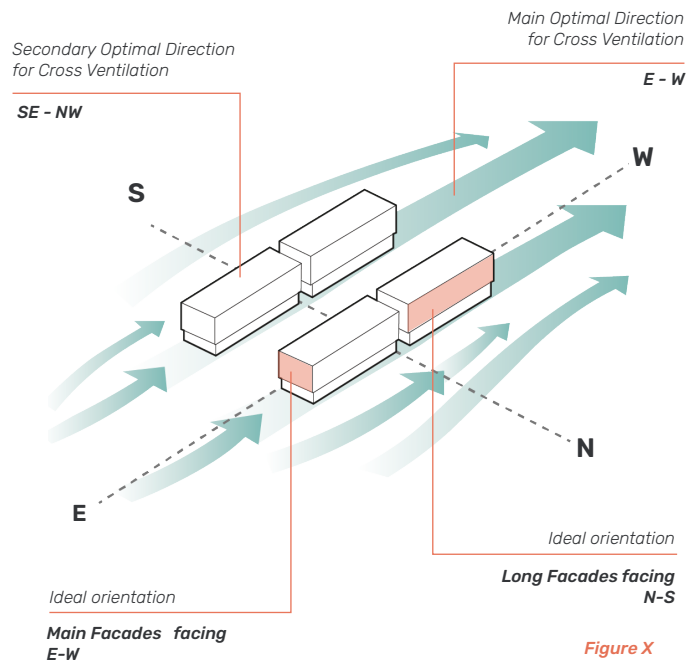


Figure X
Source: Own elaboration

Ideal Wind Speed for Comfort

1 – 1.5 m/s	— Basic comfort
2 – 4 m/s	✓ Optimal in hot and humid climates
5 m/s	✗ May be uncomfortable

The main environmental objective is not to retain heat but to facilitate its dissipation through air movement. In this context, wind becomes a key factor in shaping indoor and urban microclimate. However, the effectiveness of ventilation does not depend solely on wind speed, but largely on how the built environment interacts with airflow.

However, the effectiveness of this natural ventilation does not depend solely on the presence or intensity of wind, but largely on how the built environment interacts with airflow. Urban form becomes a critical mediator between climate and comfort. Factors such as compactness (S/V ratio), spatial configuration, orientation, and permeability directly influence the capacity of air to move through the urban fabric.

Highly compact urban forms, characterized by low surface-to-volume ratios, tend to reduce exposure and restrict airflow, often leading to heat accumulation and stagnant air conditions. In contrast, more open and permeable configurations increase the potential for air

exchange and heat dissipation, allowing wind to penetrate deeper into the urban structure. Nevertheless, increased exposure alone is not sufficient. The orientation of buildings and urban layouts in relation to prevailing winds is equally important. Forms that are misaligned with airflow can block or deflect wind, limiting ventilation even if they are not highly compact.

CLIMATE CHANGE EFFECT

Cali's macroclimatic condition is defined by a stable equatorial regime in which solar radiation acts as the primary driver of thermal behavior, while air temperature limits the capacity for heat dissipation. As established in the microclimatic analysis, thermal load does not depend on a single variable, but on the synchronization between radiation and temperature, generating cumulative heat effects that intensify during peak daytime hours.

Within this framework, climate change does not introduce new thermal dynamics, but rather amplifies existing ones. The previously identified thresholds, become increasingly significant under changing climatic conditions. As global temperatures rise and atmospheric conditions shift, these thresholds are exceeded more frequently and for longer durations, extending periods of thermal stress and reducing the capacity of the built environment to dissipate heat effectively.

At the urban scale, this intensification is not distributed uniformly, but is strongly mediated by land use patterns and spatial configuration.

In this regard, the Surface Urban Heat Island (SUHI) effect emerges as one of the most critical manifestations of climate change in Cali. The SUHI describes the phenomenon by which urban areas experience higher surface temperatures than their rural surroundings, primarily due to the replacement of natural land covers with impervious materials that absorb and re-radiate solar energy.

In Cali, this condition is directly correlated with patterns of urban development. Comunas with higher percentages of built surfaces consistently present higher land surface temperatures, confirming a strong positive relationship between urbanization and heat accumulation ($R^2 \approx 0.7$). This produces a clear spatial pattern in which central and highly consolidated areas concentrate the highest thermal loads, while peripheral zones remain relatively cooler but are increasingly exposed due to ongoing urban expansion.

However, while these dynamics are produced at the urban scale, their impact is ultimately experienced at the architectural level.

Buildings located in highly urbanized areas are exposed to elevated baseline temperatures, reduced night-time cooling, and diminished environmental buffering due to the loss of vegetation and evapotranspiration processes. This condition intensifies the interaction between solar radiation and ambient temperature previously identified in the microclimatic analysis, increasing internal heat gains and reducing the capacity for thermal dissipation.

As a result, architectural performance becomes critical in mediating these amplified conditions. The same variables identified at the micro scale, solar exposure, material behavior, ventilation capacity, and spatial configuration, operate under more demanding environmental thresholds, where climate change increases the magnitude and duration of thermal stress, while the urban fabric determines its spatial distribution.

In this sense, climate change and urbanization do not redefine the thermal logic of buildings in Cali, but rather push it beyond its previous limits, making passive design strategies not only relevant, but necessary for maintaining thermal comfort.

Number of Trees per Habitant



Figure X

Source: NASA DEVELOP National Program
California - Ames

% of Urban Development



Figure X

Source: NASA DEVELOP National Program
California - Ames



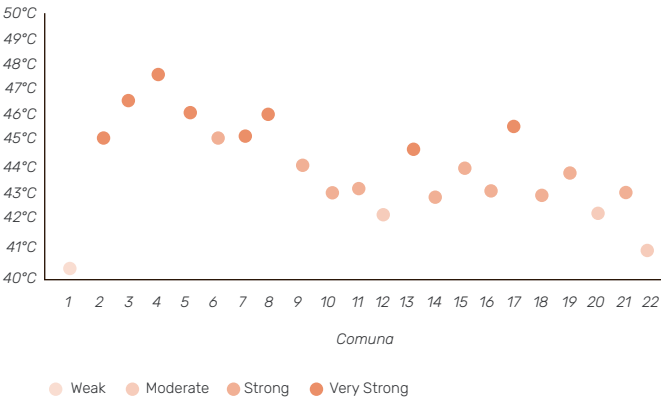
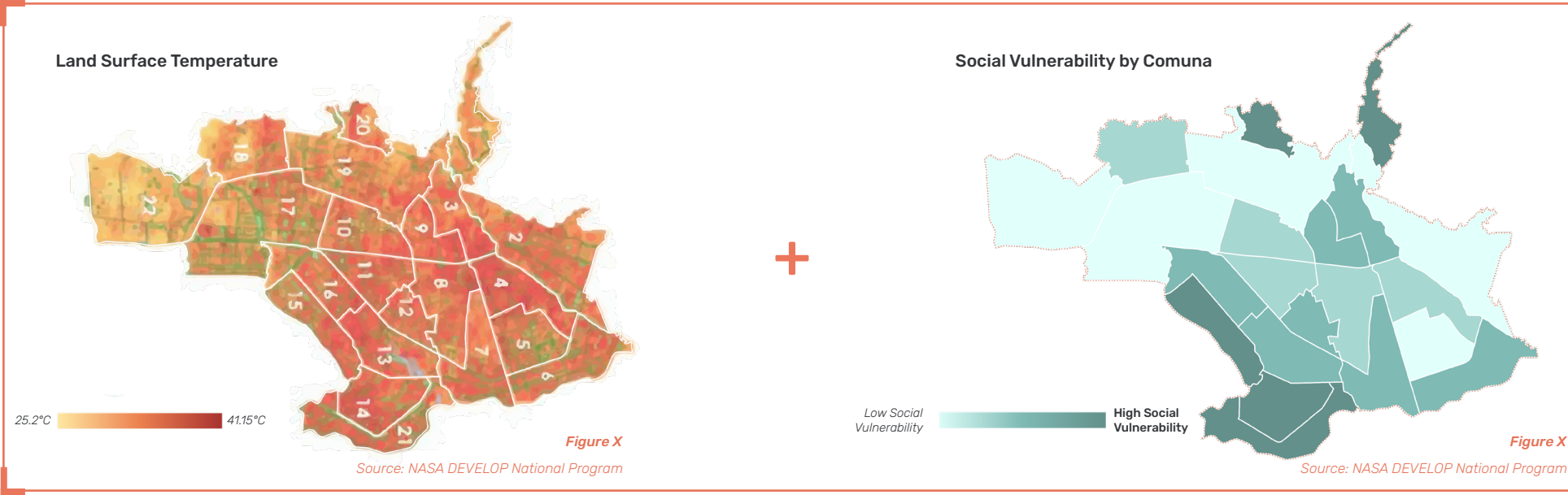
Legend:

- Urban city Subdivision into Communes
- Rural Borders
- Roads
- Rivers
- Green Open Space

Urban Heat Island



CLIMATE CHANGE EFFECT



Beyond its physical dimension, climate change in Cali operates through a socio-spatial logic in which land surface temperature (LST) and social vulnerability are structurally interconnected. According to the NASA DEVELOP (2024) Cali Urban Development II Technical Report, both variables are driven by the same processes of urbanization, where increased built density and reduced vegetation simultaneously intensify heat accumulation and limit environmental quality.

At the comuna scale, this relationship becomes explicit. The report identifies the highest social vulnerability scores in Comunas 1, 14, 15, 20, and 21, while the combined heat-risk assessment highlights Comunas 13, 14, 15, and 21 as areas where high LST and high vulnerability overlap . The recurrence of Comunas 14, 15, and 21 in both datasets confirms a spatial convergence between thermal exposure and social fragility, as explicitly mapped in the study’s heat risk assessment.

Relation between social vulnerability scores with land surface.

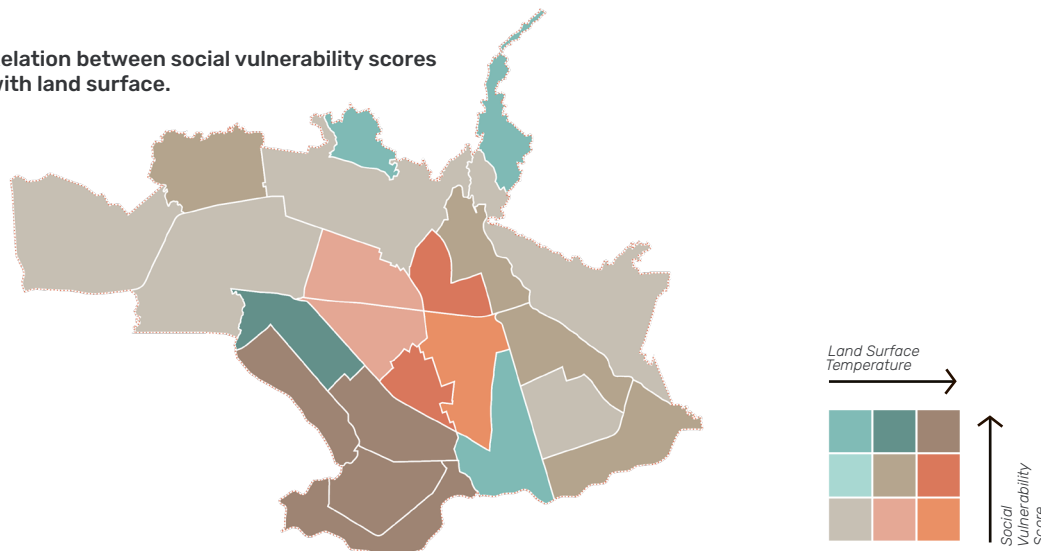
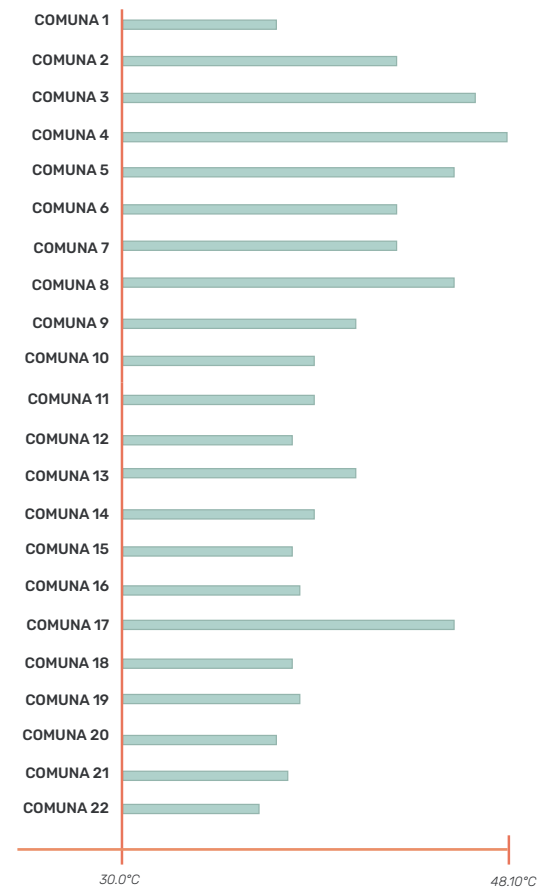


Figure X

Source: NASA DEVELOP National Program

This overlap is not incidental but systemic. The report demonstrates that areas with higher temperatures tend to have less access to green space and reduced environmental buffering capacity, while also concentrating populations with greater socioeconomic disadvantage and limited access to services. In this sense, the same spatial transformations, urban expansion, vegetation loss, and land cover change, simultaneously produce higher LST and increased social vulnerability.

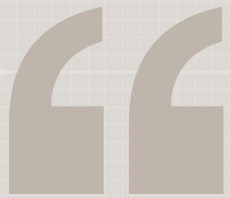
Under climate change, this relationship becomes more critical. As thermal thresholds are exceeded more frequently, populations in these comunas are exposed to higher baseline temperatures while having fewer means to mitigate their effects.



Land Surface Temperature (LST) – describes how hot a material of the earth's surface would feel to touch at a given location.

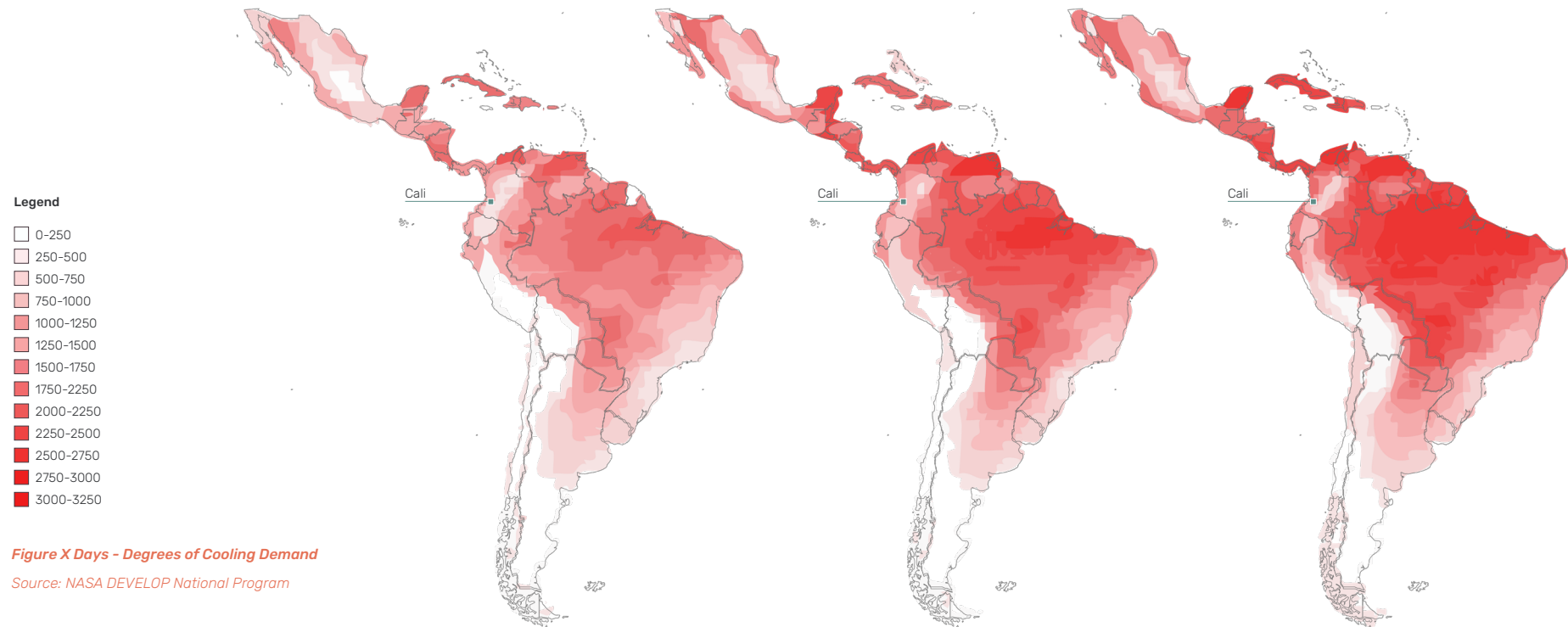
Figure X Maximum LST (°C) Classification by Comuna across the Study Period

Source: NASA DEVELOP National Program



The future climate scenario in Cali shifts from a condition where heat can be balanced and dissipated to one where heat continuously accumulates over time.

CLIMATE FUTURE SCENARIO IN CALI



Climate change is intensifying thermal conditions across Latin America and the Caribbean, with the strongest impacts in the tropical and equatorial belt. As shown in [Figure 7.1](#), future scenarios project a clear increase in cooling needs, reflected in the rise of cooling degree days from the historical period (1995–2004) to 2041–2060 and 2081–2100. Areas near the Equator, already characterized by year-round warm conditions, are expected to face even higher cooling demands.

In this context, the equatorial belt emerges as one of the most thermally vulnerable regions, not due to seasonal extremes, but because existing heat becomes more persistent and intense. This indicates not only a rise in temperature, but a shift in the thermal baseline. As heat becomes a constant condition, thermal stress increases and the demand for cooling shifts from occasional to permanent.

For cities such as Cali, located in a warm tropical valley climate, this trend points to greater heat exposure, increased indoor discomfort, and a growing dependence on cooling strategies. Climate change, therefore, should be understood not only as rising temperatures, but as a transformation of the environmental conditions under which architecture must operate.

Within the regional warming trend, Cali illustrates how climate change operates not through abrupt transformation, but through the intensification of an already warm and demanding environment. In the present scenario, thermal stress is primarily driven by the daily interaction between high solar radiation, warm air temperatures, and persistent humidity, while nighttime cooling and air movement still provide a limited capacity for heat dissipation. This creates a condition of recurrent but partially reversible thermal stress.

Future projections indicate that this balance is progressively lost. The increase in air temperature shifts the entire thermal baseline upward, reducing nocturnal cooling and extending periods of heat accumulation. At the same time, solar exposure remains constant and continues to act as a primary source of heat gain, now operating over a warmer atmospheric background. Humidity levels remain sufficiently high to limit evaporative cooling, while wind patterns do not show a significant increase capable of offsetting the additional thermal load.



As a result, the future scenario is defined by a more continuous and less reversible form of heat stress, where the capacity of the environment to dissipate accumulated heat is reduced. This implies that the challenge is no longer only to respond to peak conditions, but to manage the persistence of heat over time.



From a design perspective, this shift has clear implications. Strategies that rely on temporary relief, such as nighttime cooling or intermittent ventilation, become less effective, while those aimed at reducing heat gain and preventing accumulation gain priority. In this context, solar control, shading, and the reduction of direct radiation exposure become critical variables, as they directly limit the primary source of heat input.

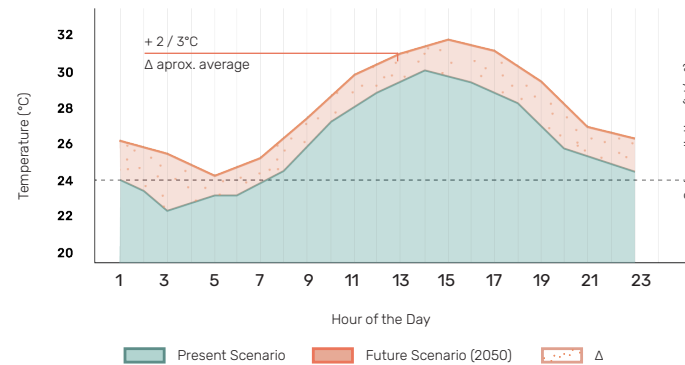
At the same time, the efficiency of natural ventilation must be reconsidered, not only in terms of airflow presence, but in its capacity to remove heat under warmer baseline conditions.

Therefore, the future climate scenario in Cali suggests a redefinition of design priorities: from mitigating heat during specific periods to controlling its continuous accumulation.

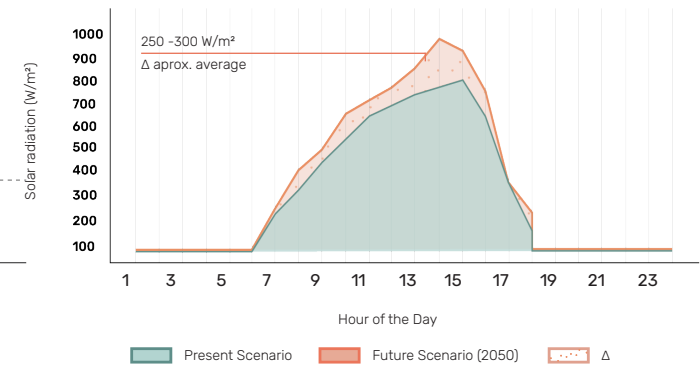
This requires a more precise integration of passive strategies, where the reduction of solar gains, the management of thermal mass, and the optimization of airflow are no longer complementary measures, but central components in achieving thermal comfort under changing climatic conditions.

Figure X Daily comparison between Present and Future Climate scenario in Cali

Source: Own Elaboration

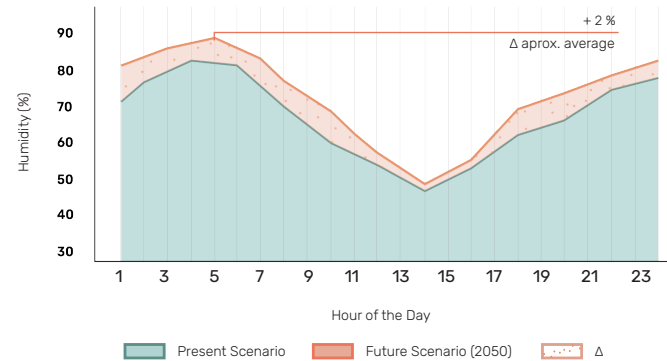


Dry Bulb Temperature

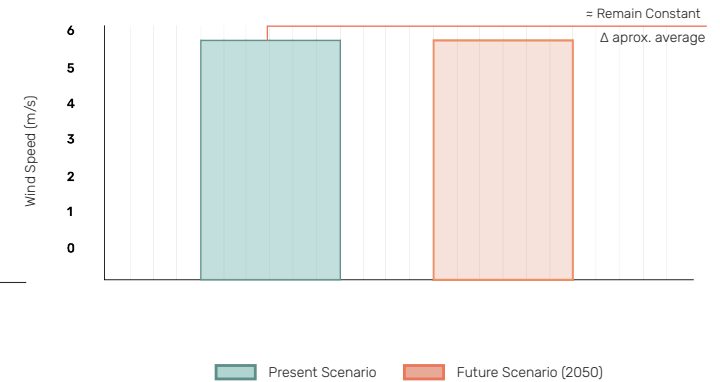


Solar Radiation (GHI)

The most significant transformation lies in the simultaneous **increase in air temperature and solar radiation**, while humidity and wind patterns remain relatively constant. This creates a more **critical imbalance between heat gain and heat dissipation**. **Higher temperatures extend thermal stress across the full daily cycle**, especially by reducing nocturnal cooling, while **stronger solar radiation increases the intensity and duration of direct heat gains** during daytime hours. At the same time, unchanged humidity and limited wind speeds reduce the effectiveness of natural cooling processes, making the environment more difficult to compensate.



Relative Humidity



Wind Speed

CLIMATIC DESIGN STRATEGIES

The climatic analysis of Cali converges on a single design challenge: a persistent heat-and-humidity load driven by constant solar radiation, limited evaporative cooling potential, and a progressively warming baseline. Each climatic driver translates into a specific passive design response, which in turn defines the variables evaluated in the simulation chapters:

CLIMATE DRIVER	PASSIVE RESPONSE	DESIGN VARIABLE TASTED
01 Strong diurnal temperature swing and narrow seasonal range.	Calibrate thermal mass and night-time cooling potential.	envelope construction, differentiated by archetype.
02 Sustained high humidity (70–80%) and weak evaporative cooling potential.	prioritise air movement	operable openings and natural cross-ventilation.
03 Constant high solar radiation and critical low-angle exposure on east–west façades.	solar control and shading	shading depth (balcony/overhang), orientation, window-to-wall ratio.
04 Roof and top-floor overheating.	reduce absorbed solar heat	roof solar absorptance (cool roof).

CLIMATE DRIVER

05

Large glazing penalty under high-radiation conditions

PASSIVE RESPONSE

control solar gain through glass

DESIGN VARIABLE TESTED

window-to-wall ratio combined with shading.

06

Future warming (+2–3 °C) and persistent heat stress

favour heat-gain reduction over nocturnal relief

all gain-control measures gain priority.

Together, these strategies define the levers tested in Chapter 05 and combined into the renovation packages in Chapter 06. The bioclimatic target is explicit: to raise the share of annually comfortable hours from the current 44.5% (Givoni baseline) toward the 65–70% achievable through well-integrated passive design, reducing the need for mechanical cooling to roughly 11% of the year.



This chapter explains how the analytical archetypes are derived from the real VIS stock. Based on the classification of 19 multifamily housing cases, it defines the criteria used to select A01, A02, and A03. The chapter shows how the archetypes allow the research to isolate two key variables: construction technology and block morphology.

ARCHETYPES

/ˈɑrkiˌtaɪp/

INTRODUCTION

The increasing thermal stress in tropical cities requires a better understanding of how climatic conditions interact with the built environment. In contexts such as Cali, where high temperatures, solar radiation, and humidity define baseline conditions, projected climate change is expected to intensify challenges related to thermal comfort and energy performance. These effects are not uniform, but shaped by urban form and environmental conditions, producing differentiated microclimates.

Within this context, urban multifamily social housing (VIS) represents a critical field of study. Its scale, repetition, and reliance on standardised construction make it a key component through which climatic conditions are experienced.

However, its architectural configuration is often driven by regulatory and economic constraints that do not prioritise environmental performance. Understanding how this housing stock is composed and organised is therefore essential to evaluate its response to current and future climatic conditions.

Rather than analysing isolated cases, this research focuses on the systematic recognition of the existing housing stock. By identifying recurrent configurations and their defining characteristics, buildings can be grouped into categories with shared spatial and constructive logic. This process does not aim to idealise the built environment, but to reconstruct its underlying typological structure based on real conditions.

“

In this sense, the use of archetypes allows for the abstraction of the most representative housing types into a limited number of comparable and scalable models. Each archetype synthesizes a set of buildings with similar characteristics, capturing their dominant spatial organization, construction logic, and expected environmental behavior. This reduction of complexity enables a more structured and accessible analysis of the housing stock, while preserving its essential variability.

”

Beyond their analytical role, these archetypes also establish a foundation for future architectural intervention. By representing recurrent building types, they make it possible to explore transformation strategies that are not only specific to individual cases, but transferable across similar conditions. In this way, the archetype-based approach operates as a bridge between the understanding of existing housing and the development of projective responses.

Accordingly, this chapter examines how multifamily VIS in Cali are structured and composed, identifies the key variables that define its main configurations, and develops a set of representative archetypes derived from the most common building types. These will serve as a general and operable basis for subsequent thermal analysis and the formulation of climate-responsive design strategies.

To translate these conceptual principles into an operational framework, the development of archetypes is approached through a structured methodological process. This process allows the identification, classification, and synthesis of the most representative housing configurations, transforming a complex and heterogeneous building stock into a set of comparable models. The following section outlines the methodological workflow through which these archetypes are defined and applied as both analytical and projective tools.

METHODOLOGICAL APPROACH

The development of archetypes in this research is conceived as a process of recognition, classification, and synthesis of the existing multifamily VIS housing stock in Cali. Rather than analysing each building as an isolated case, the methodology understands the built environment as a system of recurrent spatial, morphological, architectural, and constructive patterns. This allows the research to identify common characteristics across different housing developments and to translate the complexity of the existing stock into a more coherent and comparable structure.

This approach is particularly relevant because VIS housing is often produced through repeated design, construction, regulatory, and economic logics. Although each project may present specific variations, many buildings share similar block configurations, heights, circulation systems, envelope conditions, construction methods, and relationships with the urban context. By recognising these recurring features, the methodology makes it possible to move beyond individual examples and define broader typological groups that represent dominant ways in which VIS has been built and reproduced in Cali.

The construction of archetypes therefore involves a progressive reduction of complexity. This reduction does not aim to erase the diversity of the housing stock or transform it into idealised models. Instead, it seeks to reorganise real conditions into representative configurations that preserve the essential characteristics of the buildings they describe. In this sense, archetypes are understood as evidence-based abstractions: simplified enough to be analysed, compared, and simulated, but grounded enough to remain connected to the built reality from which they are derived.

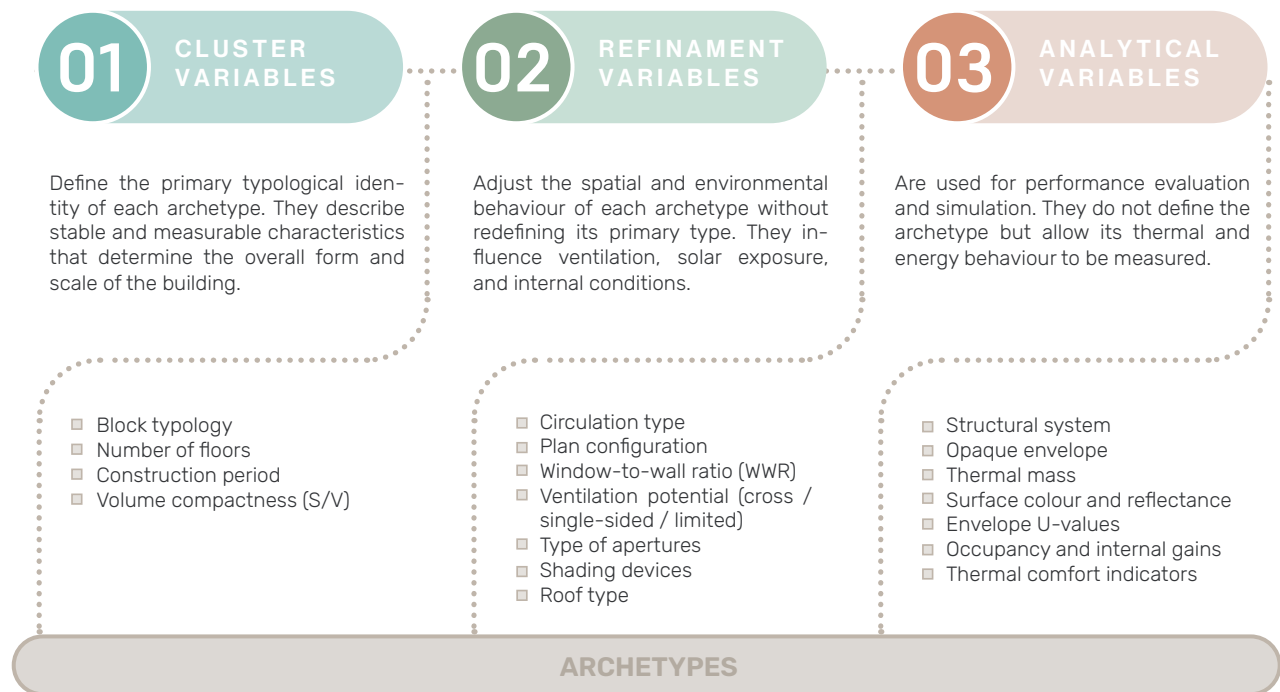
The methodology also recognises that not all variables have the same role in the construction of an archetype. Some variables define the basic typological structure, such as block form, height, construction period, and compactness. Others refine the interpretation of each group, such as circulation type, ventilation potential, roof condition, shading, or façade configuration. A third set of variables supports later evaluation, especially those related to material properties, thermal mass, openings, and envelope performance. This hierarchy allows the classification process to remain clear while still acknowledging the

complexity of architectural and environmental behaviour.

In this sense, the archetype is not only a descriptive category, but an operational model. Once defined, each archetype represents a group of buildings with similar characteristics and can therefore be used to evaluate thermal behaviour, compare performance, and explore possible transformation strategies. This is what gives the methodology its projective dimension: it does not stop at describing the existing housing stock, but creates a basis from which design decisions can be tested, adjusted, and transferred to similar conditions.

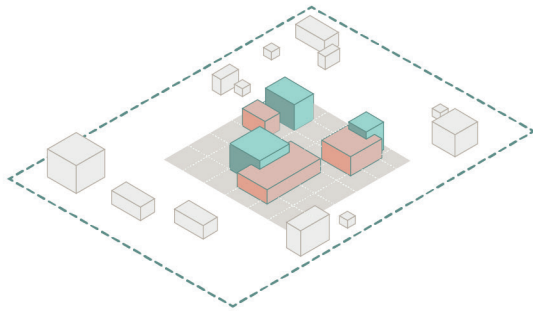
By working through archetypes, the research establishes an intermediate scale between the individual building and the entire housing stock. This is essential for a study that aims to address climate-responsive design in a realistic and applicable way. The archetypes make it possible to work with a limited number of representative models while maintaining a connection to the broader urban and architectural reality of VIS in Cali.

Based on this approach, the research is structured as a step-by-step workflow that organises the process from stock recognition and variable definition to typological clustering, archetype construction, validation, and later application in thermal analysis and projective development.



METHOD

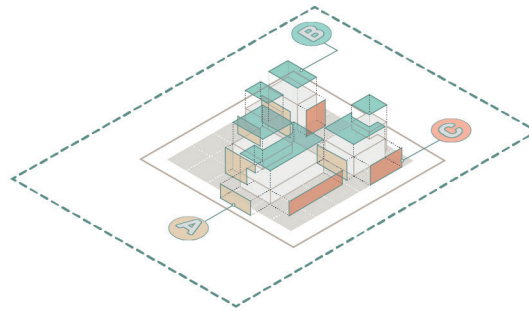
ANALYTICAL PHASE



01

DEFINITION OF SCOPE & STUDY FRAMEWORK

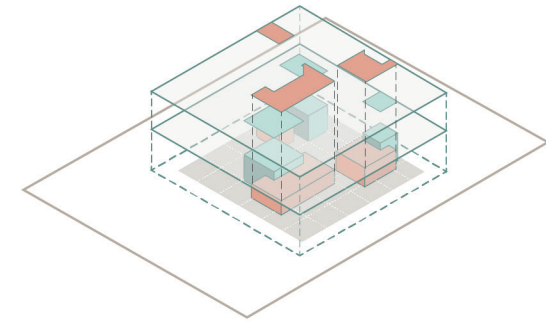
Defines the boundaries of the research. It establishes urban multifamily VIS in Cali as the target housing stock, defines the spatial scope of analysis, and organises the stock according to construction periods. It also identifies the available sources of information, including project documentation, municipal records, satellite imagery, and selected case studies. The output of this phase is a clear study framework with inclusion criteria, temporal categories, and an initial building inventory.



02

IDENTIFICATION OF CHARACTERISING VARIABLES

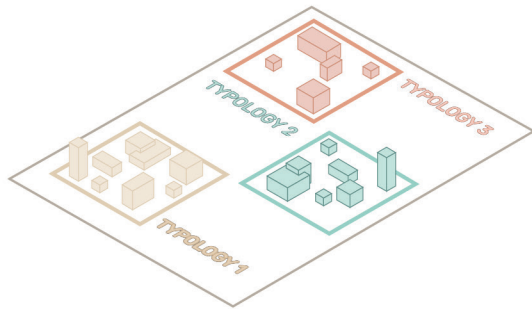
Defines the variables used to compare and interpret the housing stock. These variables are organised into urban-morphological, architectural, envelope-construction, and thermal comfort/energy layers. Not all variables have the same methodological weight: some define the archetype, others refine its interpretation, and others support later simulation or design analysis. The output is a variable matrix that structures the data collection and classification process.



03

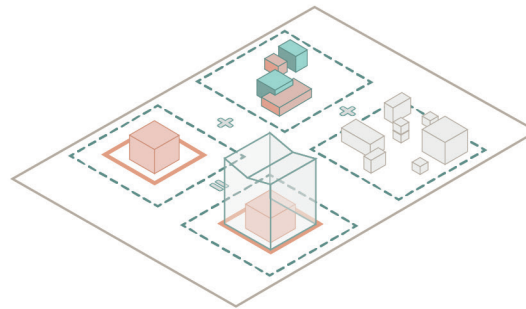
DATA COLLECTION & SYSTEMATISATION

Information is collected and organised into a comparable dataset. Quantitative data is extracted where available, while remote observation and case study analysis are used to identify recurring spatial, formal, and constructive patterns. Because data availability is uneven, the process also records assumptions and confidence levels. The result is a systematised reading of the existing stock and an initial recognition of recurrent configurations.



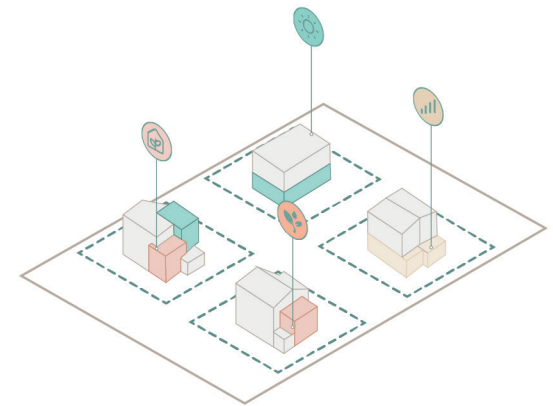
04 CLASSIFICATION & TYPOLOGY CLUSTERING

The collected cases are grouped according to shared characteristics. Primary classification is based on construction period, block typology, number of floors, and, where possible, volume compactness. Secondary refinement considers circulation type, ventilation potential, envelope logic, roof type, shading, and aperture conditions. This phase reduces the diversity of the stock into coherent typological clusters that represent dominant VIS configurations in Cali.



05 ARCHETYPES DEFINITION & VALIDATION

Each typological cluster is translated into a representative archetype. These archetypes are based on real average conditions rather than idealised forms, synthesising geometry, spatial organisation, material logic, and climatic behaviour. Where information is incomplete, assumptions are made explicit. The archetypes are then checked against real cases to ensure that they remain representative of the built stock. The output is a validated set of residential archetypes with standardised descriptions.

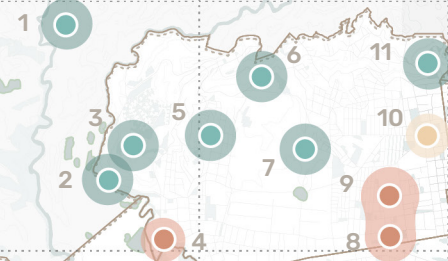


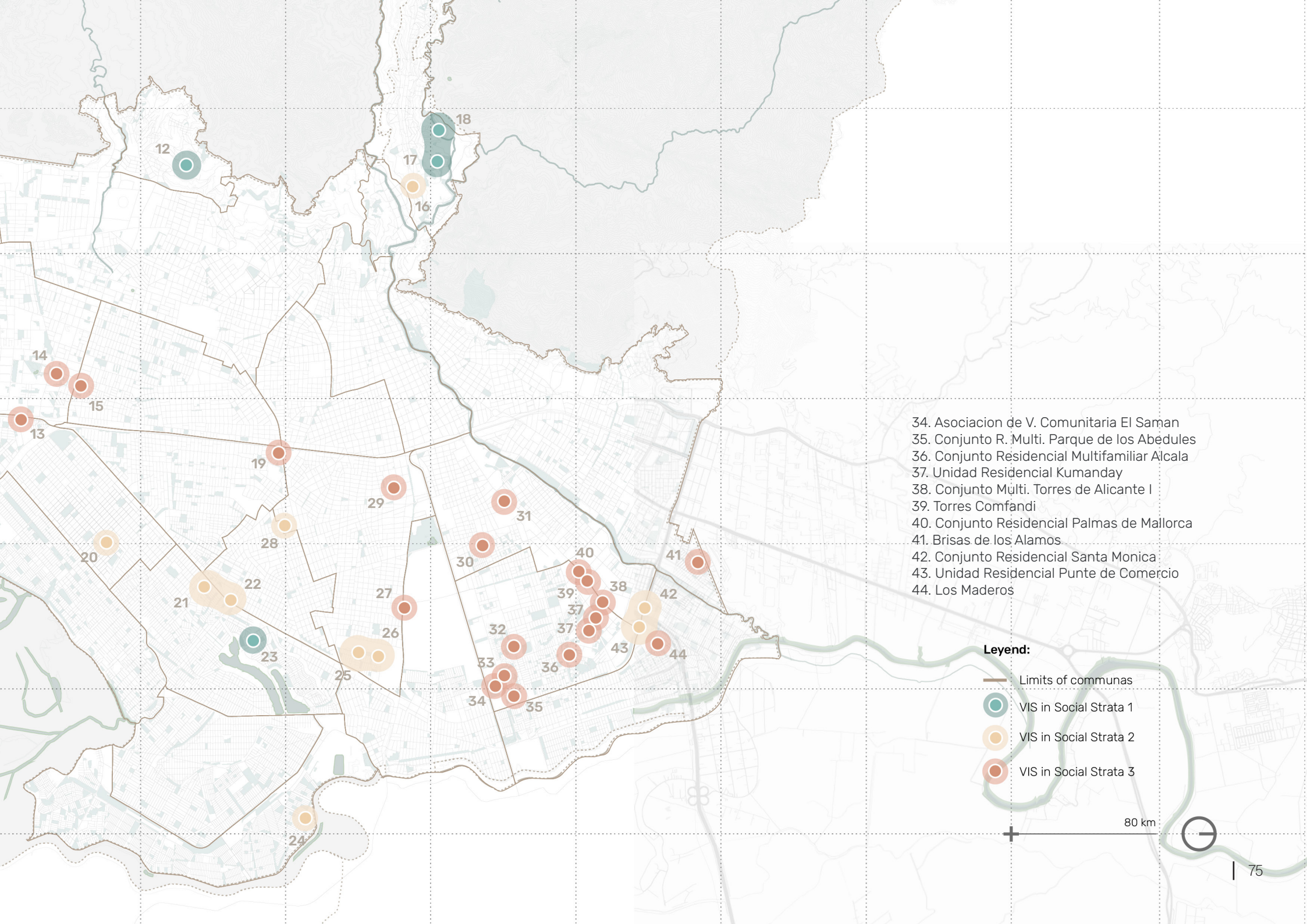
06 APPLICATION FOR ANALYSIS & DESIGN DEVELOPMENT

Once defined, the archetypes become operational models for thermal comfort analysis, energy evaluation, and projective exploration. They allow different housing types to be compared under current and future climatic conditions and provide a basis for testing passive strategies, retrofit scenarios, and architectural transformations. In this sense, the methodology moves from recognising the existing housing stock to defining transferable design strategies for climate-responsive VIS.

SOCIAL HOUSING BUILDINGS TO BE STUDIED

1. Altos de Santa Elena
2. Portal de Madrigal
3. Conjunto Residencial Madrigal Campestre
4. Conjunto Residencial Ribera Campestre
5. Conjunto Residencial Lomalinda
6. Urbanización Altos de la Luisa
7. Conjunto Residencial Atabanza
8. Conjunto R. Multifamiliares La Arboleda
9. Conjunto Residencial Arboleda del Sur II
10. Proyecto Habitacional Colinas de San Miguel
11. Cúmbres del Refugio
12. Mirador de Conny
13. Multifamiliar La Arboleda
14. Multifamiliar Jardín de la Camelia I
15. Torres de Santa Juliana I
16. Conjunto Residencial Altos de Aguacatal
17. Conjunto Residencial Santa Martha de los Caballeros.
18. Conjunto Residencial Mirador del Aguacatal I y II
19. Edificio el Prado
20. Conjunto Residencial El Eden Comfandi
21. Conjunto Residencial Horizontes
22. Unidad Residencial Sorrento I y II
23. Multifamiliar Sol de Oriente I Etapa
24. Multifamiliar Reserva de Vallegrande
25. Multifamiliares La Base
26. Agrupación Multifamiliares Brisas de la Base
27. Unidad Residencial Torre 52 Norte, I Etapa.
28. Conjunto Residencial Santa Monica
29. Torres de Santa Juliana I
30. Unidad Residencial Torre 52 norte, I etapa.
31. Los Maderos
32. Torres Comfandi
33. Conjunto Residencial Bosques de Abadía



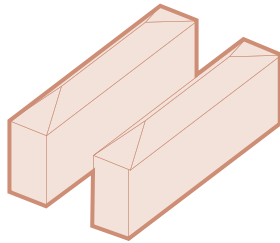


URBAN & MORPHOLOGICAL

URBAN BLOCK

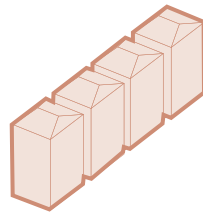
Urban block arrangement refers to the way residential buildings are organized within a plot or housing complex. It shapes how each type of housing complex occupies the plot and mediates the relationship between built volume, open space, orientation, building separation, and common areas. In terms of thermal comfort, it influences solar exposure, shading, wind flow, and heat accumulation in outdoor spaces.

Compact configurations may provide more shade, but they can also reduce ventilation. Parallel or linear configurations can support air movement when they are properly oriented, although they may also increase solar exposure on façades and paved surfaces. Courtyard-like configurations can help define common open space, but they may also accumulate heat if they lack sufficient vegetation, shade, or cross-ventilation.



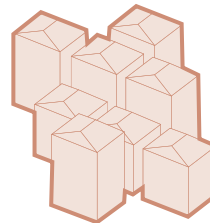
36 %
Parallel Grouped Blocks

Repeated blocks organized in parallel bands.



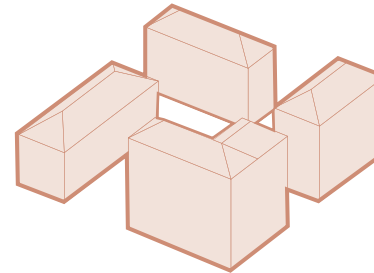
10 %
Linear Grouped Blocks

Simple rectangular buildings, and well-proportioned mid-rise buildings.



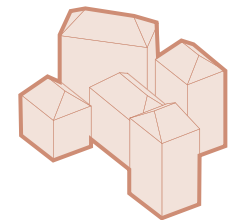
31 %
Compact Grouped Blocks

Blocks placed close to each other, with reduced intermediate spaces.



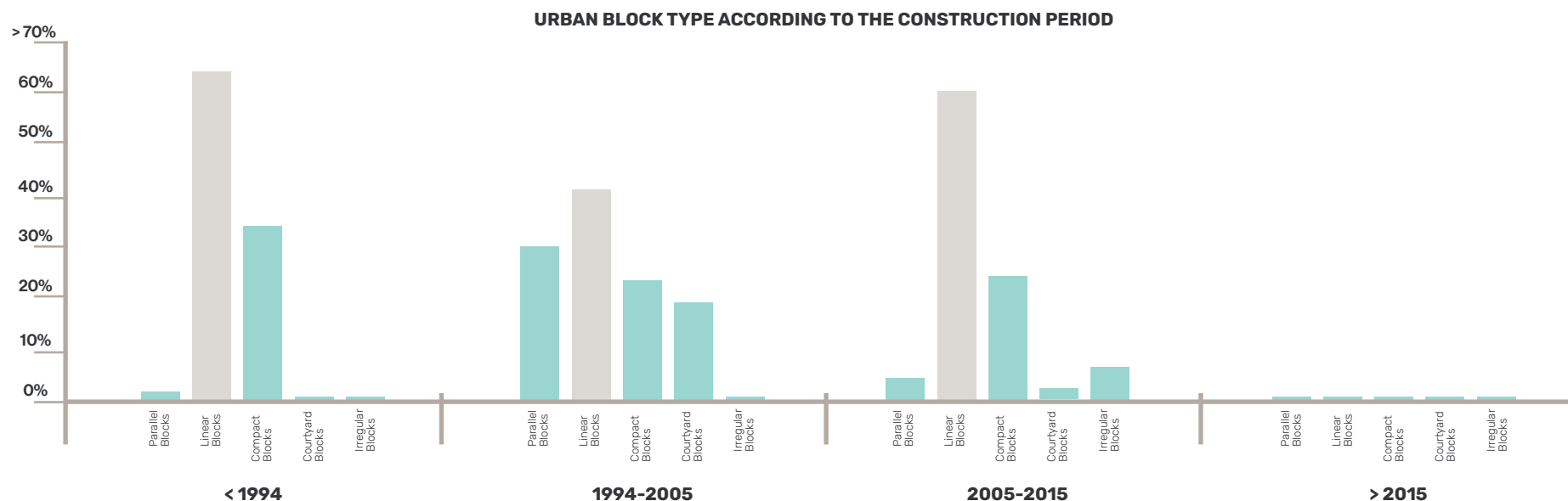
5 %
Courtyard-like Grouped Blocks

Blocks that define a central or semi-central open space.



15 %
Irregular Grouped Blocks

Blocks adapted to slopes, urban edges, or irregular plot geometries.



The urban blocks defines the relationship between the building and the climate: it determines the exposed surface area, the potential for cross-ventilation, and the number of dwellings with dual orientation.

The shape of the block is the first design decision that defines the relationship between the building and the climate. It determines the exposed surface area, the potential for cross-ventilation, and the number of dwellings with dual orientation. Therefore, urban block typology directly influences the possibilities for thermal comfort at the dwelling scale.

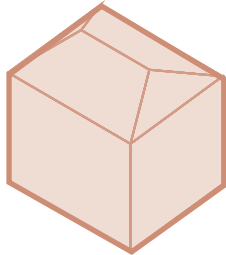
A linear block generally allows a higher number of units with cross-ventilation and dual orientation, while compact blocks tend to produce more internal units with limited façade exposure. In the sample, the linear slab block is the dominant typology, representing 53% of the cases, followed by compact blocks with 21% and U-shaped or courtyard blocks with 16%. Parallel blocks represent only 5%.

URBAN & MORPHOLOGICAL

VOLUMEN COMPACTNESS | S/V RATIO

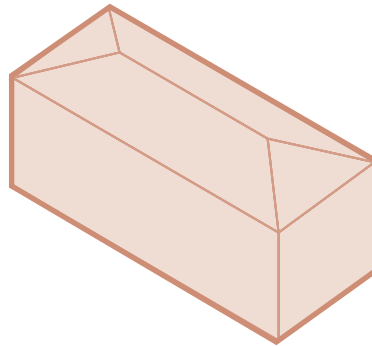
Volume compactness S/V refers to the relationship between the external envelope surface of a building and its total volume. It defines how exposed or compact each archetype is, influencing heat exchange through the envelope, solar exposure, and the potential for thermal gain or dissipation.

A lower S/V ratio means that the building has less external surface in relation to its volume, making it more compact. A higher S/V ratio means that the building has more exposed surface, increasing the contact between the indoor spaces and the outdoor climate.



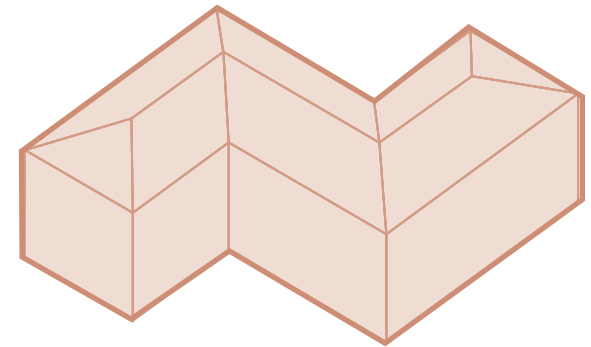
0%
 $S/V \leq 0.4$
Highly Compact

Lower exposed surface;
reduced heat exchange
through the envelope.



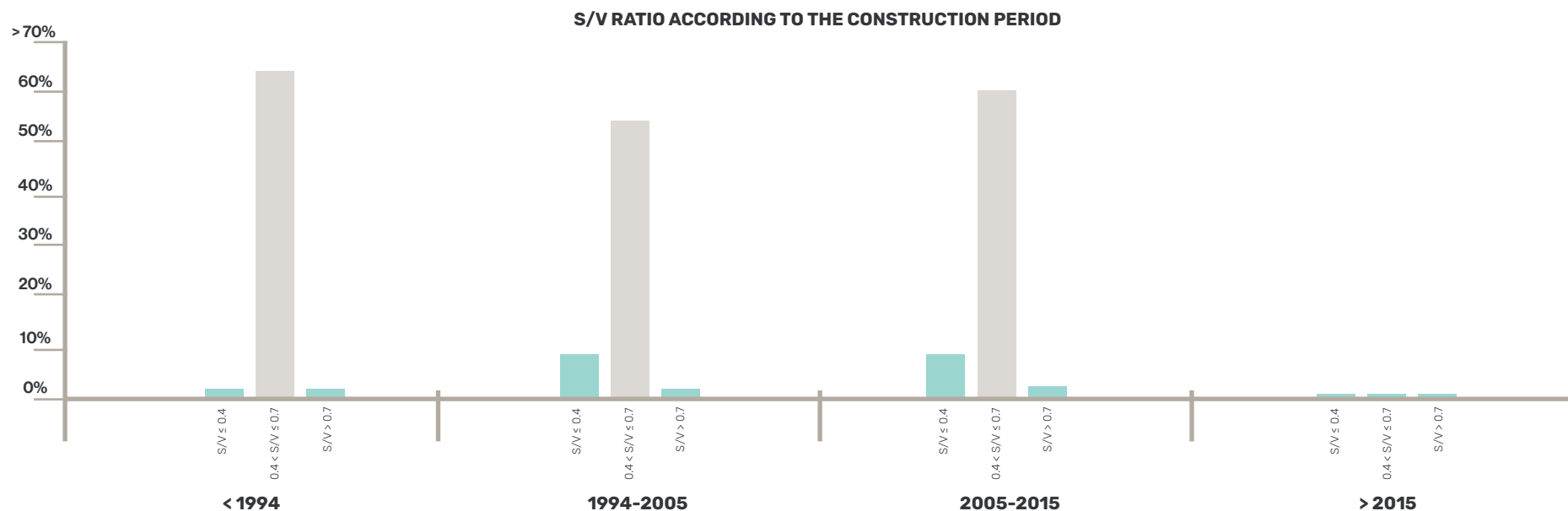
100%
 $0.4 < S/V \leq 0.7$
Medium Compact

Balanced relation between
volume and exposed surface.



0%
 $S/V > 0.7$
Low Compactness

Higher exposed surface;
greater potential for heat
gain/loss.



The S/V ratio defines how exposed or compact each building is, determining how much energy can be exchanged with the surrounding environment throughout the day. It influences heat transfer through the envelope, solar exposure, and the building's potential either to gain heat or to dissipate it.

The S/V compactness ratio is a parameter that summarizes the building form in terms of energy exchange with the surrounding environment.

the lowest value, 0.46, corresponds to the block with the lowest relative perimeter and the most regular volume, while the highest value, 0.65, indicates a more irregular plan with a larger exposed perimeter. The average value of the sample is 0.56. Since all projects have the same number of floors and similar floor-area ranges, the differences in S/V are mainly explained by variations in plan geometry: more

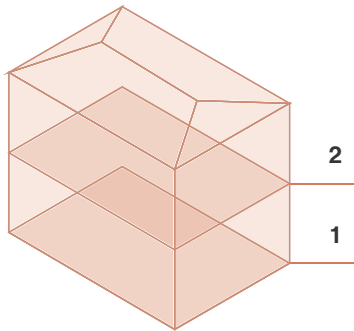
elongated or articulated layouts generate higher ratios.

In terms of requalification, the S/V ratio can only be substantially modified through volumetric additions or reductions. Buildings with a high S/V ratio, above 0.60, require more urgent façade treatment than more compact buildings, as a larger proportion of their volume is exposed to external climatic conditions.

URBAN & MORPHOLOGICAL

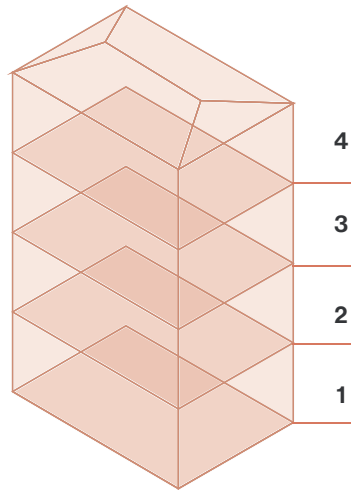
NUMBER OF FLOORS

Number of floors refers to the vertical scale of a residential building, measured by the number of levels above ground. Taller buildings tend to be more compact because they concentrate a larger amount of built volume on a smaller footprint. In terms of thermal comfort, the number of floors affects façade exposure, solar radiation, shading between buildings, wind access, and vertical heat distribution.



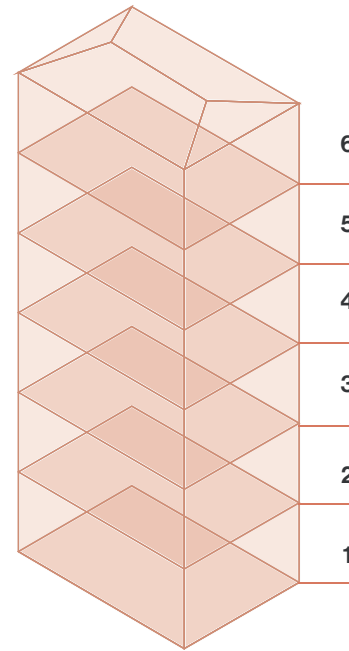
0%
1-2 Floors
Low-rise

Low vertical compactness;
greater land occupation for
the same density.



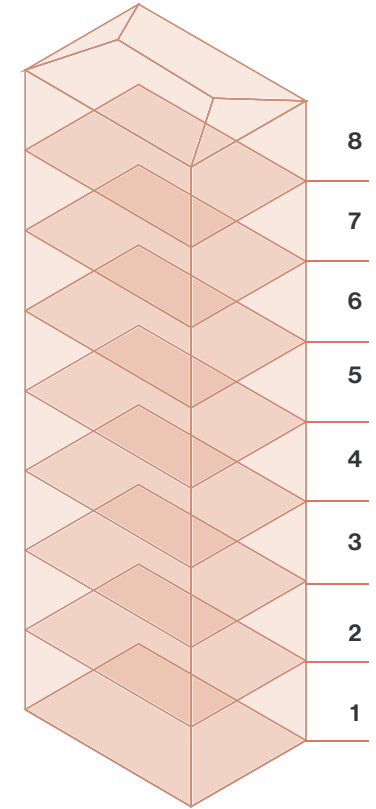
0%
3-4 Floors
Mid-low rise

Intermediate height with
moderate density and enve-
lope exposure.



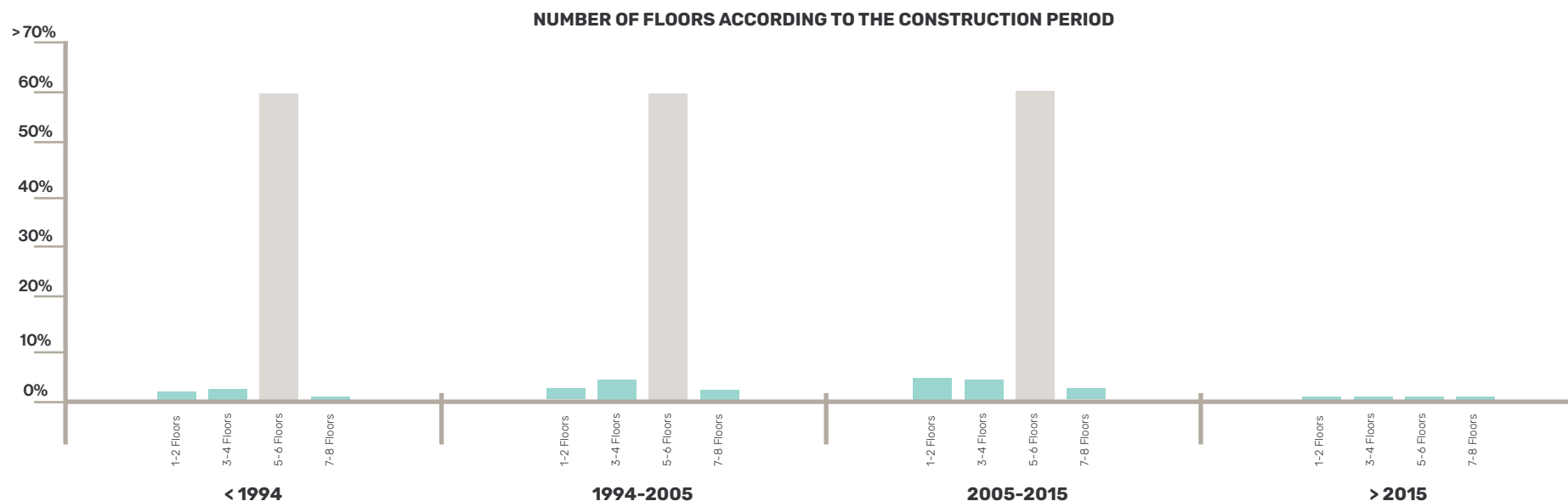
100%
5-6 Floors
Mid-rise

Balanced vertical compact-
ness, common in multifamily
housing blocks.



0%
7-8 Floors
Mid-high rise

Higher vertical density and
greater shading potential
and more sun exposure.



The number of floors influences in building compactness, density, solar exposure, wind access, and energy performance.

The number of floors has direct thermal implications that vary according to the position of each dwelling within the building. Units on the top floor receive the full impact of solar radiation through the roof, which can increase indoor temperatures by approximately 3–6 °C compared to intermediate floors when no roof insulation is provided.

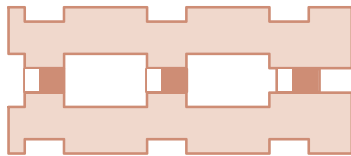
Ground-floor units benefit from the thermal buffering effect of the soil and surrounding mass, but they may experience lower ventilation potential. Intermediate floors generally present the most stable thermal behaviour, as they are less exposed to direct roof gains and less affected by ground-level ventilation constraints.

ARCHITECTONICAL & CONSTRUCTIVE TECHNOLOGY

INTERNAL DISTRIBUTION

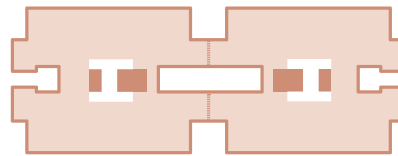
Internal distribution refers to the way interior spaces are organized within the residential block, including the position of apartments, corridors, stairs, vertical cores, common circulation areas, and service spaces. This category it defines how each block operates internally and how dwelling units relate to light, ventilation, access, and shared circulation.

In terms of thermal comfort, internal distribution influences the possibility of natural ventilation, cross-ventilation, façade exposure, heat accumulation in corridors or cores, and the thermal quality of interior spaces.



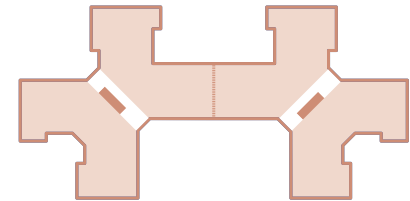
16 %
Linear Block

A single elongated building body, usually organized along a central or lateral circulation axis.



79%
Point block

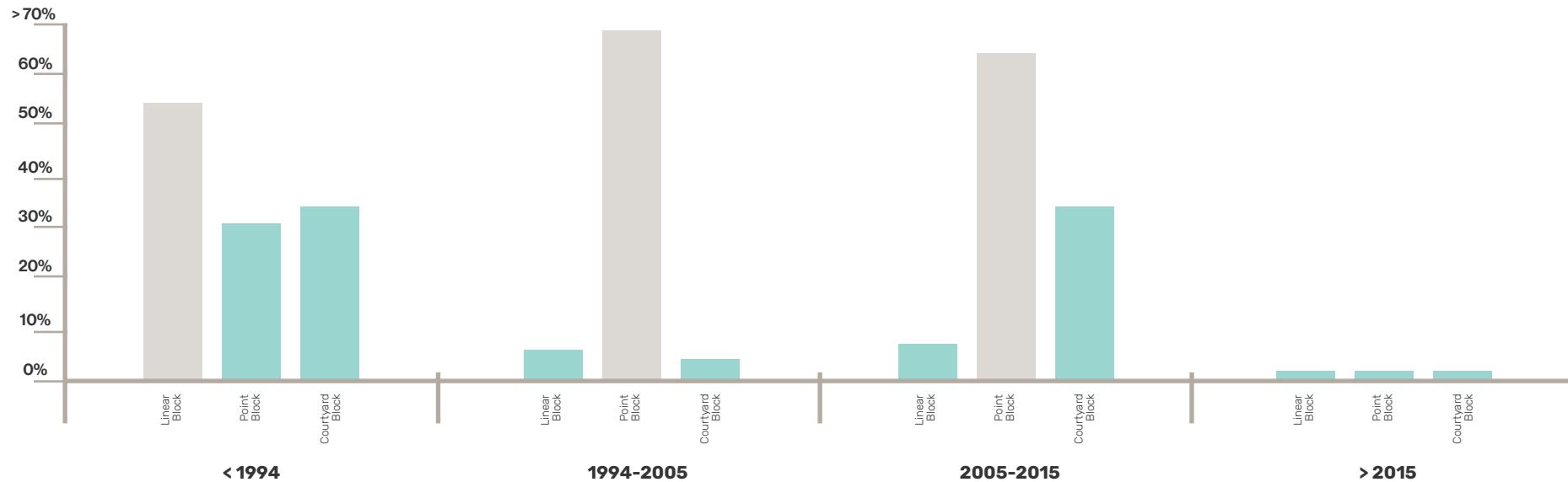
A compact block organized around a vertical circulation core, usually with several units per floor.



11%
Courtyard block

Units are organized around an internal courtyard or open void.

INTERNAL DISTRIBUTION ACCORDING TO THE CONSTRUCTION PERIOD



The internal distribution determines how dwellings can achieve real cross-ventilation. It's the link between urban form and the inhabitant's indoor thermal comfort.

The internal layout defines the proportion of dwellings with simultaneous access to two opposite façades, a necessary condition for effective cross-ventilation in a warm-humid climate. The point block distribution dominates, representing 79% of the case studies. It's often efficient and compact, but ventilation and daylight depend on the number of exposed façades per unit. Therefore, ventilation depends mainly on infiltration or on air movement through internal openings.

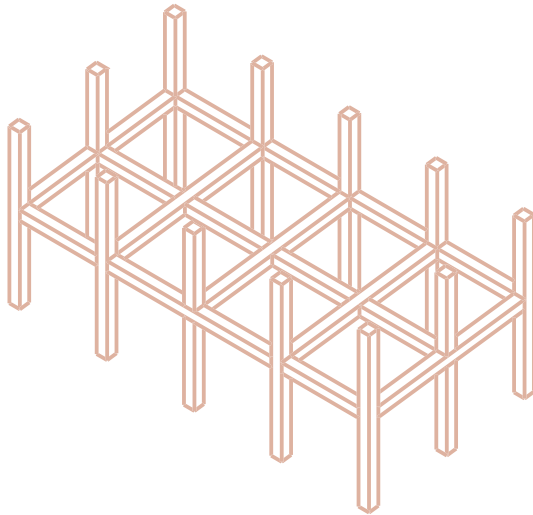
Linear block distribution represents 16% of the cases. It can provide good façade exposure, but thermal performance depends on orientation and the possibility of cross-ventilation, while courtyard-based distribution accounts for only 5%. It can improve daylight and ventilation, but may also accumulate heat if it lacks shade or airflow.

ARCHITECTONICAL & CONSTRUCTIVE TECHNOLOGY

STRUCTURAL SYSTEM

Structural system refers to the construction technology that defines the load-bearing elements of the building, such as walls, frames, slabs, beams, columns, and prefabricated components. They influences the building's spatial flexibility, construction logic, façade configuration, material behavior, and potential for transformation or adaptation over time. In terms of thermal comfort, affects the thermal

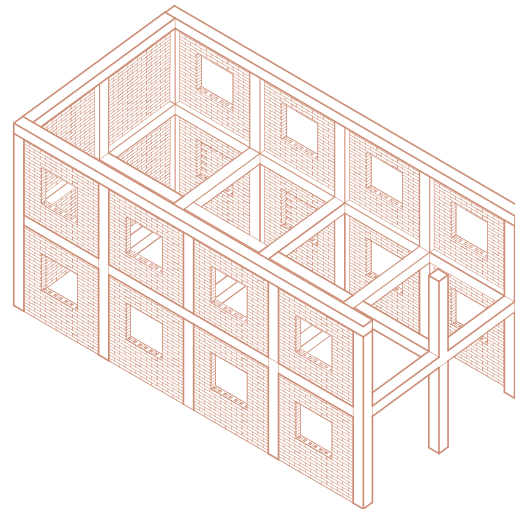
mass of the building, heat storage, heat transfer through the envelope, and the possibility of modifying façades, openings, or shading devices. Therefore, the structural system is not only a construction variable, but also a key factor for understanding the environmental performance and transformation potential.



11%

Reinforced Concrete Frame

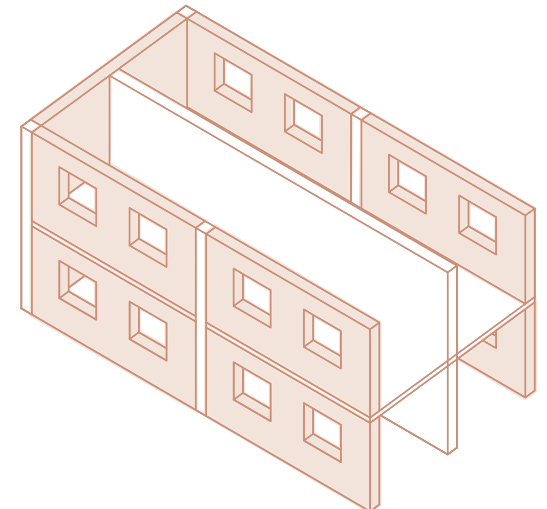
Columns, beams, and slabs in reinforced concrete, with non-load-bearing infill walls.



40%

Rainforce Masonry

Load-bearing masonry walls reinforced with steel and concrete elements.

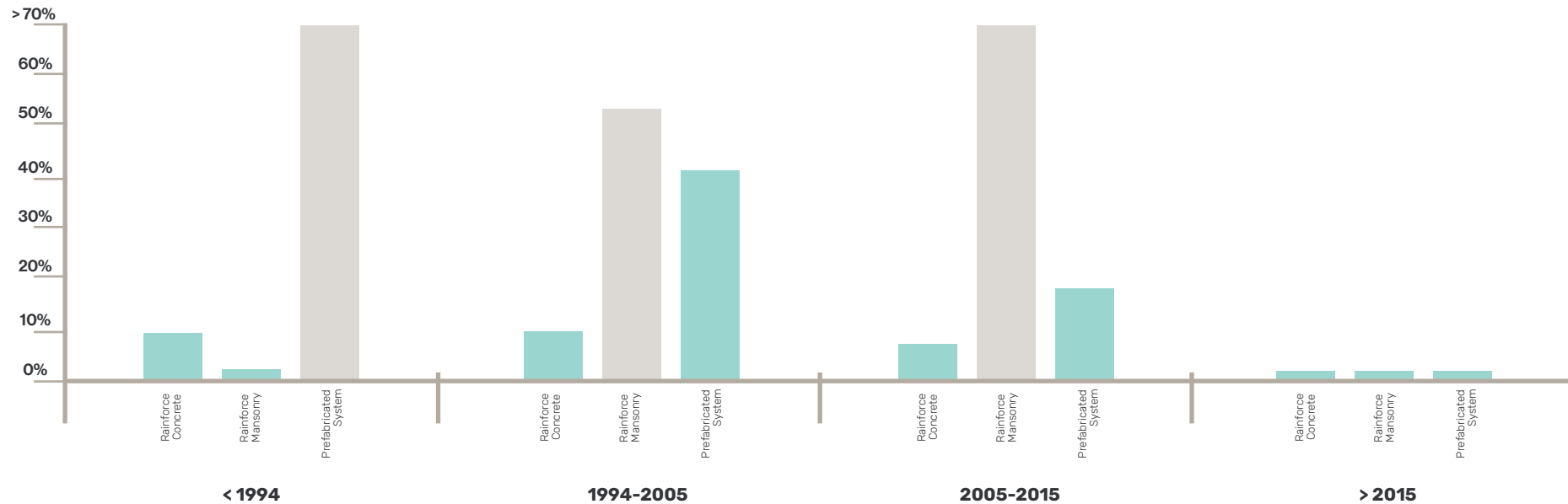


49%

Prefabricated Structural System

Structural concrete elements produced in series and assembled on site.

STRUCTURAL SYSTEM ACCORDING TO THE CONSTRUCTION PERIOD



The structural system not only defines the constructive logic of the building, but also influences the thermal performance of the envelope through its materiality. It determines the mass, conductivity, and thermal inertia of the walls, which regulate heat exchange with the exterior.

The structural system defines the physical nature of the load-bearing walls and, therefore, their thermal transmittance and heat storage capacity. Among the most common systems, reinforced masonry and prefabricated concrete panels present different thermal and constructive

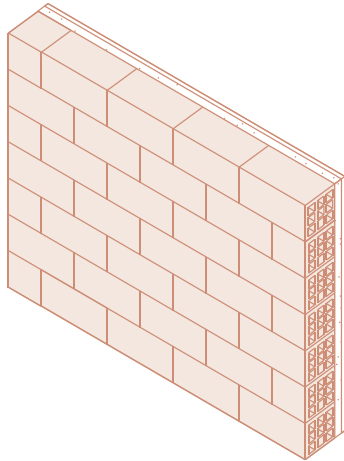
implications. Masonry provides structural rigidity and thermal mass, while precast concrete panels allow faster construction and repetition. From a thermal perspective, precast concrete transfers heat faster than ceramic masonry and stores slightly more thermal energy.

ARCHITECTONICAL & CONSTRUCTIVE TECHNOLOGY

OPAQUE ENVELOPE

The opaque envelope refers to the solid external building elements that enclose the interior spaces, such as walls and non-transparent façade components. it describes the constructive solution of the building enclosure and directly affects energy performance, heat transfer, and the indoor thermal environment.

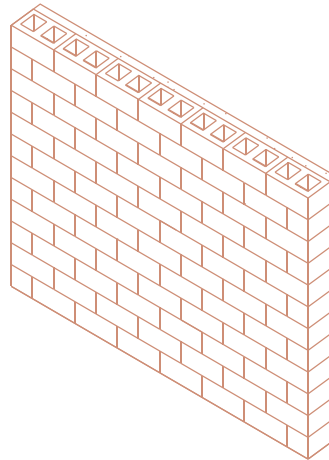
In terms of thermal comfort, the opaque envelope influences heat gains and losses, thermal lag, surface temperatures, and the capacity of the building to buffer external climatic conditions.



U-Value: 2.643 (W/m²K)
Thermal Mass: 160.5 (kJ/m²K)

40% **Structural Clay Bricks**

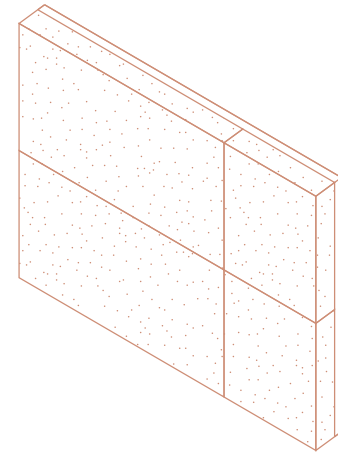
Opaque wall system based on structural clay brick masonry.



U-Value: 2.605 (W/m²K)
Thermal Mass: 190 (kJ/m²K)

11% **Concrete Blocks**

Load-bearing masonry walls reinforced with steel and concrete elements.

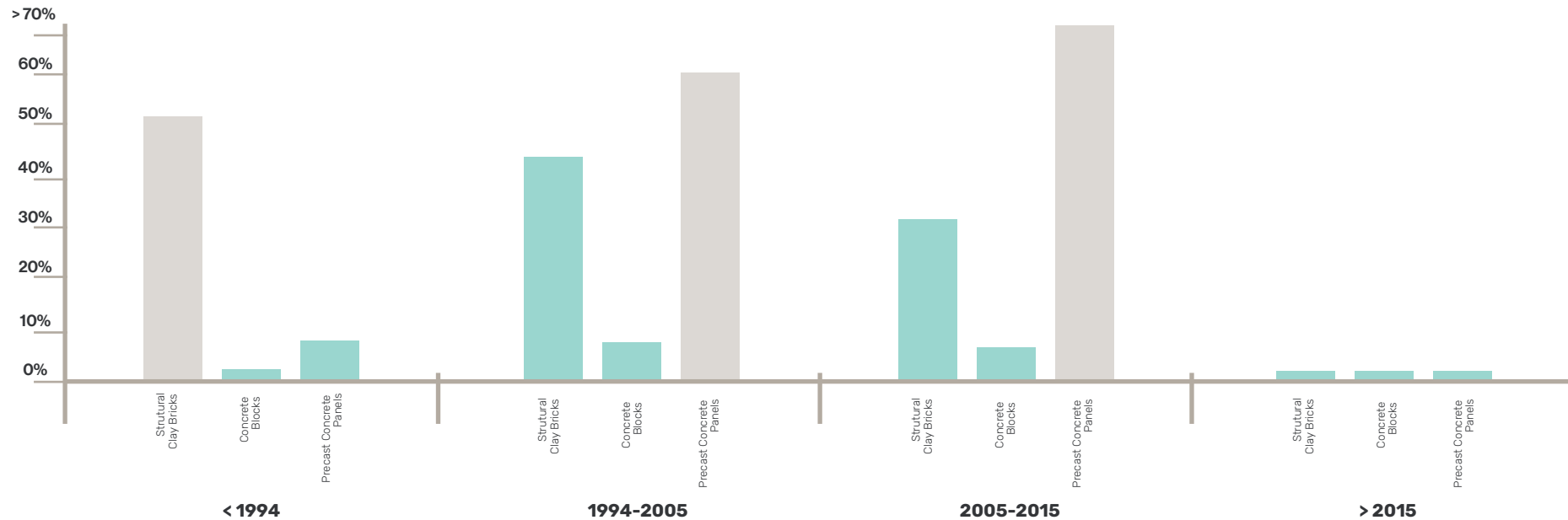


U-Value: 3.363 (W/m²K)
Thermal Mass: 173.4 (kJ/m²K)

49% **Precast Concrete Panels**

Opaque wall system based on prefabricated concrete panels.

OPAQUE ENVELOPE ACCORDING TO THE CONSTRUCTION PERIOD



The opaque envelope define how the building stores, transmits, and releases heat, influencing thermal transmittance, thermal mass, and the capacity of the building to moderate indoor conditions.

The analysed materials show different thermal behaviours. Structural clay brick has a U-value of 2.643 W/m²K and a thermal mass of 160.5 kJ/m²K, while dense precast concrete reaches 3.363 W/m²K and 173.4 kJ/m²K. Concrete blocks provide moderate to high thermal mass, allowing heat storage, but also increasing the risk of heat release toward indoor spaces when the envelope is highly exposed. Precast concrete transfers heat around 27% faster than structural clay brick, while storing

approximately 8% more thermal energy.

In Cali's warm-humid climate, where the aim is to delay and reduce daytime heat peaks, this thermal inertia can be beneficial when façades are shaded. However, on façades with high solar exposure and no protection, the same inertia becomes problematic: the wall absorbs heat during the day and releases it at night, acting as a thermal radiator and reducing comfort during the hours when dwellings are most occupied.

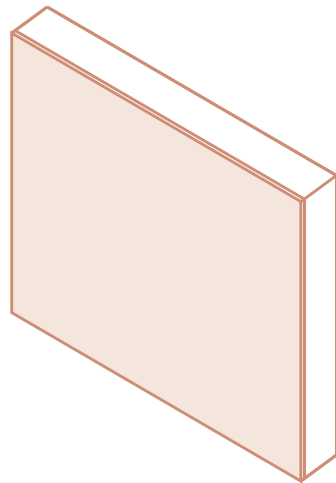
ARCHITECTONICAL & CONSTRUCTIVE TECNOLOGY

EXTERNAL ENVELOPE

The External envelope refers to the outer surface layer applied to the façade, it describes the final layer of the external envelope and affects the façade's durability, maintenance, visual character, and environmental behavior.

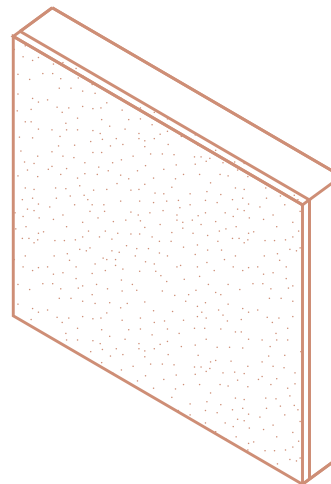
In terms of thermal comfort, the external finish influences solar absorption

surface temperature, weather protection, and the way heat is transferred toward the interior. Although it does not usually provide strong insulation by itself, it can modify the thermal response of the façade depending on its colour, texture, reflectance, thickness, and exposure.



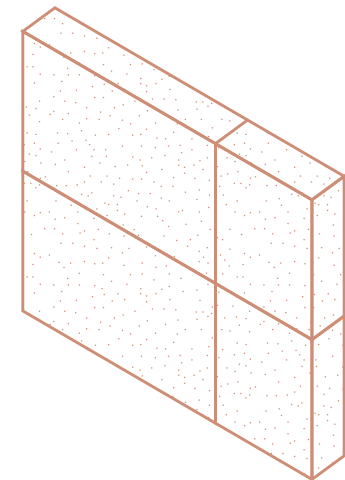
53%
Exterior Paint

Painted finish applied directly over the wall surface or over a plaster layer.



26%
Cement Plaster

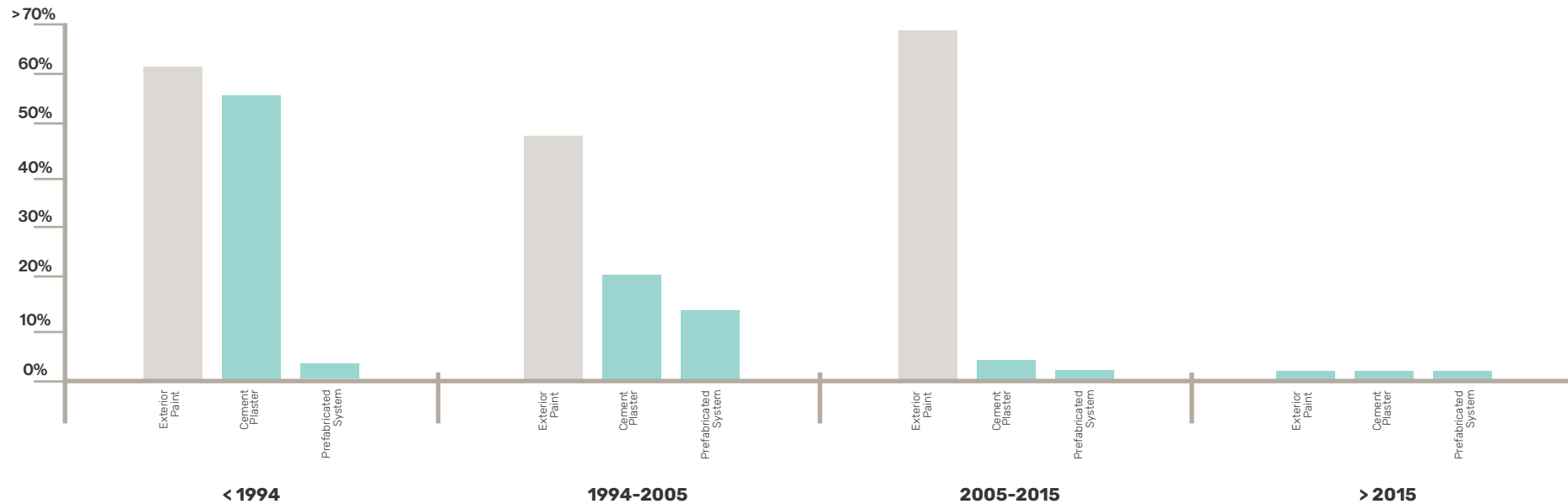
Cement-based coating applied to the external wall surface to protect and regularize the façade.



22%
Prefabricated Structural System

Concrete surface left visible without an additional finish.

EXTERNAL ENVELOPE ACCORDING TO THE CONSTRUCTION PERIOD



The exterior finish is the building's first line of thermal resistance and one of the parameters with the greatest potential for intervention in the requalification of existing housing.

The finish of the opaque envelope influences the exterior surface resistance to heat flow, the solar absorptance of the façade, and the durability of the wall system. 53% of the cases use exterior paint, a low-cost solution with almost no thermal resistance, although its colour can significantly affect solar absorptance.

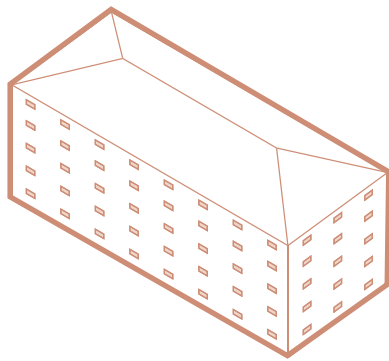
Cement mortar is used in 26% of the cases, adding a thin layer of thermal mass but no real insulation. The remaining 21% corresponds to exposed load-bearing envelopes, such as precast concrete panels or exposed brick, without a differentiated exterior finish. Across all case studies, there is a complete absence of thermal insulation or ventilated façade strategies.

ARCHITECTONICAL & CONSTRUCTIVE TECHNOLOGY

WINDOW TO WALL RATIO (WWR)

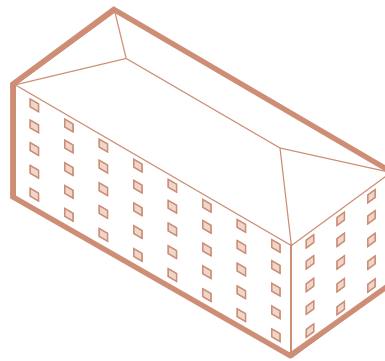
The window-to-wall ratio (WWR) describes how much of the façade is occupied by windows in relation to the total wall surface. It shows how open or closed each façade is, and how much the dwelling can access daylight, views, and natural ventilation. In terms of thermal comfort, WWR influences solar heat gains, indoor brightness, air movement and heat transfer

through the façade. A lower WWR can help reduce overheating, but it may also limit daylight and ventilation; a higher WWR can improve openness and natural light, but it increases the need for solar protection.



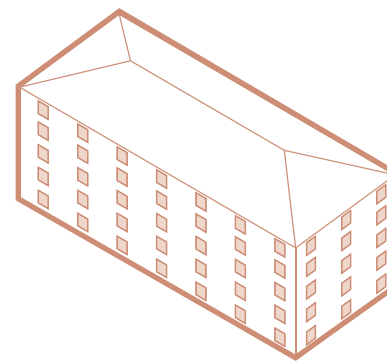
26%
WWR < 15%

Mostly opaque façade; lower solar gain, but limited daylight and ventilation.



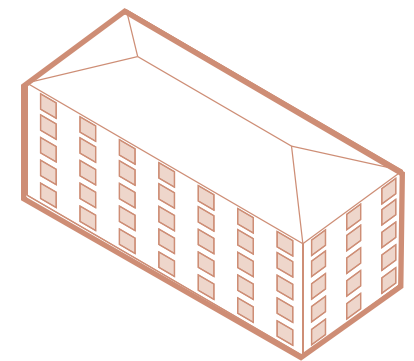
47%
WWR 15-25%

Controlled façade openings; moderate daylight and ventilation potential.



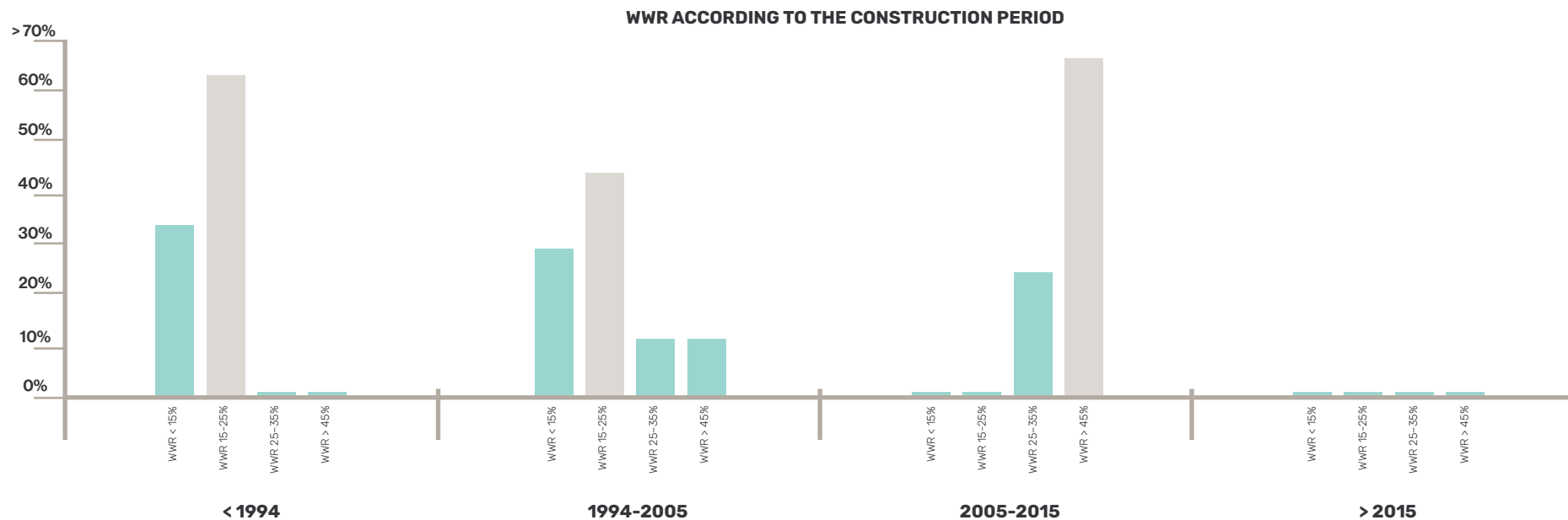
11%
WWR 25-35%

More open façade; better daylight, but higher solar exposure.



16%
WWR > 45%

Highly glazed façade; strong daylight and views, but greater overheating risk.



The window-to-wall ratio directly affects solar heat gains and the potential for natural ventilation. When it is poorly calibrated, even a simple envelope can become an unintended solar collector, increasing indoor heat stress rather than supporting thermal comfort.

The window-to-wall ratio (WWR) controls three critical variables at the same time: direct solar heat gain, daylight availability, and the potential for natural ventilation. In a warm-humid climate such as Cali, WWR values above 20% without effective solar protection can create a significant risk of overheating, especially on east and west facing façades.

The 21% of the cases exceed this threshold, all of them using horizontal sliding windows and lacking deep overhangs or other meaningful shading elements.

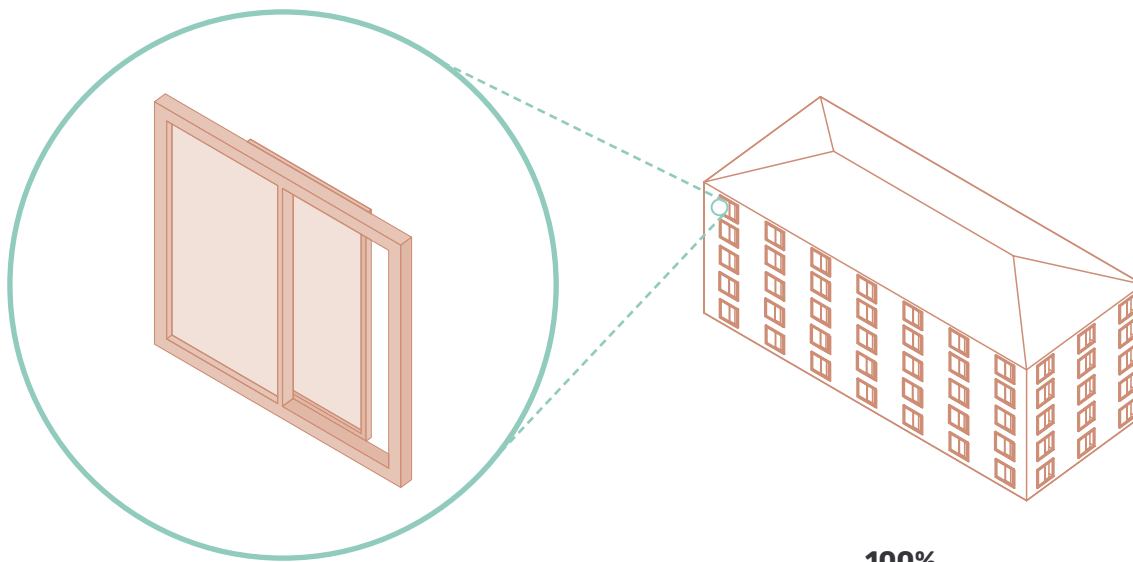
On the other hand, WWR values below 10% may limit daylight access and reduce the capacity for air renewal through natural ventilation.

ARCHITECTONICAL & CONSTRUCTIVE TECHNOLOGY

TYPE OF APERTURE

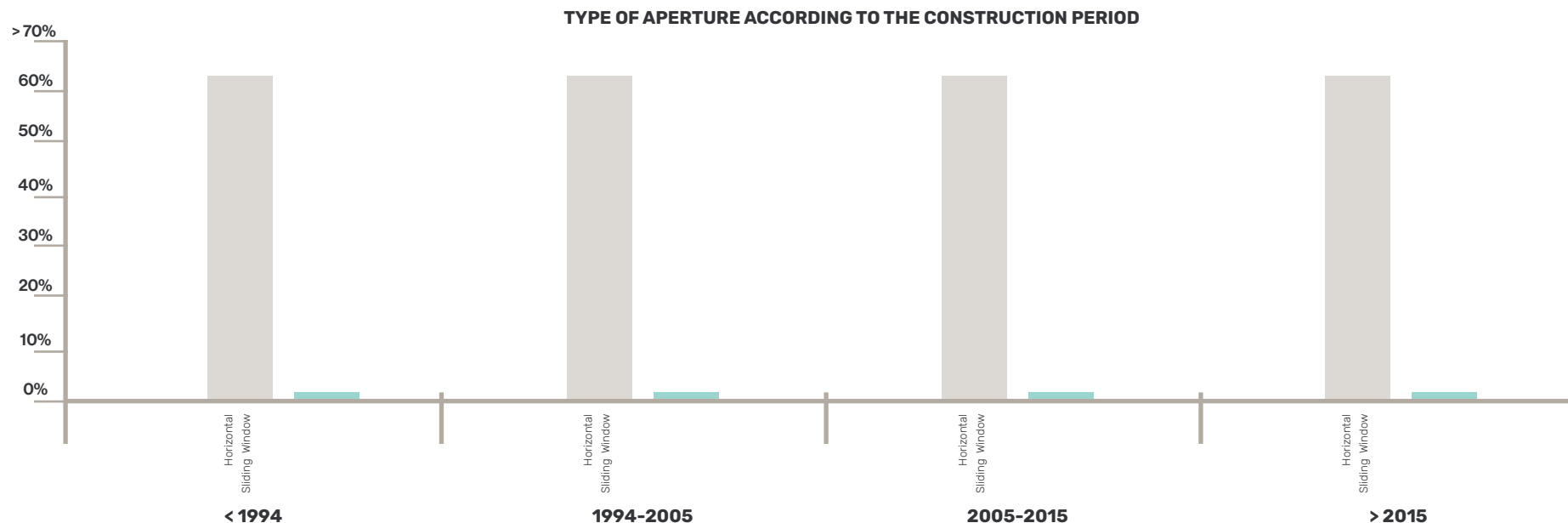
The type of aperture refers to the way façade openings are designed and operated, especially windows. It defines windows control the relationship between indoor spaces and the exterior environment. They influence daylight, views, air movement, façade permeability, and the possibility

of natural ventilation. In terms of thermal comfort, the type of aperture influences the air changes per hour for ventilation, also how solar heat gains are managed through the façade.



100% Horizontal sliding windows

Windows composed of movable panels that slide horizontally along a frame.



The type of aperture defines how the building allows air, light, and views into the dwelling, directly influencing natural ventilation, solar exposure, and indoor thermal comfort.

The type of window opening determines three aspects of the dwelling's environmental performance at the same time: the proportion of the window that can actually be opened for ventilation, the type of air movement generated, and the possibility of controlling solar heat gain independently from ventilation.

Horizontal sliding windows offer an effective opening factor of approximately 50%.

It allows controlled ventilation and is commonly used in compact housing façades; however, the actual ventilation area is limited to only part of the total window surface. As a result, their capacity to support cross-ventilation is lower than that of fully operable systems, especially when no additional openings or façade devices are provided.

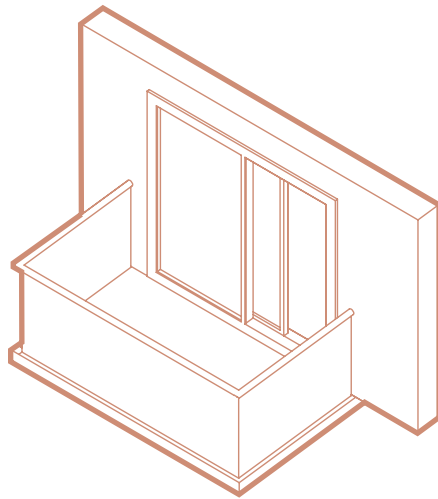
ARCHITECTONICAL & CONSTRUCTIVE TECHNOLOGY

ARCHITECTURAL EXTERNAL AGENTS

Architectonic external agents refer to façade elements that project from or are attached to the external envelope, such as balconies, overhangs, galleries, or shading devices. In the case-study database, this category is simplified into two conditions: the presence or absence of balconies.

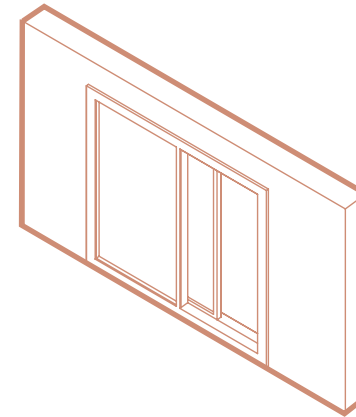
In terms of thermal comfort, balconies can act as intermediate spaces

that provide shade, reduce direct solar radiation on windows and walls, and improve the adaptive use of the façade. However, their performance depends on depth, orientation, material, and exposure. When no external architectural element is present, the façade is more directly exposed to solar radiation, making window design, WWR, shading, and material reflectance more critical.



32%
Balcony

Projecting or recessed external space attached to the dwelling façade.



68%
None

Façade without balconies or relevant external architectural elements.

ARCHITECTONICAL EXTERNAL AGENTS ACCORDING TO THE CONSTRUCTION PERIOD



Architectonic external agents define whether the façade has intermediate elements that can mediate solar exposure, shading, outdoor use, and thermal protection.

External architectural elements such as balconies, overhangs, and cantilevers act as passive shading devices, reducing direct solar gains on windows and on the lower portions of the façade. In the case studies, 68% of the cases do not include any external shading element, while 32% incorporate balconies.

In the buildings that include balconies, the WWR is generally above 15% suggesting that

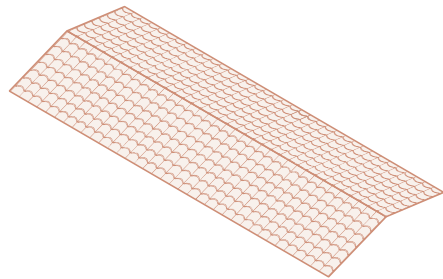
the design anticipated the need for solar protection in response to larger façade openings. However, the absence of balconies or similar elements in the remaining 68% of the cases, combined with horizontal sliding windows and no integrated solar control, represents the most vulnerable condition in terms of overheating risk.

ARCHITECTONICAL & CONSTRUCTIVE TECHNOLOGY

ROOF TYPE

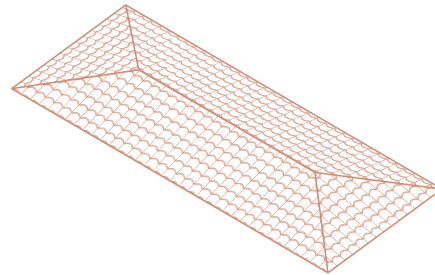
Roof is one of the most exposed elements of the envelope and plays a major role in energy performance, heat gain, water drainage, maintenance, and the potential integration of passive or renewable systems.

In terms of thermal comfort, roof type influences solar heat absorption, heat transfer toward the upper-floor dwellings, ventilation of the roof assembly, and the possibility of reducing indoor overheating through reflective materials, insulation, or ventilated roof layers.



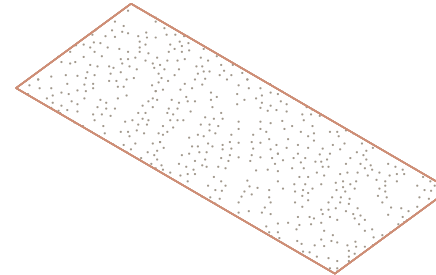
32%
Gable Roof

Roof formed by two inclined planes meeting along a central ridge.



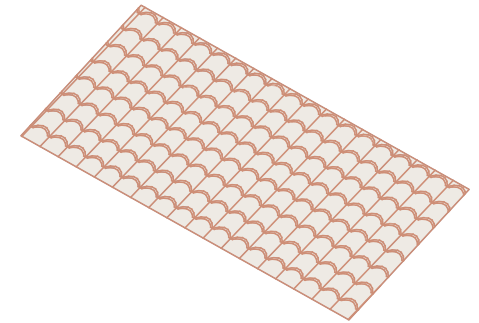
16%
Hip Roof

Roof formed by inclined planes on all sides, usually converging toward a ridge or central point.



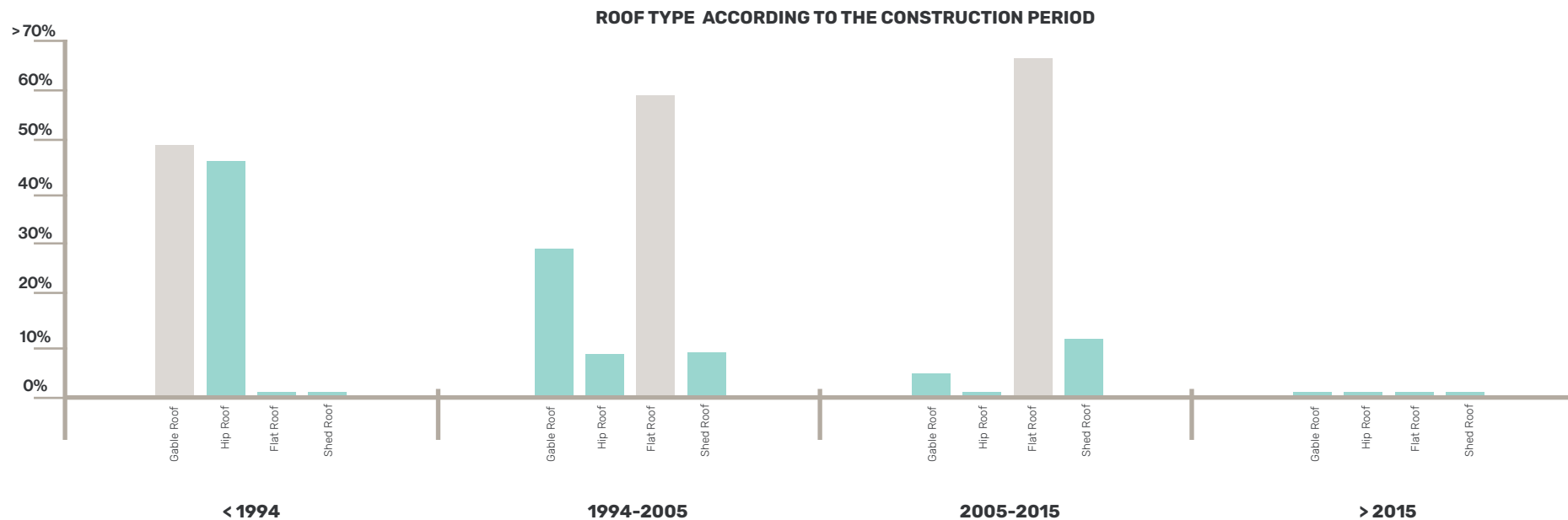
47%
Flat Roof

Horizontal or slightly sloped roof surface designed for drainage.



5%
Shed Roof

Roof formed by a single inclined plane.



The roof type defines how each archetype receives, absorbs, drains, and transfers heat through its upper envelope, making it a critical element for thermal comfort and passive re-trofit strategies.

The roof type defines the geometry of the upper surface of the building and, therefore, influences three key environmental variables: the horizontal surface exposed to solar radiation, the possibility of ventilating the space between the roofing material and the structure, and the management of rainwater runoff. A flat concrete roof without an intermediate air cavity transfers heat directly to the interior through conduction across the slab, reaching its highest surface temperature around solar noon.

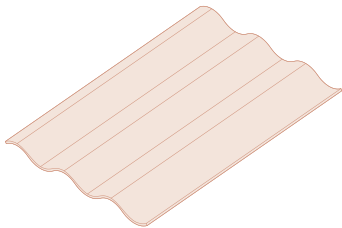
In contrast, pitched roofs with lightweight materials supported on purlins can create a ventilated air gap beneath the roofing layer, which acts as a passive thermal buffer. Shed roofs are the only typology that could potentially use their height difference to capture prevailing winds and support roof-level ventilation, depending on their orientation.

ARCHITECTONICAL & CONSTRUCTIVE TECHNOLOGY

ROOF MATERIAL

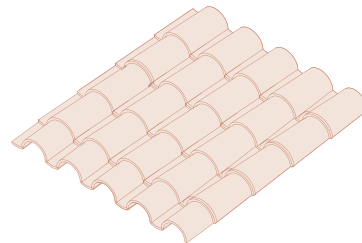
Roof material defines how the upper envelope absorbs, stores, and transfers solar heat, making it a critical variable for thermal comfort. The roof is one of the most exposed parts of the envelope and strongly affects heat absorption, heat transfer, durability, maintenance, and protection against rain.

In terms of thermal comfort, roof material influences how quickly solar heat is absorbed, stored, and transmitted toward the upper-floor dwellings. Heavy materials, such as reinforced concrete slabs, can store heat and release it later, while lightweight materials, such as metal sheets or fiber cement, may transfer heat more rapidly if they are not insulated or ventilated.



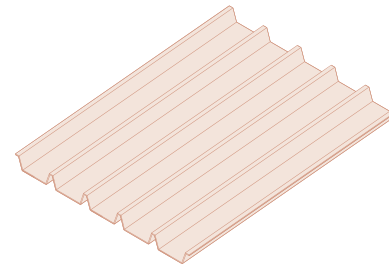
32%
Fiber Cement

Lightweight cement-based roof sheets, commonly used in pitched roofs.



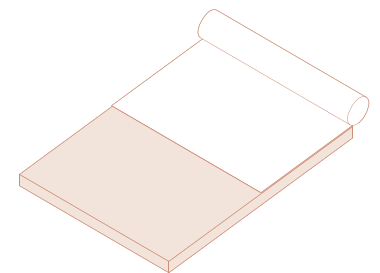
11%
Clay Tile

Ceramic roof tiles placed on a sloped roof structure.



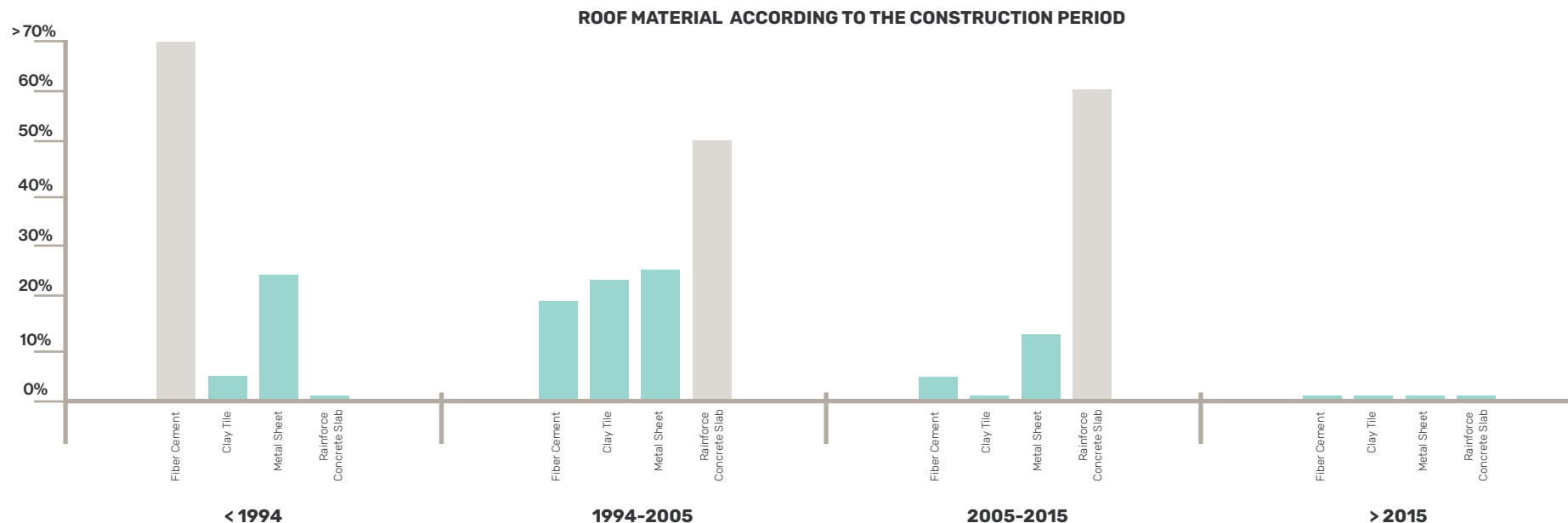
3%
Metal Sheet

Lightweight metal roof panels or sheets.



42%
Reinforced Concrete Slab

Solid concrete roof slab, usually used in flat roof systems.



The roof material defines the thermal behaviour of the most exposed surface of the building. Its conductivity, mass, and solar absorptance determine how much heat the roof stores and how much it transfers to the interior during each daily cycle.

Reinforced concrete slabs, present in 42% of the cases, have high thermal mass and can delay the daytime heat peak. However, their conductivity allows stored heat to be released indoors with a delay of 4–6 hours, increasing discomfort during evening and night-time occupancy.

Fibre cement roofs, present in 32% of the cases, have low thermal mass and limited insulation, so heat transfer can be rapid without ventilation or insulation beneath the roof layer. Metal sheets represent the highest thermal risk, as their high absorptance and low mass

allow them to reach very high surface temperatures and transfer heat almost immediately indoors.

Ceramic tiles offer a more balanced performance, combining moderate mass, medium absorptance, and the possibility of ventilation beneath the tiles.

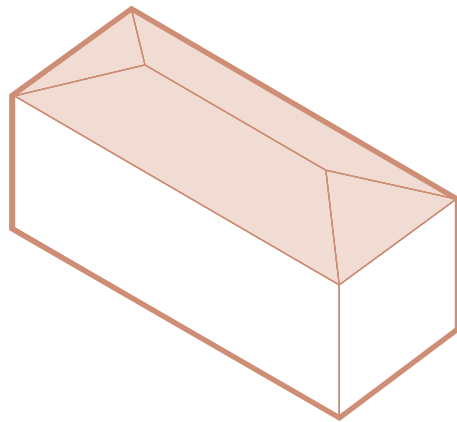
However, the most critical finding is the absence of high-reflectance treatments, such as cool-roof coatings, elastomeric membranes, or roof insulation, which could reduce heat gains.

ARCHITECTONICAL & CONSTRUCTIVE TECHNOLOGY

ROOF COLOR

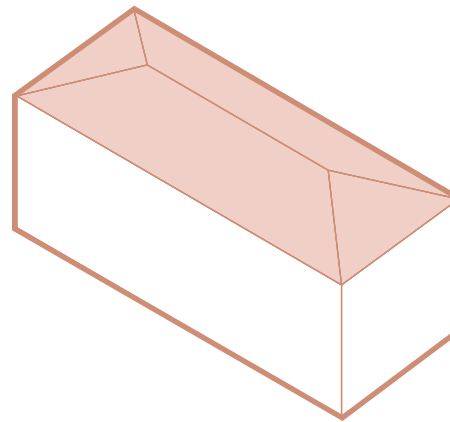
Roof colour refers to the tonal quality of the roof surface and its capacity to reflect or absorb solar radiation. the roof is one of the most exposed parts of the building envelope, especially in warm climates. Light-coloured roofs generally reflect more solar radiation and absorb less heat, while darker roofs absorb more solar energy and can increase surface temperatures.

In terms of thermal comfort, roof colour influences heat gain through the upper envelope, indoor overheating risk in top-floor dwellings, and the effectiveness of passive strategies such as cool roofs, insulation, or ventilated roof layers.



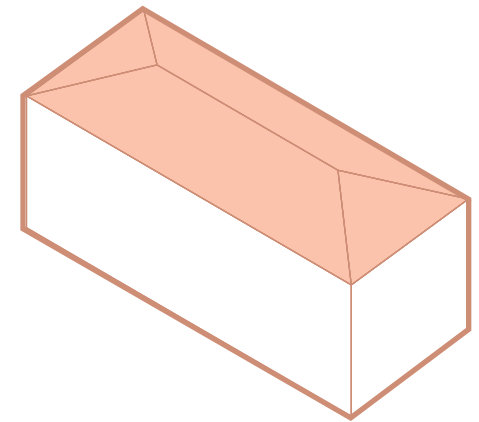
21%
Light Colour

Higher solar reflectance and lower heat absorption; generally more favourable for reducing roof surface temperature.



63%
Medium Colour

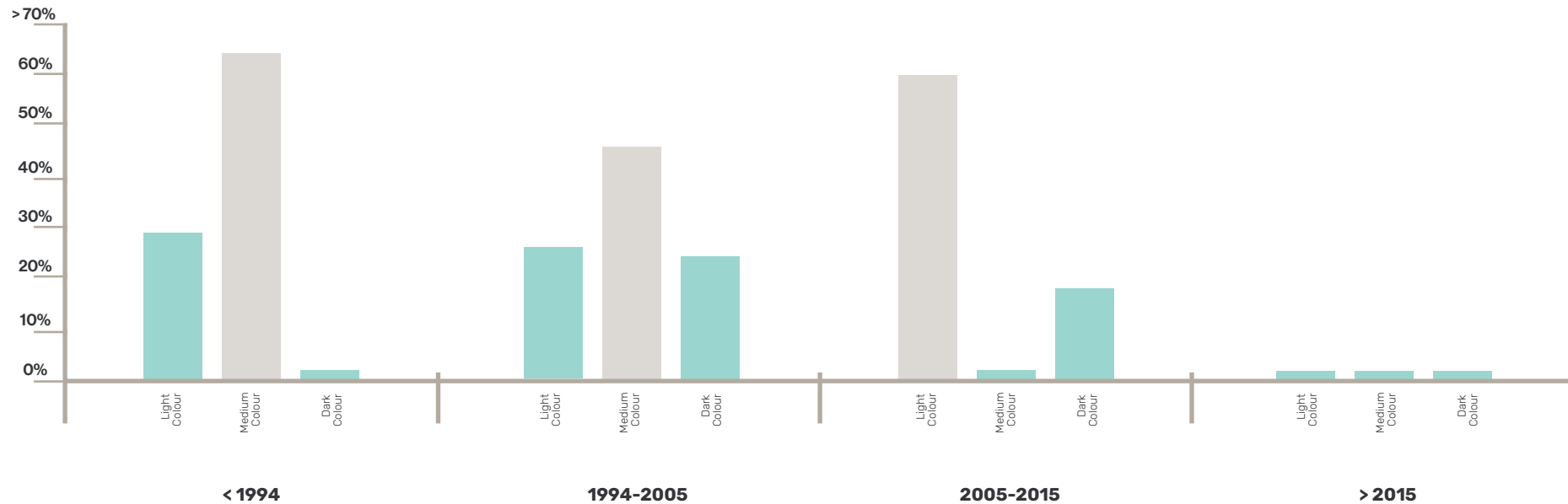
Intermediate condition, with a balance between reflectance and heat absorption.



16%
Dark Colour

Lower reflectance and higher solar absorption; greater potential for roof overheating and heat transfer indoors

ROOF COLOUR ACCORDING TO THE CONSTRUCTION PERIOD



Roof colour is one of the parameters with the most immediate impact on the thermal comfort of the upper floor, while also being one of the least costly to modify.

Roof colour directly determines solar absorptance, consequently, the surface temperature reached under direct solar radiation. In Cali, where global horizontal radiation is high, a dark grey roof can reach surface temperatures of 65–75 °C around solar noon. This heat is then transferred indoors by conduction in concrete slabs, or by convection and radiation in lightweight metal roofs.

Grey is the dominant roof colour in the case studies, representing 63%. White roofs appear in only 21% of the cases and have a lower estimated absorptance ($\approx 0.25\text{--}0.35$), reducing surface temperatures to approximately 35–45 °C under similar conditions. The dark colour roofs, including, brown ceramic tiles and metal roofs represent the 16% show an intermediate behaviour ($\approx 0.55\text{--}0.65$).

ARCHETYPE SELECTION

The three archetypes translate Cali's multi-family social housing stock into a controlled comparative model. Instead of selecting a single "representative" building, the study defines three archetypes that allow the main differences in the sample to be tested in a structured way.

Two archetypes share the same compact morphology but differ in construction system, while the third changes the morphology itself. This makes it possible to compare the influence of material technology and urban form without losing the link to real buildings.

This approach avoids treating the VIS stock as a homogeneous category. Instead, it recognises that overheating is shaped by the interaction between form, envelope, exposure, and construction system. Together, the three archetypes cover the dominant multifamily VIS typologies built in Cali between 1990 and 2015, while providing a clear analytical framework for simulation, sensitivity testing, and retrofit-package definition.

“

The methodological principle behind the archetype selection is to isolate one dominant variable at a time while keeping each case anchored to a real and statistically representative housing project.

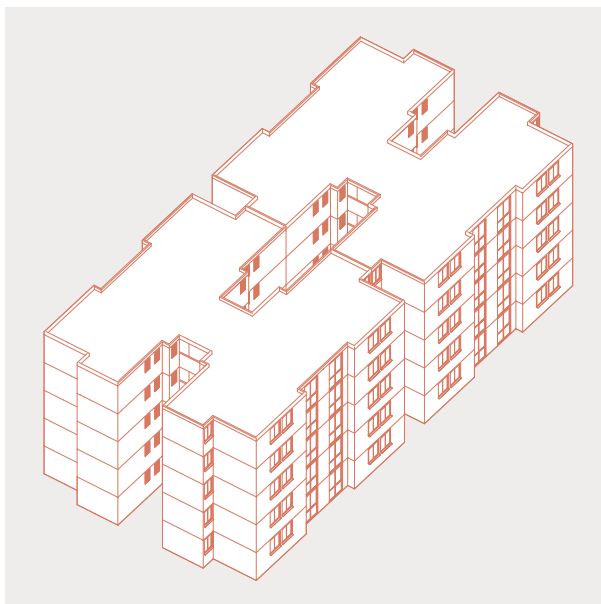
A01 and A02 allow the technological variable to be compared, since both are compact blocks but use different envelope and structural systems. A01 and A03, in turn, allow the morphological variable to be tested, since they belong to a comparable broad construction family but

”

01

COMPACT PREFABRICATED

Brisas de los Álamos

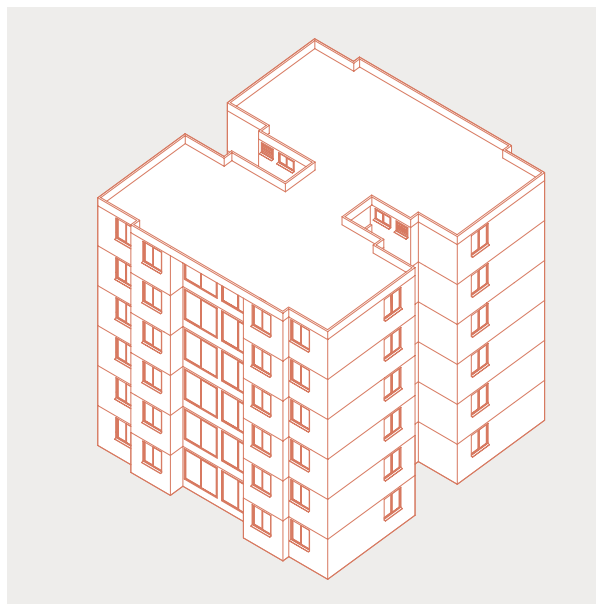


Built by Constructora Alpes between 1994 and 1998, A01 represents the compact prefabricated concrete-panel block. It is the most representative group in the sample and therefore acts as the baseline archetype. Its compact plan, low WWR of approximately 13%, and south-west critical exposure define a heavy, solar-exposed envelope.

02

COMPACT MASONRY

Edén de Comfandi

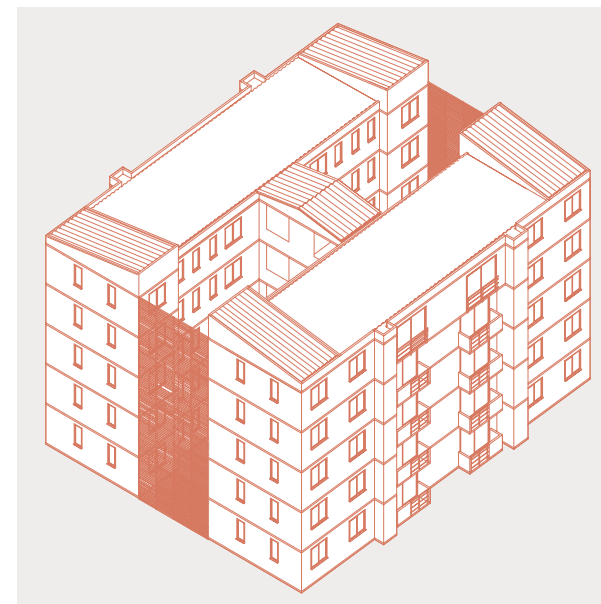


Built by Comfandi between 1994 and 1998, A02 keeps the compact morphology of A01 but replaces the envelope with reinforced brick masonry. It isolates the technological variable by showing how a different construction system changes thermal behaviour within the same urban form.

03

LINEAR MIXED

Jardín de la Camelia

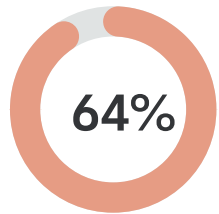


Built by ConCali between 2002 and 2006, A03 introduces the morphological variable through a linear block with a mixed construction system. Its elongated form offers higher cross-ventilation potential, but also greater solar exposure, making it the most demanding archetype under future climate conditions.

ARCHETYPE 01

A01| BRISAS DE LOS ÁLAMOS

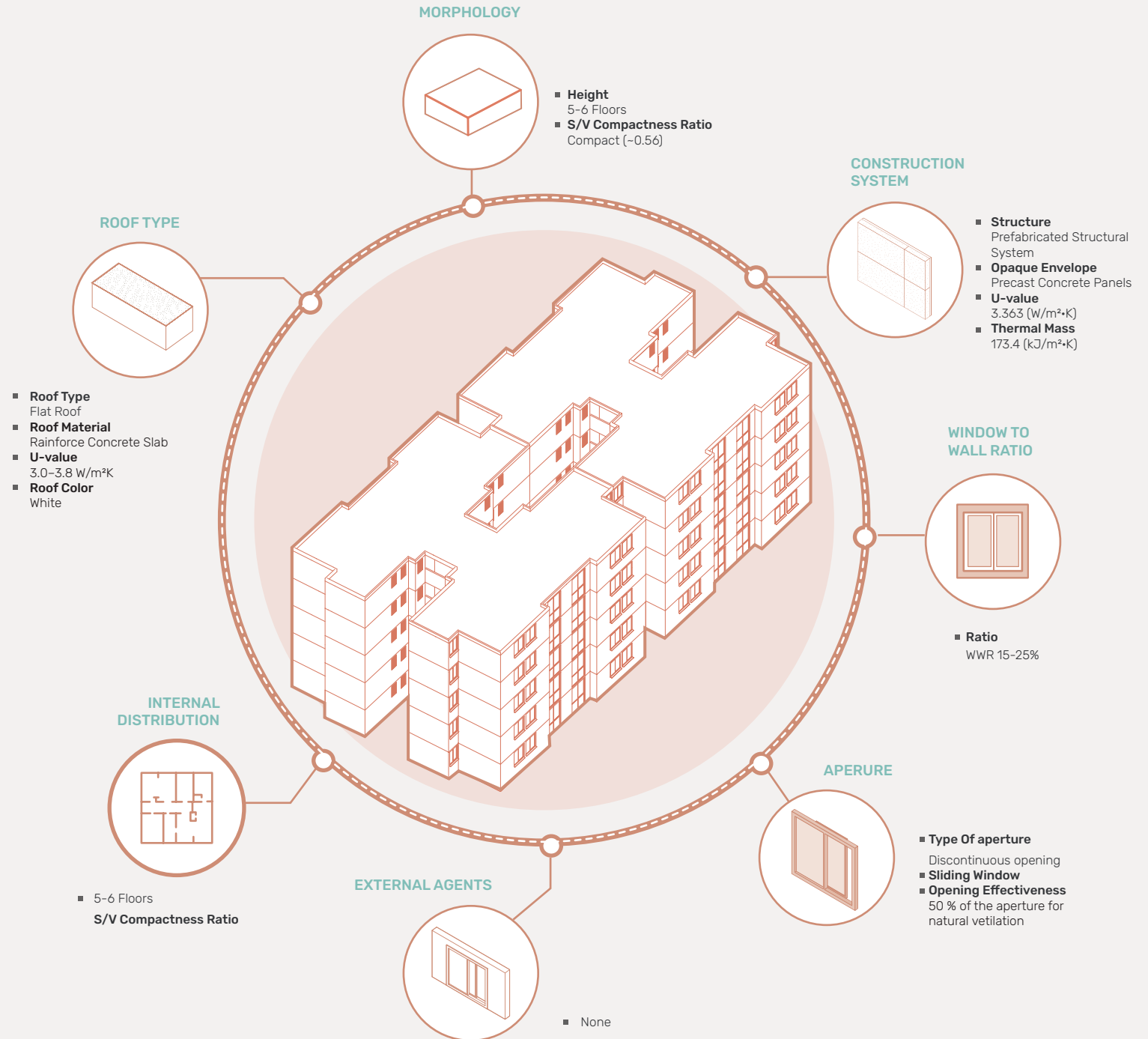
REPRESENTATIVENESS



* The percentage of cases that share the characteristics of the archetype in relation to the total sample analysed.

GENERAL INFORMATION

-  **Construction Period**
1994–1998
-  **Use**
Residential - Multifamily
-  **Number of dwellings**
4 units per floor
-  **Occupation**
3–4 people per dwelling
(Remain constant)



CHARACTERISTICS & FREQUENCIES IN THE ARCHETYPE

	Number of Floors 5-6 Floors	100%
	Volume compactness S/V Medium - Compact (~0.54)	100%
	Individual Morphology Compact	58%
	Internal Distribution Point Block	79%
	Structure Prefabricated Structural System	49%
	Opaque Envelope Precast Concrete Panels	49%
	External Envelope Paint	53%
	Window to Wall Ratio 12.9% - Small windows	26%
	Aperture Sliding openings (~50% effective)	100%
	External Agents None	68%
	Roof Type Flat Roof - Concrete Slab	47%
	Roof Color Medium - Grey	63%

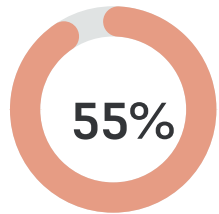
MODELING HYPOTHESES

	Thermal Zoning 5-6 Floors		Natural Ventilation 5-6 Floors		Adaptive Comfort Free-floating - ASHRAE 55 adaptive - % hours
	Occupancy / Loads 5-6 Floors		Cooling setpoint 5-6 Floors		
	Infiltration 5-6 Floors		Base orientation North-South		

ARCHETYPE 02

A02|
EDÉN DE COMFAND I

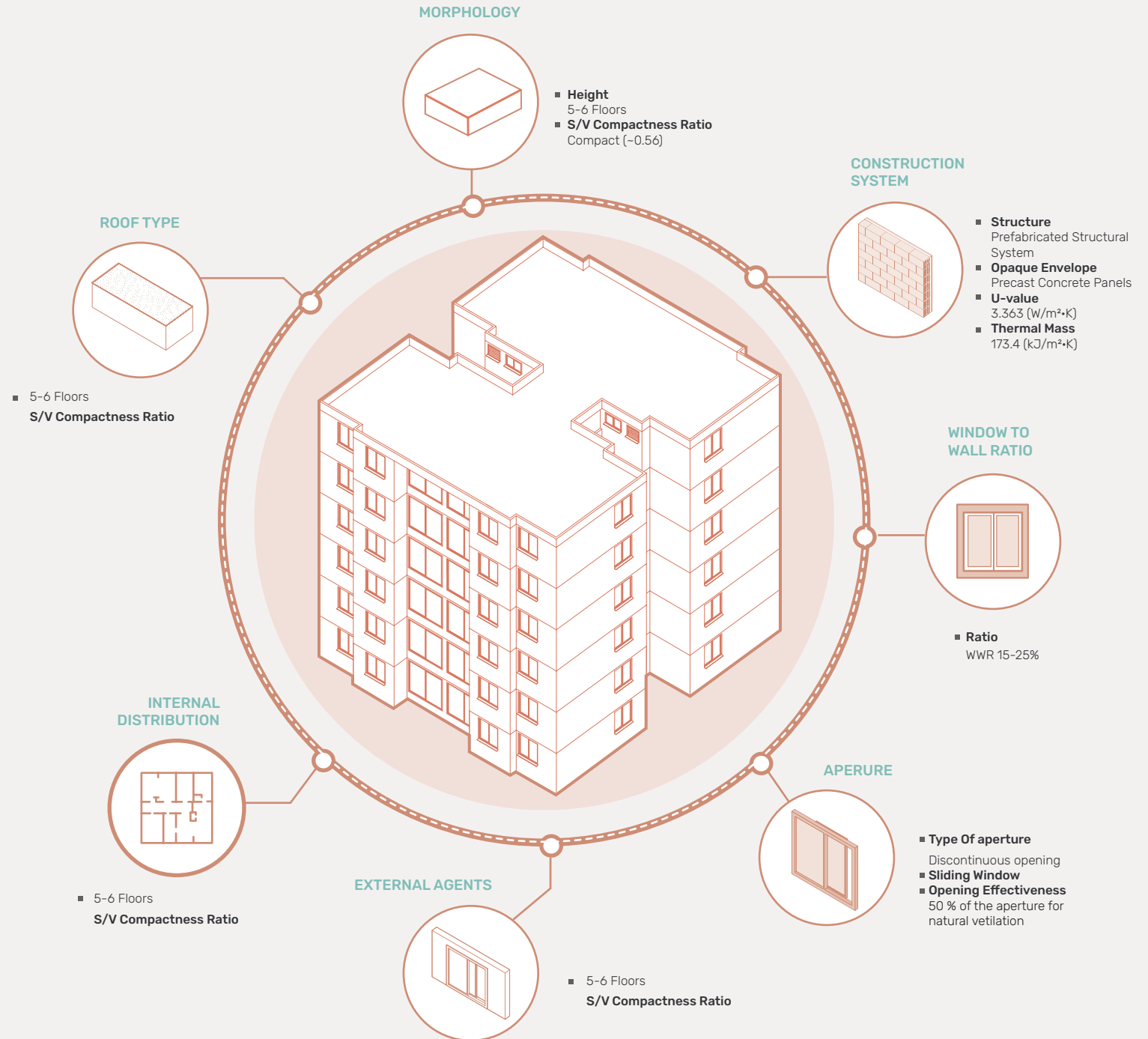
REPRESENTATIVENESS



* The percentage of cases that share the characteristics of the archetype in relation to the total sample analysed.

GENERAL INFORMATION

-  **Construction Period**
1994-1998
-  **Use**
Residential - Multifamily
-  **Number of dwellings**
4 units per floor
-  **Occupation**
3-4 people per dwelling
(Remain constant)



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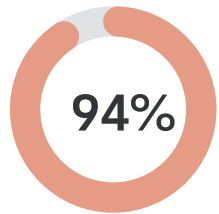
MODELING HYPOTHESES

	Thermal Zoning 5-6 Floors		Natural Ventilation 5-6 Floors		Adaptive Comfort Free-floating • ASHRAE 55 adaptive - % hours
	Occupancy / Loads 5-6 Floors		Cooling setpoint 5-6 Floors		
	Infiltration 5-6 Floors		Base orientation North-South		

ARCHETYPE 03

A03|
JARDIN DELASCARMELIAS

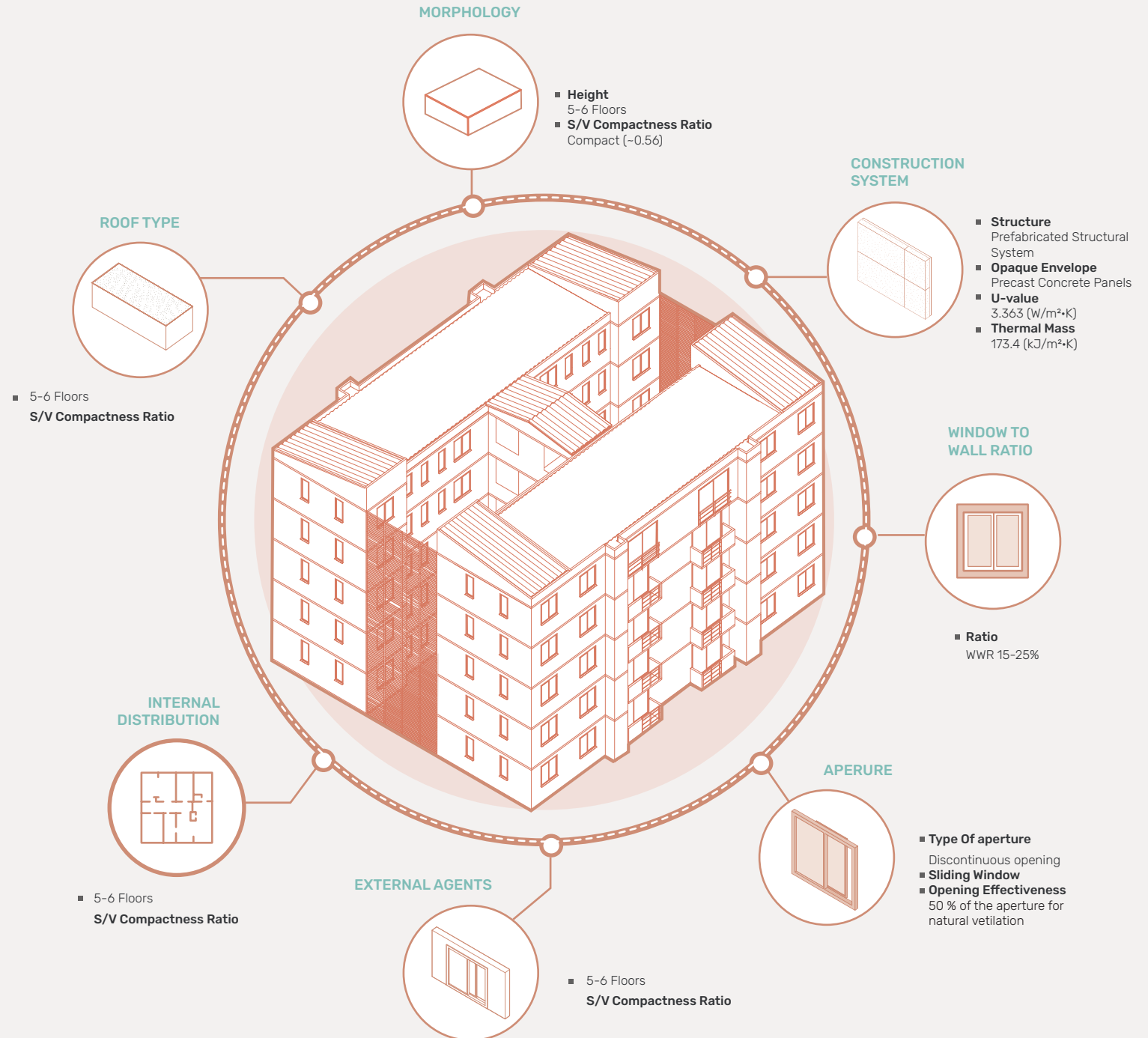
REPRESENTATIVENESS



* The percentage of cases that share the characteristics of the archetype in relation to the total sample analysed.

GENERAL INFORMATION

-  **Construction Period**
1994–1998
-  **Use**
Residential - Multifamily
-  **Number of dwellings**
4 units per floor
-  **Occupation**
3–4 people per dwelling
(Remain constant)



CHARACTERISTICS & FREQUENCIES IN THE ARCHETYPE

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04

CHAPTER



This chapter presents the simulation framework and the main performance results. It first defines the baseline scenario for each archetype and evaluates overheating under the 2050 climate scenario. It then develops the sensitivity analysis of individual passive strategies, showing that controlled natural ventilation is the dominant measure, that the two-directional solar grid outperforms horizontal overhangs, and that insulation worsens overheating. Finally, it combines the effective measures into Low, Medium, and High renovation packages and explains their assignment by optimality

POSSIBILITY OF ACTION

Before testing the individual measures, this section defines the range of possible passive interventions for social housing in Cali's warm climate under free-running conditions.

Unlike retrofits in temperate climates, where the main objective is often to increase thermal resistance, the interventions considered here operate through three physical mechanisms that directly address overheating:

01 DISSIPATE ACCUMULATED HEAT
(Controlled natural and cross-ventilation)

02 SOLAR GAIN CONTROL
(External shading, as horizontal overhangs and vertical shading devices)

03 REDUCE HEAT ABSORBED
by opaque surfaces (reflective wall paint and cool roofs)

***** INCREASE THERMAL RESISTANCE
through insulation, or enlarging the glazed area.

However, these measures are considered primarily in order to test their relevance and, where necessary, to assess their limitations in this climatic context.

These actions are not applied in isolation, but are combined into renovation packages. Following an incremental logic, two levels of ambition are defined:

1 | Cost-efficiency package, based on low-cost and low-disruption measures that capture most of the achievable benefit.

2| Maximum-performance package, which combines the full set of solar-control and heat-dissipation strategies.

Each package is adapted to the construction system and morphology of its corresponding archetype. The same measure does not perform equally in a low-U precast envelope and a higher-U masonry envelope; therefore, the composition of the cost-efficiency package differs across A01, A02, and A03.

By crossing the three archetypes with these levels of action, the analytical framework of

the intervention study is established. The specific composition of each package, including the type of measure, its depth, and its reflectance level, is not assumed in advance. Instead, it is derived from the sensitivity analysis presented in Chapter 5, which quantifies the contribution of each measure under the 2050 design climate. This section therefore defines what can be done, while the following sections explain how each action is modelled and how much each one contributes to performance improvement.

THERMAL AND ENERGY COMFORT SIMULATION METODOLOGY

SIMULATION APPROACH AND TOOLS

The thermal and energy behaviour of each archetype was assessed through dynamic building-energy simulation (BPS). Rather than modelling each building in full, the analysis followed a shoebox approach, in which representative apartment-level thermal zones are simulated in detail. This allows the systematic, comparable testing of design variables across archetypes.

The workflow was built in a parametric environment. Each archetype was modelled in Rhinoceros and parameterised in Grasshopper, which enabled the controlled variation of the design parameters for the Sensitivity analysis design. The Ladybug Tools plugins (Ladybug and Honeybee) were used to assign material properties, schedules and boundary conditions and to translate the parametric model into an EnergyPlus input file. Annual simulations were run in EnergyPlus through OpenStudio 3.7.0.

MODEL DEFINITION

Each apartment was represented as a single thermal zone. For each archetype, two representative apartments were selected as the

thermally critical cases along the vertical gradient of the block:

1 | Top Floor Apartment : Where dwelling ceiling is exposed to the roof and therefore carries the worst-case solar and thermal load.

2 | Mid Floor Apartment: Representative of the stacked middle floors, bounded above and below by other dwellings.

Both critical units face the most unfavourable orientation (south-west), which receives the strongest afternoon solar load.

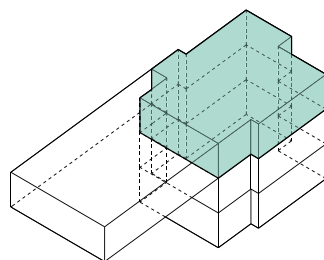
Each apartment has a single exposed façade. All other surfaces, the party walls shared with adjacent apartments and, for the intermediate apartment, the floor and ceiling shared with the dwellings above and below, were modelled as adiabatic boundaries.

The modelled apartment floor areas are 57 m² (A01), 55 m² (A02) and 55.1 m² (A03). The same two-apartment shoebox scheme, with a single exposed façade at a fixed base orientation, was applied identically to all three archetypes, so that differences in results derive

03



Mid Floor Apartment



Top Floor Apartment

05

GENERAL SIMULATION FIXED PARAMETERS FOR ALL THE ARCHETYPES

The following operational and boundary parameters were defined to be kept constant across the three archetypes and all parametric simulations. This methodological decision, intended to ensure that differences in the results could be attributed to the envelope, morphology, and design variables under study, rather than to variations in use, occupancy, or operation.



OCCUPANCY

Number of people per m²

0.028 pers/m²

Occupation period

Schedule - Midrise Apartment (Open Studio Standard Schedule)



NATURAL VENTILATION

Open the window when:

Minimum indoor temperature: 23°C

Minimum outdoor temperature: 15°C

Maximum indoor temperature: 40°C

Maximum outdoor temperature: 40 °C

Temperature difference (Δ): 2-3°C



ARTIFICIAL LIGHTING

Number of Watt per m²

3 W/m²



SETPOINT

Cooling

26 °C



ELECTRICAL EQUIPMENT

Number of Watt per m²

2 W/m²



COMFORT AND BOUNDARIES

Comfort Model

ASHRAE 55 • free-running (no A/C)

Shared walls

Adiabatic

Mech. vent / DHW

None



INFILTRATION

Rate

0.0003 m³/s•m²

Reference

per exterior area



Simulation period

8760 h/year

PERFORMANCE METRICS AND DIAGNOSTICS

Two complementary outputs were obtained from the same simulation model, using two different modes.

1. Primary metric | Adaptive Comfort Condition.

For this assessment, the model was run in free-running mode, without mechanical conditioning, and the indoor operative temperature was evaluated hourly against the ASHRAE 55 adaptive comfort model.

this comfort model is particularly suitable for naturally ventilated buildings because it relates acceptable indoor operative temperatures to the prevailing outdoor climatic conditions. Unlike fixed comfort ranges, the adaptive model assumes that occupants can tolerate and accept different indoor temperatures depending on recent outdoor temperatures and their capacity for behavioural adaptation, such as opening windows, adjusting clothing, or increasing air movement. Each of the 8,760 annual hours was classified into one of three conditions: cold discomfort, comfort, or overheating.

* Base formula ASHRAE 55 adaptive comfort model

$$T_{comfort} = 0.31 \times T_{out} + 17.8$$

$T_{comfort}$ = Neutral indoor comfort temperature.

T_{out} = Predominant average outdoor temperature.

0.31 / 17.8 = Model coefficients

80% acceptability: ± 3.5 °C.

90% acceptability: ± 2.5 °C.

< 23°C

-1 | Cold Discomfort

(below the adaptive comfort band)

23°C - 26°C

0 | Comfort

(within the band)

> 23°C

1 | Overheating Discomfort

(above the band)

Since Cali has a warm- dry / humid climate and the dominant thermal risk is overheating, the number of +1 hours was used as the main performance indicator to compare scenarios and archetypes. This value was reported for each critical apartment, while comfort hours and cold discomfort hours were included to provide a complete annual overview.

2. Diagnostic | Annual Heat Balance.

To explain the origin of heat gains and the effect of each strategy, the same model was also run in ideal-loads mode. From this simulation, the annual heat balance of each critical apartment was extracted in kWh/year, including solar gains, occupants, lighting, equipment, opaque conduction, window conduction, infiltration, controlled ventilation, and residual cooling.

This diagnostic output is used to interpret the sensitivity results. It shows which sources dominate the heat input and how each strategy contributes to heat removal, particularly the role of controlled ventilation once it is activated.

ARCHETYPES BASE SCENARIO

The base scenario for each archetype combines its real envelope characteristics with the fixed parameters, the shoebox geometry described in the model definition and a common set of baseline conditions.

These include:

- No external shading
- Closed windows with no natural ventilation.
- Fixed Orientation.

For each archetype, this base scenario was evaluated in two critical apartments: the worst-case intermediate unit on the 2nd floor and the roof-exposed unit on the 5th floor. Both units were selected according to the most unfavourable facade exposure within each archetype. This critical exposure varies across the cases, reflecting their specific facade layout: south-west for A01, south-east for A02, and north-east for A03.

This doesn't imply that orientation was tested parametrically; rather, each archetype was assessed under its fixed baseline orientation, while the critical apartments were chosen according to their most exposed condition.

Archetype	Apartment Units	System	Opaque Envelope	U-Value *	WWR Base	Orientation	Baseline overheating (Int / Roof)
A01 Brisas de los Álamos	A01_P7SO Intermediate Unit	Precast Concrete	$e = 0.150$	3.363 (W/m²K)	12.9%	SW	1999 / 1854 h
	A01_P19SO Roof Unit		$k = 0.505$ $\rho = 2400$ $c_p = 482$				
A02 Edén de Comfandi	A02_P8SE Intermediate Unit	Brick Masonry	$e = 0.106$	2.643 (W/m²K)	16.2%	SE	1714 / 1362 h
	A02_P20SE Roof Unit		$k = 0.509$ $\rho = 1800$ $c_p = 840$				
A03 Jardín de la Camelia	A03_P8NE Intermediate Unit	Mixed	$e = 0.130$	2.392 (W/m²K)	15.6%	NE	1607 / 1555 h
	A03_P20NE Roof Unit		$k = 0.524$ $\rho = 2100$ $c_p = 611$				

* e = Wall Thickness (m) k = Thermal Conductivity (W/m·K) ρ = Material Density (kg/m³) c_p = Specific heat (kg/m³)

* **Transparent Envelope:** U-Value Glazing = Solar Heat Gain Coefficient (SHGC) =

Overall, the baseline results confirm the severity of the overheating problem and reveal the expected vertical thermal gradient, with roof-level apartments showing a higher risk of heat stress than intermediate-floor units.

SENSITIVITY ANALYSIS DESIGN

The sensitivity analysis is used to understand how individual design parameters affect the thermal performance of the selected housing archetypes. Since the aim of this research is not only to diagnose overheating, but also to define effective passive retrofit strategies, it is necessary to identify which variables have the greatest influence on indoor comfort before combining them into renovation packages.

For this reason, the analysis functions as an intermediate methodological step between the base-case diagnosis and the development of integrated design strategies. The baseline scenario provides the reference condition against which each passive measure is tested.

At this stage, a one-factor-at-a-time (OFAT) approach is used, in which each passive design variable is modified independently in order to isolate its specific effect on annual comfort hours, cold discomfort hours, and overheating hours. This enables a clear comparison of the relative impact of strategies related to the envelope, roof, windows, shading, and ventilation, while keeping the climate data and modelling assumptions constant.

Therefore, the OFAT screening is not treated as a final evaluation method, but as a diagnostic stage that informs the selection and combination of the renovation packages developed in the following phase.

The tasted variables are :

Variable	Base	Tested Values	Design Meaning
Controlled Natural Ventilation	Off (closed)	On	Passive night / cross-ventilation dissipation
External shading (balcony depth)	0 m	0.80 / 1.20 / 1.50 m	External solar control (Honeybee Louver, horizontal overhang)
External shading (grid)	0 m	0.80 / 1.20 / 1.50 m	Two-directional solar control
Window-to-wall ratio (WWR)	As built	15% / 20% / 25%	Daylight vs solar-heat trade-off
Roof solar absorptance (cool roof)	0.70	0.45 / 0.25 (cool roof)	Roof heat absorption (top-floor unit only)
Wall surface absorptance (reflective paint)	0.70	0.25	Surface reflectance of the opaque wall
Opaque insulation (wall and roof)	none	added	Thermal resistance (tested and rejected)

1 | Controlled Natural Ventilation :

This variable is modelled through operable windows using the Honeybee Window Opening component. Windows are allowed to open only when conditions support passive cooling:

- Indoor air temperature ≥ 23 °C
- Outdoor air temperature ≥ 15 °C,
- Indoor temperature is at least 2 °C higher than the outdoor temperature.

This control logic activates ventilation mainly to remove internal heat gains and reduce overheating, while avoiding unnecessary ventilation when it could cause overcooling. A permanently open scenario, with windows fixed at 50% openness, was initially tested but discarded because it does not represent realistic occupant-controlled operation. Therefore, controlled ventilation is the strategy carried forward in the analysis.

2 | WWR :

This variable is varied by proportionally scaling the real window geometry of each archetype. A linear scale factor of $\sqrt{(WWR_target / WWR_base)}$ is applied to the existing openings, so that their original position and proportions are

maintained as much as possible. Because the whole window is scaled, including the operable portion, an increase in WWR also increases the potential ventilation area.

For this reason, WWR is evaluated under two conditions:

- A.** First with closed windows, to isolate the solar-gain penalty of larger glazed areas.
- B.** Second with controlled natural ventilation, to capture the possible compensating effect of larger operable openings.

This makes explicit the trade-off between increased solar exposure and improved ventilation potential.

The base WWR differs across the three archetypes, 12.9% (A01), 16.2% (A02), 15.6% (A03). Consequently, not all target values are applicable to every case. The 15% target is not applied to A02 and A03 because their existing WWR already meets or exceeds that value.

3 | Orientation:

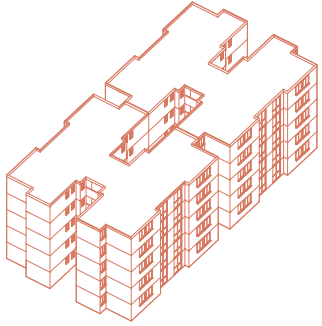
Orientation was initially considered during the

screening process, but it was not retained as a primary sensitivity variable. In the first stage, each archetype was modelled according to its real orientation, as observed in the existing case study. This allowed the identification of the most critical apartment units to be carried forward into the sensitivity analysis.

Therefore, orientation was used as a filtering criterion to select the apartments with the most unfavourable façade exposure, rather than as a variable to be modified parametrically. Preliminary tests showed that, for the compact shoebox configurations used in the simulations, orientation had a more limited effect than envelope properties, shading, roof absorptance, WWR, and ventilation. For this reason, the selected critical units were kept in their baseline orientation throughout the sensitivity analysis.

4 | External shading:

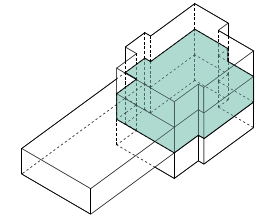
Is tested in two forms: a single horizontal overhang and a two-directional grid, both at increasing depths. The grid provides stronger control because it shades low-angle as well as high-angle sun.



ARCHETYPE 01

A01 |
BRISAS DE LOS ÁLAMOS

CASE A01_1
Mid Floor Apartment



SENSITIVITY ANALYSIS RESULTS

Adaptive Comfort

Metric. The main performance metric is the adaptive comfort condition, based on the ASHRAE 55 adaptive comfort model in free-running mode. Results are reported as annual hours over an 8,760-hour simulation and classified into three categories: cold discomfort (−1), comfort (0), and heat discomfort or overheating (+1).

The headline indicator is the number of overheating hours. The percentage variation ($\Delta\%$) expresses the change in overheating hours relative to the closed-window baseline of each archetype. Results are reported for the two critical apartments in each archetype: the worst-performing intermediate unit on the 2nd floor and the worst-performing roof unit on the 5th floor.

Baseline	Cold (−1)	Comfort (0)	Heat (+1)	$\Delta\%$ Heat	Δ Comfort (h)
	8	5388	3364	0.00%	0

VENTILATION

Scenario	Int. Comfort Model			Δ% Heat	Δ Comfort (h)
	Cold (-1)	Comfort (0)	Heat (+1)		
Controlled natural ventilation	71	7889	800	-76.2%	+2501

ROOF

Scenario	Int. Comfort Model			Δ% Heat	Δ Comfort (h)
	Cold (-1)	Comfort (0)	Heat (+1)		
Roof absorptance =0.45	12	4896	3852	14.5%	-492
Roof absorptance =0.25	11	5357	3392	0.80%	-31

SHADING

Scenario	Int. Comfort Model			Δ% Heat	Δ Comfort (h)
	Cold (-1)	Comfort (0)	Heat (+1)		
Balcony/shading 0.80 m	0	5705	3055	-9.2%	+ 317
Balcony/shading 1.20 m	0	5992	2768	14.5%	+604
Balcony/shading 1.50 m	0	6147	2613	-22.3%	+759
Vertical Fins 0.80 m	6	6922	1933	-42.5%	+1534
Vertical Fins 1.20 m	6	6892	1862	-44.6%	+1504
Vertical Fins 1.50 m	6	6922	1832	-45.5%	+1534

OPAQUE ENVELOPE

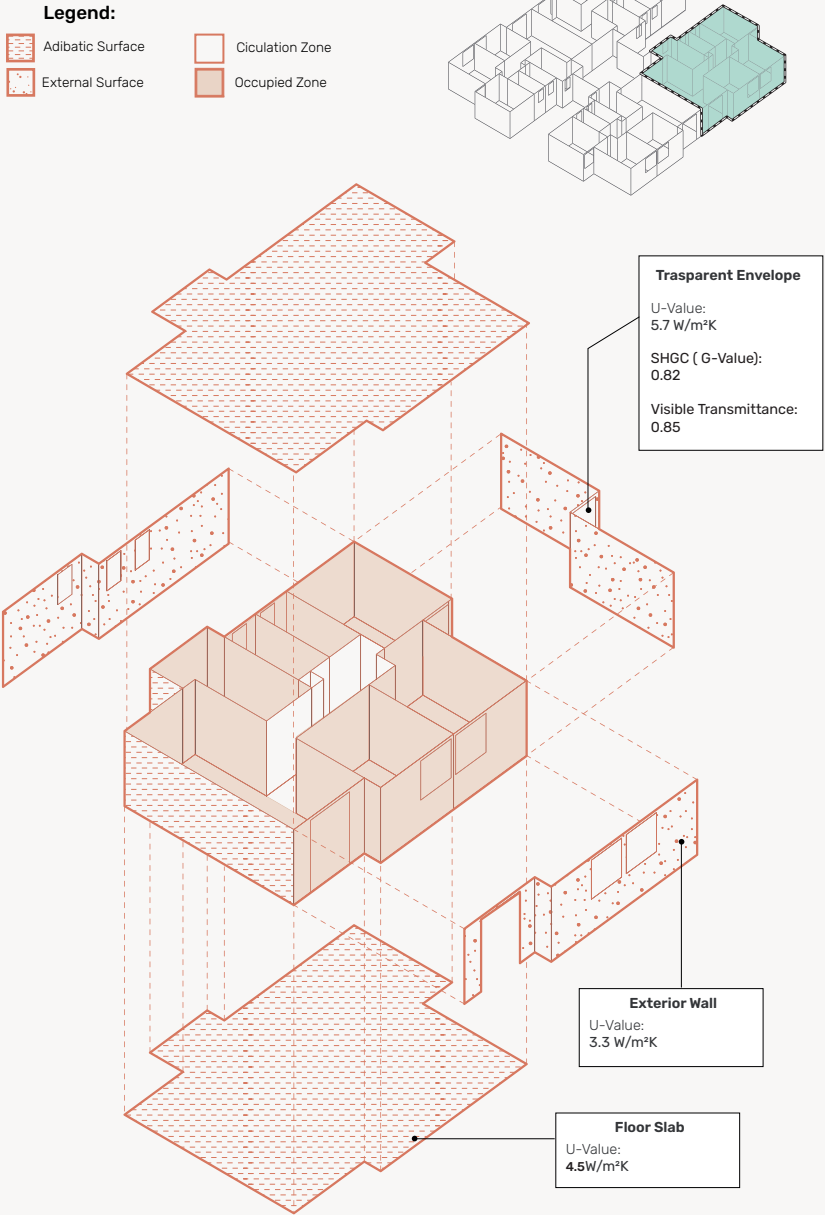
Scenario	Int. Comfort Model			Δ% Heat	Δ Comfort (h)
	Cold (-1)	Comfort (0)	Heat (+1)		
Wall paint α=0.25	0	5874	2886	-14.2%	+486
Wall paint α=0.35	0	5541	3219	-4.3%	+153
Wall paint α=0.45	0	5203	3557	5.7%	-185
Wall paint α=0.55	0	4926	3834	14.0%	-462
Isolated Wall U=0.86	0	4527	4233	25.8%	-861

WWR

Scenario	Int. Comfort Model			Δ% Heat	Δ Comfort (h)
	Cold (-1)	Comfort (0)	Heat (+1)		
WWR 15% + closed windows	N/A	N/A	N/A	N/A	N/A
WWR 20% + closed windows	11	3831	4918	46.2%	-1557
WWR 25% + closed windows	12	3650	5098	51.5%	-1738
WWR 15% + Open windows	N/A	N/A	N/A	N/A	N/A
WWR 20% + open windows	183	6529	2048	-39.1%	+1141
WWR 25% + open windows	197	6291	2272	-32.5%	+903

ENERGETIC MODEL

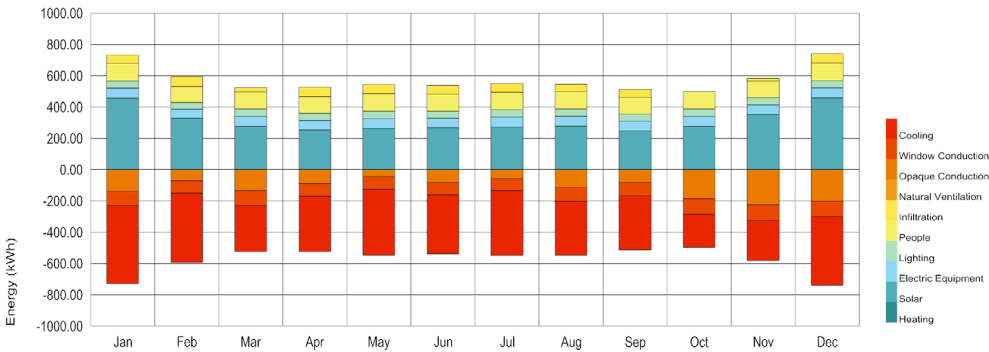
Before Refurbishment



THERMAL BALANCE

Figure X

Source: Open Studio-Honey Bee and Grasshopper



The baseline apartment gains more heat than it can dissipate.

Solar gains account for 1,750.8 kWh and can be reduced through shading or window-area control, while internal gains from occupants, equipment, and lighting reach approximately 2,603 kWh. Since these internal loads are generated inside the dwelling, they cannot be shaded and must be removed through air movement.

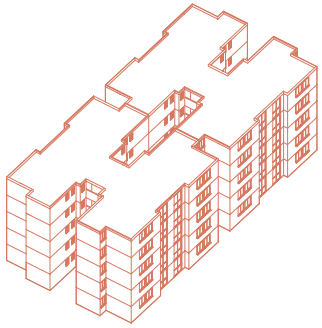
The only significant passive heat sink is the opaque precast-concrete envelope, which accounts for , -1,147.4 kWh and releases stored heat mainly at night. Other paths are almost neutral, such as window conduction (+72.7 kWh), or inactive, as in the case of natural ventilation (0.0 kWh). As a result, the remaining surplus appears as residual cooling demand (-3,690.0 kWh), which in free-running conditions becomes overheating.

The thermal balance study defines a clear order of intervention:

1. Controlled natural ventilation must be activated to create a heat-removal path.
2. Existing thermal mass should be supported through night-time ventilation and a high-reflectance roof finish to reduce daytime heat storage.
3. External shading should reduce solar gains before they enter the apartment.

Main gains chart

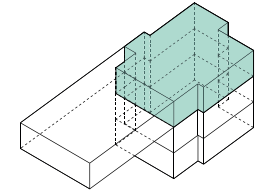
Baseline Scenario	Total Main Gains (kWh)	Solar (kWh/year)	Infiltration (kWh/year)	Internal Loads (kWh/year)
	4121.6	1750.77	426.0	2,603



ARCHETYPE 01

A01 |
BRISAS DE LOS ÁLAMOS

CASE A01_2
Top Floor Apartment



SENSITIVITY ANALYSIS RESULTS

Adaptive Comfort

Metric. The main performance metric is the adaptive comfort condition, based on the ASHRAE 55 adaptive comfort model in free-running mode. Results are reported as annual hours over an 8,760-hour simulation and classified into three categories: cold discomfort (−1), comfort (0), and heat discomfort or overheating (+1).

The headline indicator is the number of overheating hours. The percentage variation ($\Delta\%$) expresses the change in overheating hours relative to the closed-window baseline of each archetype. Results are reported for the two critical apartments in each archetype: the worst-performing intermediate unit on the 2nd floor and the worst-performing roof unit on the 5th floor.

Baseline	Cold (−1)	Comfort (0)	Heat (+1)	$\Delta\%$ Heat	Δ Comfort (h)
	8	5637	3115	0.00%	0

VENTILATION

Scenario	Int. Comfort Model			Δ% Heat	Δ Comfort (h)
	Cold (-1)	Comfort (0)	Heat (+1)		
Controlled natural ventilation	70	8015	675	-78.3%	+2378

ROOF

Scenario	Int. Comfort Model			Δ% Heat	Δ Comfort (h)
	Cold (-1)	Comfort (0)	Heat (+1)		
Roof absorptance =0.45	16	5085	3659	17.5%	-552
Roof absorptance =0.25	18	5501	3241	4.00%	-136

SHADING

Scenario	Int. Comfort Model			Δ% Heat	Δ Comfort (h)
	Cold (-1)	Comfort (0)	Heat (+1)		
Balcony/shading 0.80 m	0	5937	2823	-9.4%	+ 300
Balcony/shading 1.20 m	0	6220	2540	-18.5%	+583
Balcony/shading 1.50 m	0	6385	2375	-23.8%	+748
Vertical Fins 0.80 m	6	7131	1746	-43.9%	+1494
Vertical Fins 1.20 m	6	7094	1660	-46.7%	+1457
Vertical Fins 1.50 m	6	7131	1623	-47.9%	+1494

OPAQUE ENVELOPE

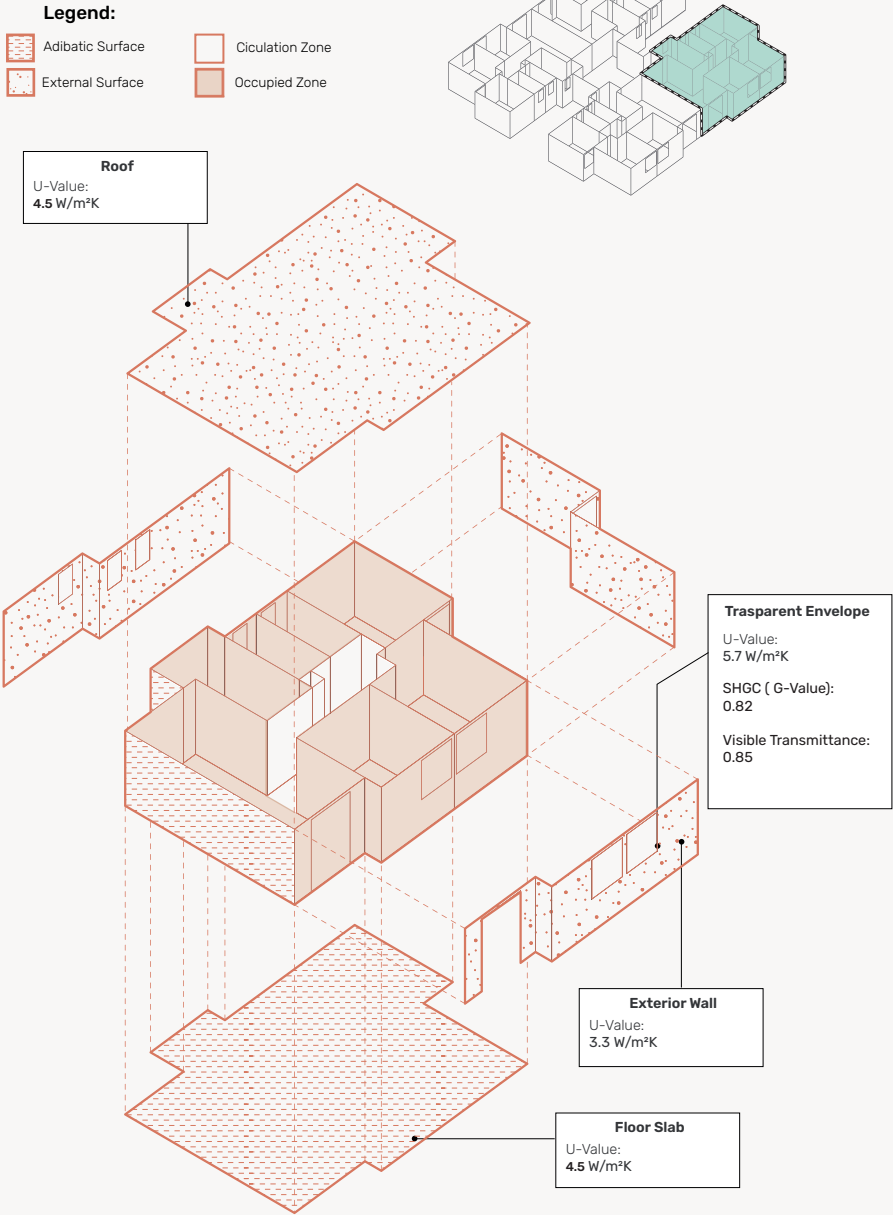
Scenario	Int. Comfort Model			Δ% Heat	Δ Comfort (h)
	Cold (-1)	Comfort (0)	Heat (+1)		
Wall paint α=0.25	0	6106	2654	-14.8%	+469
Wall paint α=0.35	0	5775	2985	-4.2%	+138
Wall paint α=0.45	0	5473	3287	5.5%	-164
Wall paint α=0.55	0	5189	3571	14.6%	-448
Isolated Wall U=0.86	0	4818	3942	26.5%	-819

WWR

Scenario	Int. Comfort Model			Δ% Heat	Δ Comfort (h)
	Cold (-1)	Comfort (0)	Heat (+1)		
WWR 15% + closed windows	N/A	N/A	N/A	N/A	N/A
WWR 20% + closed windows	14	3980	4766	53.0%	-1657
WWR 25% + closed windows	15	3752	4993	60.3%	-1885
WWR 15% + Open windows	N/A	N/A	N/A	N/A	N/A
WWR 20% + open windows	184	6621	1955	-37.2%	+984
WWR 25% + open windows	199	6377	2184	-29.9%	+740

ENERGETIC MODEL

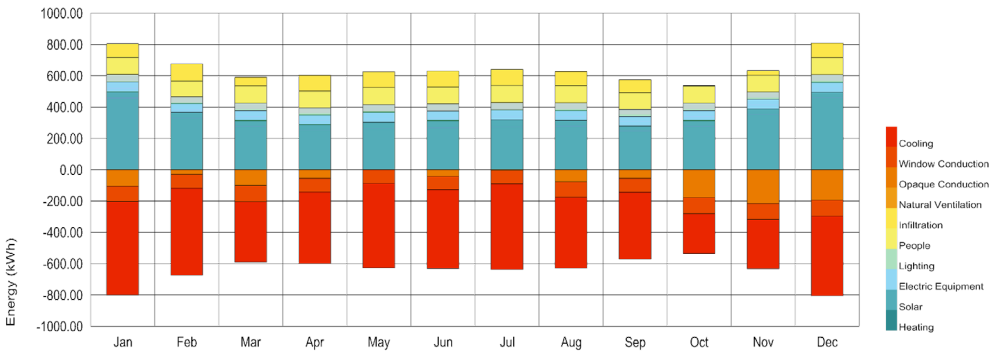
Before Refurbishment



THERMAL BALANCE

Figure X

Source: Open Studio-Honey Bee and Grasshopper



The roof unit follows the same cooling-driven pattern as the intermediate unit, but with greater intensity.

Internal gains remain the same, at approximately 2,603 kWh, so the difference is caused by exposure. Solar gains rise to 1,967.5 kWh and infiltration increases to 724.9 kWh, reflecting the added impact of the roof surface.

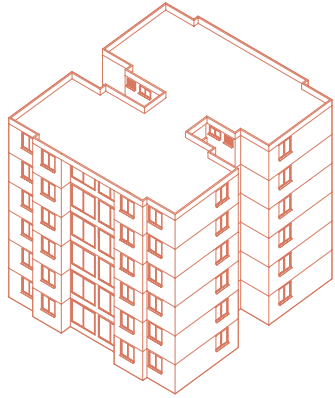
The key change is the weakening of the passive heat sink. Opaque conduction removes only -700.3 kWh, compared with -1,147.4 kWh in the intermediate unit. This occurs because the roof acts as an additional heat-gaining surface during the day, reducing the envelope's capacity to release heat at night. With ventilation inactive, the remaining surplus becomes residual cooling demand, which increases to -4,669.6 kWh.

Compared with the intermediate apartment, the roof increases heat gains while weakening the only passive mechanism available for heat release.

1. Roof treatment becomes a structural priority for top-floor apartments.
2. Controlled ventilation remains necessary, but it must be combined with a high-reflectance roof finish to reduce daytime heat absorption and allow the thermal mass to function more effectively as a night-time sink.

Main gains chart

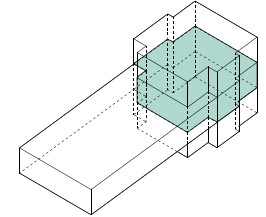
Baseline Scenario	Total Main Gains (kWh)	Solar (kWh/year)	Infiltration (kWh/year)	Internal Loads (kWh/year)
	3,422.9	1967.5	724.9	2,603



ARCHETYPE 02

A02 |
EDÉN DE COMFANDI

CASE A02_1
Mid Floor Apartment



SENSITIVITY ANALYSIS RESULTS

Metric. The main performance metric is the adaptive comfort condition, based on the ASHRAE 55 adaptive comfort model in free-running mode. Results are reported as annual hours over an 8,760-hour simulation and classified into three categories: cold discomfort (−1), comfort (0), and heat discomfort or overheating (+1).

The headline indicator is the number of overheating hours. The percentage variation ($\Delta\%$) expresses the change in overheating hours relative to the closed-window baseline of each archetype. Results are reported for the two critical apartments in each archetype: the worst-performing intermediate unit on the 2nd floor and the worst-performing roof unit on the 5th floor.

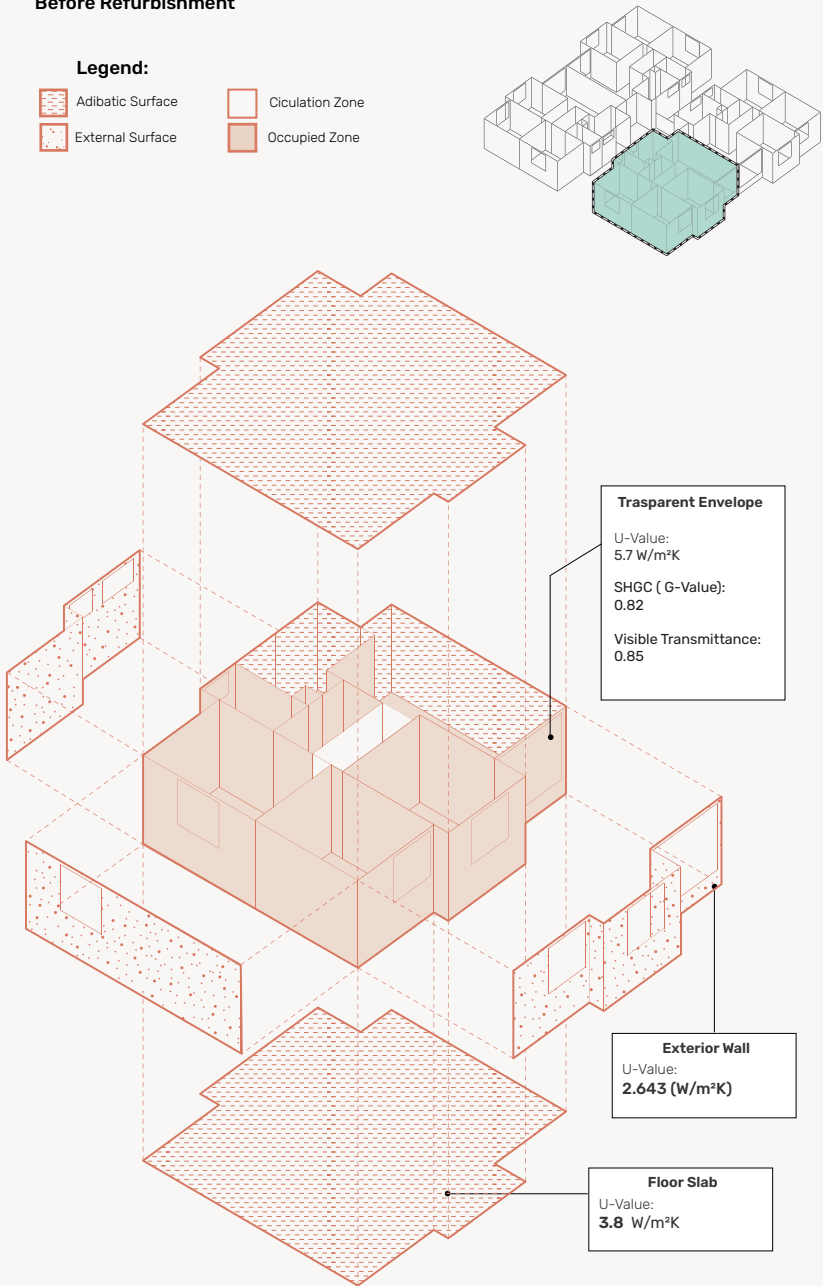
Baseline	Cold (−1)	Comfort (0)	Heat (+1)	$\Delta\%$ Heat	Δ Comfort (h)
	17	5212	3531	0.00%	0

VENTILATION	Int. Comfort Model				
	Scenario	Cold (−1)	Comfort (0)	Heat (+1)	$\Delta\%$ Heat
					Δ Comfort (h)
	Controlled natural ventilation	214	7467	1079	−69.4%
ROOF	Int. Comfort Model				
	Scenario	Cold (−1)	Comfort (0)	Heat (+1)	$\Delta\%$ Heat
					Δ Comfort (h)
	Roof absorbance =0.45	127	5,282	3351	17.5%
SHADING	Int. Comfort Model				
	Scenario	Cold (−1)	Comfort (0)	Heat (+1)	$\Delta\%$ Heat
					Δ Comfort (h)
	Balcony/shading 0.80 m	18	6426	2316	−34.4%
	Balcony/shading 1.20 m	25	6688	2047	−42.0%
	Balcony/shading 1.50 m	27	6857	1876	−46.9%
	Vertical Fins 0.80 m	42	7310	1408	−60.1%
	Vertical Fins 1.20 m	50	7382	1328	−62.4%
	Vertical Fins 1.50 m	54	7420	1286	−63.6%

OPAQUE ENVELOPE	Int. Comfort Model				
	Scenario	Cold (−1)	Comfort (0)	Heat (+1)	$\Delta\%$ Heat
					Δ Comfort (h)
	Wall paint $\alpha=0.25$	10	6635	2115	−40.1%
	Wall paint $\alpha=0.35$	N/A	N/A	N/A	N/A
	Wall paint $\alpha=0.45$	10	6002	2748	−22.2%
	Wall paint $\alpha=0.55$	N/A	N/A	N/A	N/A
	Isolated Wall $U=0.86$	N/A	N/A	3379	−4.3%
WWR	Int. Comfort Model				
	Scenario	Cold (−1)	Comfort (0)	Heat (+1)	$\Delta\%$ Heat
					Δ Comfort (h)
	WWR 15% + closed windows	N/A	N/A	N/A	N/A
	WWR 20% + closed windows	N/A	N/A	3791	7.5%
	WWR 25% + closed windows	N/A	N/A	4352	23.4%
	WWR 15% + Open windows	N/A	N/A	N/A	N/A
	WWR 20% + open windows	N/A	N/A	N/A	−64.0%
	WWR 25% + open windows	N/A	N/A	1536	−56.4%

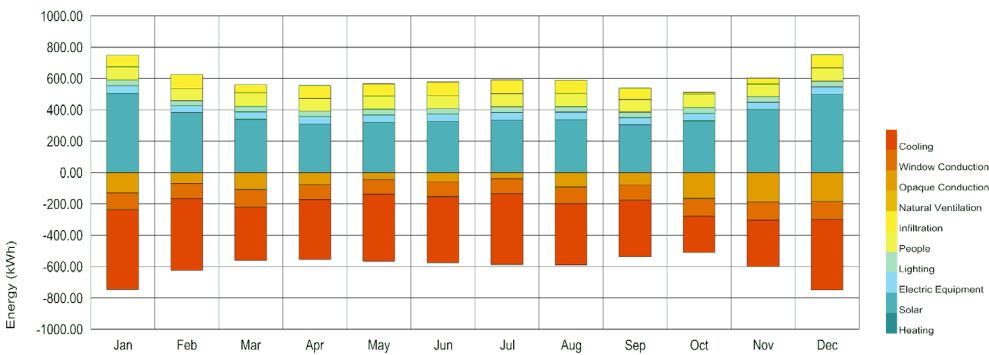
ENERGETIC MODEL

Before Refurbishment



THERMAL BALANCE

Figure X
Source: Open Studio-Honey Bee and Grasshopper



Its internal gains are lower, with occupants, equipment, and lighting adding approximately 1,987 kWh, compared with 2,603 kWh in A01. This reduction is mainly explained by the smaller floor area of the corner apartment, since internal loads scale with area.

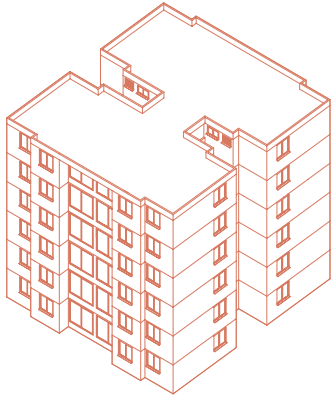
Solar gain is also lower in absolute terms, at 1,512.6 kWh, but proportionally higher per square metre. This reflects the higher WWR of A02 and its corner condition, which increase façade exposure, even though its south-east orientation receives less intense afternoon radiation than A01.

The key difference appears on the loss side. Opaque conduction removes -1,255.6 kWh, more than in A01, despite the smaller size of the apartment. This indicates a stronger passive heat sink, produced by the combination of two exposed façades and the thermal mass of brick masonry. With ventilation inactive and window conduction remaining a small net gain, the remaining surplus becomes residual cooling demand, reaching -2,659.6 kWh, around 28% lower than in A01.

This comparison shows that the masonry archetype starts from a less severe imbalance and a more effective passive sink. As a result, controlled natural ventilation has a particularly strong effect, becoming the main retrofit action for this archetype.

Main gains chart

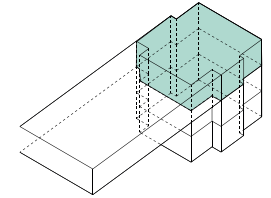
Baseline Scenario	Total Main Gains (kWh)	Solar (kWh/year)	Infiltration (kWh/year)	Internal Loads (kWh/year)
	3928.1	1512.6	299.3	1987.3



ARCHETYPE 02

A02 |
EDÉN DE COMFANDI

CASE A02_2
Top Floor Apartment



SENSITIVITY ANALYSIS RESULTS

Metric. The main performance metric is the adaptive comfort condition, based on the ASHRAE 55 adaptive comfort model in free-running mode. Results are reported as annual hours over an 8,760-hour simulation and classified into three categories: cold discomfort (−1), comfort (0), and heat discomfort or overheating (+1).

The headline indicator is the number of overheating hours. The percentage variation ($\Delta\%$) expresses the change in overheating hours relative to the closed-window baseline of each archetype. Results are reported for the two critical apartments in each archetype: the worst-performing intermediate unit on the 2nd floor and the worst-performing roof unit on the 5th floor.

Baseline	Cold (−1)	Comfort (0)	Heat (+1)	$\Delta\%$ Heat	Δ Comfort (h)
	14	5162	3584	0.00%	0

VENTILATION	Scenario	Int. Comfort Model			$\Delta\%$ Heat	Δ Comfort (h)
		Cold (−1)	Comfort (0)	Heat (+1)		
	Controlled natural ventilation	219	7549	992	−72.3%	+2387

ROOF	Scenario	Int. Comfort Model			$\Delta\%$ Heat	Δ Comfort (h)
		Cold (−1)	Comfort (0)	Heat (+1)		
	Roof absorbance =0.45	N/A	N/A	3351	−6.3%	N/A
	Roof absorbance =0.25	206	5235	3319	−7.40%	−136

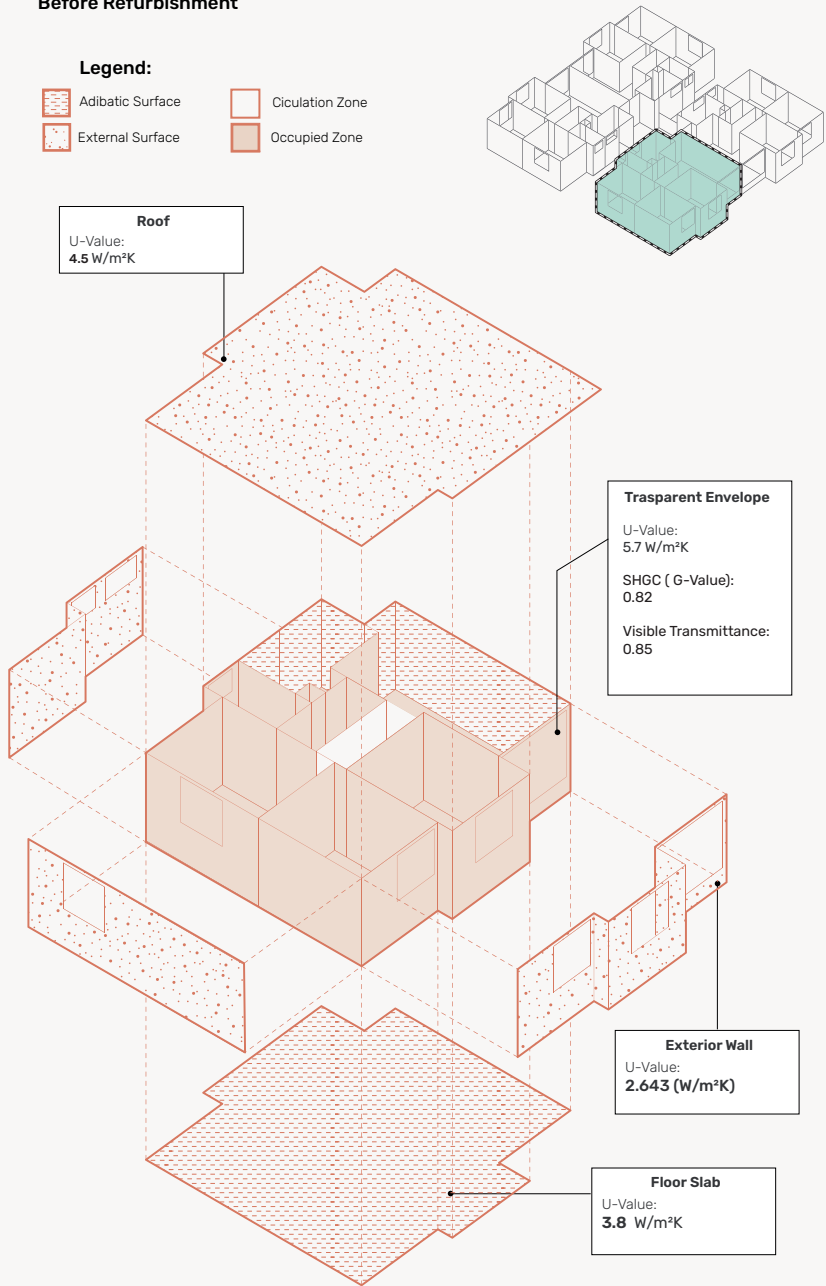
SHADING	Scenario	Int. Comfort Model			$\Delta\%$ Heat	Δ Comfort (h)
		Cold (−1)	Comfort (0)	Heat (+1)		
	Balcony/shading 0.80 m	28	6165	2567	−28.4%	+1003
	Balcony/shading 1.20 m	33	6372	2355	−34.3%	+1210
	Balcony/shading 1.50 m	33	6523	2204	−38.5%	+1361
	Vertical Fins 0.80 m	46	6947	1767	−50.7%	+1785
	Vertical Fins 1.20 m	46	7018	1696	−52.7%	+1856
	Vertical Fins 1.50 m	48	7072	1640	−54.2%	+1910

OPAQUE ENVELOPE	Scenario	Int. Comfort Model			$\Delta\%$ Heat	Δ Comfort (h)
		Cold (−1)	Comfort (0)	Heat (+1)		
	Wall paint $\alpha=0.25$	27	7087	1646	−54.1%	+1925
	Wall paint $\alpha=0.35$	N/A	N/A	N/A	N/A	N/A
	Wall paint $\alpha=0.45$	25	6277	2458	−31.4%	+1115
	Wall paint $\alpha=0.55$	N/A	N/A	N/A	N/A	N/A
	Isolated Wall $U=0.86$	N/A	N/A	3341	−6.8%	N/A

WWR	Scenario	Int. Comfort Model			$\Delta\%$ Heat	Δ Comfort (h)
		Cold (−1)	Comfort (0)	Heat (+1)		
	WWR 15% + closed windows	N/A	N/A	N/A	N/A	N/A
	WWR 20% + closed windows	N/A	N/A	3791	7.5%	N/A
	WWR 25% + closed windows	N/A	N/A	4352	23.4%	N/A
	WWR 15% + Open windows	N/A	N/A	N/A	N/A	N/A
	WWR 20% + open windows	N/A	N/A	N/A	−64.0%	N/A
	WWR 25% + open windows	N/A	N/A	1536	−56.4%	N/A

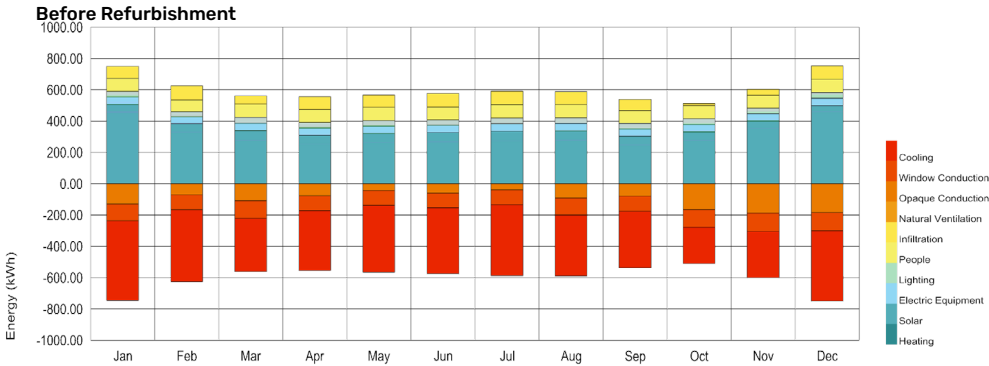
ENERGETIC MODEL

Before Refurbishment



THERMAL BALANCE

Figure X
Source: Open Studio-Honey Bee and Grasshopper



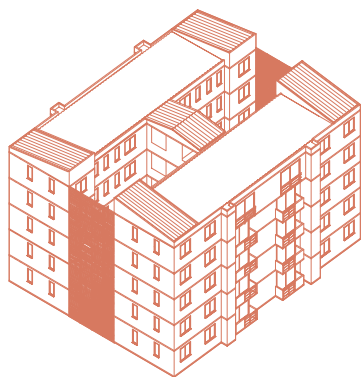
The roof unit confirms that the weakening of the opaque heat sink at roof level. Internal gains remain identical to the intermediate unit, at approximately 1,987 kWh, since intermediate unit and roof unit apartments share the same area and load densities. However, exposure changes the balance: solar gain rises from 1,512.6 to 1,702.8 kWh, and infiltration increases from 299.3 to 574.7 kWh, reflecting the stronger exposure of the top-floor condition.

The decisive change is the reduction of the passive sink. Opaque conduction falls from -1,255.6 kWh in the intermediate unit to -800.0 kWh in the roof unit. This occurs because the roof becomes an additional heat-gaining surface during the day, reducing the envelope's capacity to release heat at night. With ventilation inactive and window conduction remain a small net gain, residual cooling demand increases to -3,605.2 kWh, around 36% higher than in the intermediate unit.

Although A02 still performs better than the precast roof unit, its roof penalty is proportionally stronger because masonry depends more on the opaque envelope as a passive sink. This confirms that top-floor units require not only controlled ventilation, but also a high-reflectance roof finish to reduce daytime heat absorption and protect the night-time cooling role of the thermal mass.

Main gains chart

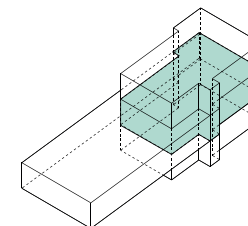
Baseline Scenario	Total Main Gains (kWh)	Solar (kWh/year)	Infiltration (kWh/year)	Internal Loads (kWh/year)
	4423.4	1702.8	574.7	1987.3



ARCHETYPE 03

A03 |
JARDIN DE LA CARMELIA

CASE A03_1
Mid Floor Apartment



SENSITIVITY ANALYSIS RESULTS

Metric. The main performance metric is the adaptive comfort condition, based on the ASHRAE 55 adaptive comfort model in free-running mode. Results are reported as annual hours over an 8,760-hour simulation and classified into three categories: cold discomfort (-1), comfort (0), and heat discomfort or overheating (+1).

The headline indicator is the number of overheating hours. The percentage variation ($\Delta\%$) expresses the change in overheating hours relative to the closed-window baseline of each archetype. Results are reported for the two critical apartments in each archetype: the worst-performing intermediate unit on the 2nd floor and the worst-performing roof unit on the 5th floor.

Baseline	Cold (-1)	Comfort (0)	Heat (+1)	$\Delta\%$ Heat	Δ Comfort (h)
	30	4544	4186	0.00%	0

VENTILATION	Scenario	Int. Comfort Model			$\Delta\%$ Heat	Δ Comfort (h)
		Cold (-1)	Comfort (0)	Heat (+1)		
	Controlled natural ventilation	249	6548	1963	-53.1%	+2004

ROOF	Scenario	Int. Comfort Model			$\Delta\%$ Heat	Δ Comfort (h)
		Cold (-1)	Comfort (0)	Heat (+1)		
	Roof absorbance =0.45	N/A	N/A	N/A	N/A	N/A
	Roof absorbance =0.25	N/A	N/A	N/A	N/A	N/A

SHADING	Scenario	Int. Comfort Model			$\Delta\%$ Heat	Δ Comfort (h)
		Cold (-1)	Comfort (0)	Heat (+1)		
	Balcony/shading 0.80 m	76	5686	2998	-28.4%	+1142
	Balcony/shading 1.20 m	83	5918	2759	-34.1%	+1374
	Balcony/shading 1.50 m	98	6069	2593	-38.1%	+1525
	Vertical Fins 0.80 m	131	6947	1984	-52.6%	+2101
	Vertical Fins 1.20 m	139	6713	1908	-54.4%	+2169
	Vertical Fins 1.50 m	142	6769	1849	-55.8%	+2225

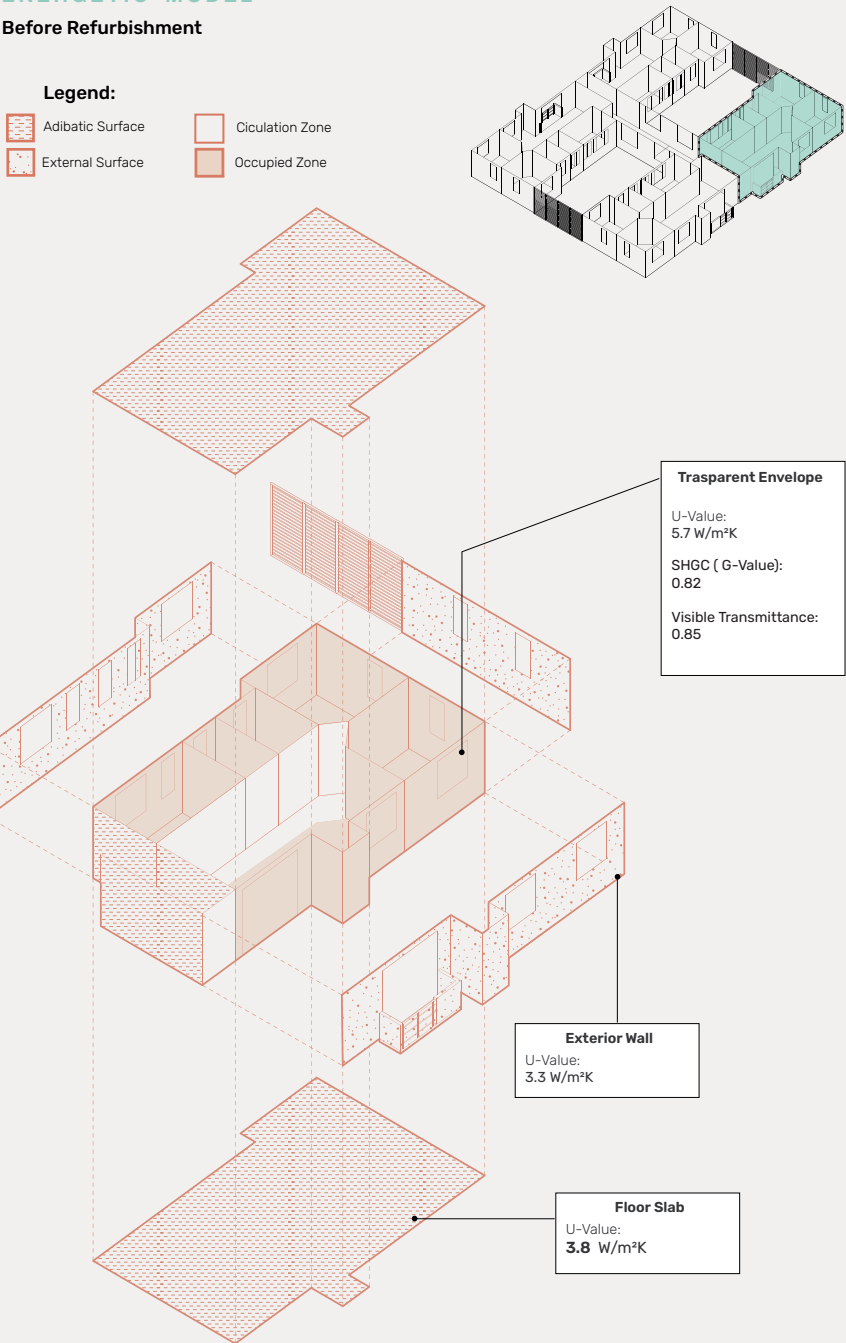
OPAQUE ENVELOPE	Scenario	Int. Comfort Model			$\Delta\%$ Heat	Δ Comfort (h)
		Cold (-1)	Comfort (0)	Heat (+1)		
	Wall paint $\alpha=0.25$	34	5126	3600	-14.0%	+582
	Wall paint $\alpha=0.35$	N/A	N/A	N/A	N/A	N/A
	Wall paint $\alpha=0.45$	30	4840	3890	-7.1%	+296
	Wall paint $\alpha=0.55$	N/A	N/A	N/A	N/A	N/A
	Isolated Wall U=0.86	1	2711	6048	44.5%	-1833

WWR	Scenario	Int. Comfort Model			$\Delta\%$ Heat	Δ Comfort (h)
		Cold (-1)	Comfort (0)	Heat (+1)		
	WWR 15% + closed windows	N/A	N/A	N/A	N/A	N/A
	WWR 20% + closed windows	34	4207	4519	8.0%	-337
	WWR 25% + closed windows	39	3918	4803	14.7%	-626
	WWR 15% + Open windows	N/A	N/A	N/A	N/A	N/A
	WWR 20% + open windows	273	6237	2250	-46.2%	+1693
	WWR 25% + open windows	333	5931	2496	-40.4%	+1387

ENERGETIC MODEL

Before Refurbishment

- Legend:
- Adiabatic Surface
 - External Surface
 - Circulation Zone
 - Occupied Zone



THERMAL BALANCE

Before Refurbishment

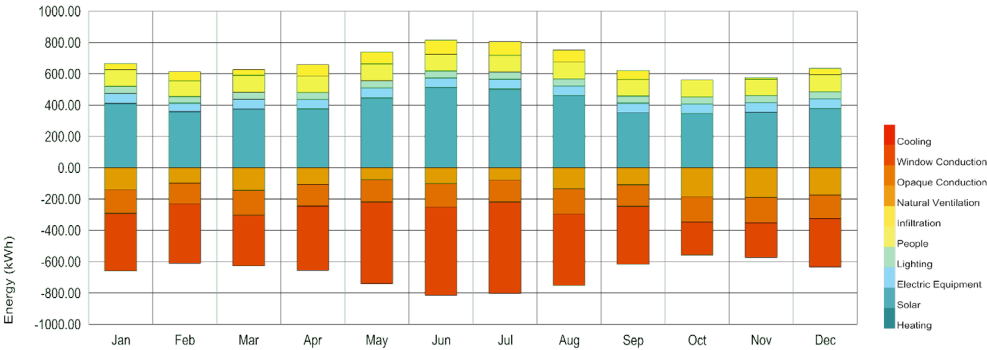


Figure X

Source: Open Studio-Honey Bee and Grasshopper

Archetype A03 differs from A01 and A02 because its heat balance shifts strongly toward solar gain. Its internal loads are almost identical to A01, at approximately 2,547 kWh, which means that the higher cooling demand is not caused by floor area, but by envelope and exposure conditions.

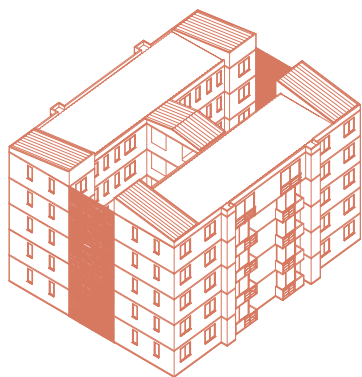
Solar gain reaches 2,279.7 kWh, around 30% higher than in A01. This is explained by the north-east exposure, which receives strong morning radiation, and by the higher WWR of 15.59%. As a result, solar gain becomes almost as important as internal gains, making A03 the most solar-driven intermediate unit.

Although the opaque envelope provides the strongest passive sink among the intermediate cases, with -1,324.7 kWh, this is not enough to compensate for the additional solar load. With ventilation inactive, the surplus appears as residual cooling demand, reaching -3,942.3 kWh, the highest value among the intermediate units.

This shows that A03 is not limited by a weak heat sink, but by excessive solar gain. Therefore, controlled ventilation is necessary but insufficient on its own. External shading becomes essential, and WWR optimisation is required to reduce the solar load admitted through the façade.

Main gains chart

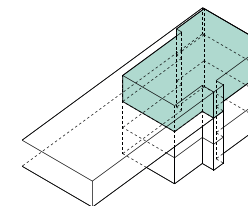
Baseline Scenario	Total Main Gains (kWh)	Solar (kWh/year)	Infiltration (kWh/year)	Internal Loads (kWh/year)
	5331.7	2279.7	505.2	2546.8



ARCHETYPE 03

A03 |
JARDIN DE LA CARMELIA

CASE A03_2
Mid Floor Apartment



SENSITIVITY ANALYSIS RESULTS

Metric. The main performance metric is the adaptive comfort condition, based on the ASHRAE 55 adaptive comfort model in free-running mode. Results are reported as annual hours over an 8,760-hour simulation and classified into three categories: cold discomfort (-1), comfort (0), and heat discomfort or overheating (+1).

The headline indicator is the number of overheating hours. The percentage variation ($\Delta\%$) expresses the change in overheating hours relative to the closed-window baseline of each archetype. Results are reported for the two critical apartments in each archetype: the worst-performing intermediate unit on the 2nd floor and the worst-performing roof unit on the 5th floor.

Baseline	Cold (-1)	Comfort (0)	Heat (+1)	$\Delta\%$ Heat	Δ Comfort (h)
	26	4,955	3779	0.00%	0

VENTILATION	Int. Comfort Model				
	Scenario	Cold (-1)	Comfort (0)	Heat (+1)	$\Delta\%$ Heat
					Δ Comfort (h)
	Controlled natural ventilation	249	6548	1723	-54.4%
					+2004

ROOF	Int. Comfort Model				
	Scenario	Cold (-1)	Comfort (0)	Heat (+1)	$\Delta\%$ Heat
					Δ Comfort (h)
	Roof absorptance =0.45	N/A	N/A	N/A	N/A
	Roof absorptance =0.25	N/A	N/A	N/A	N/A

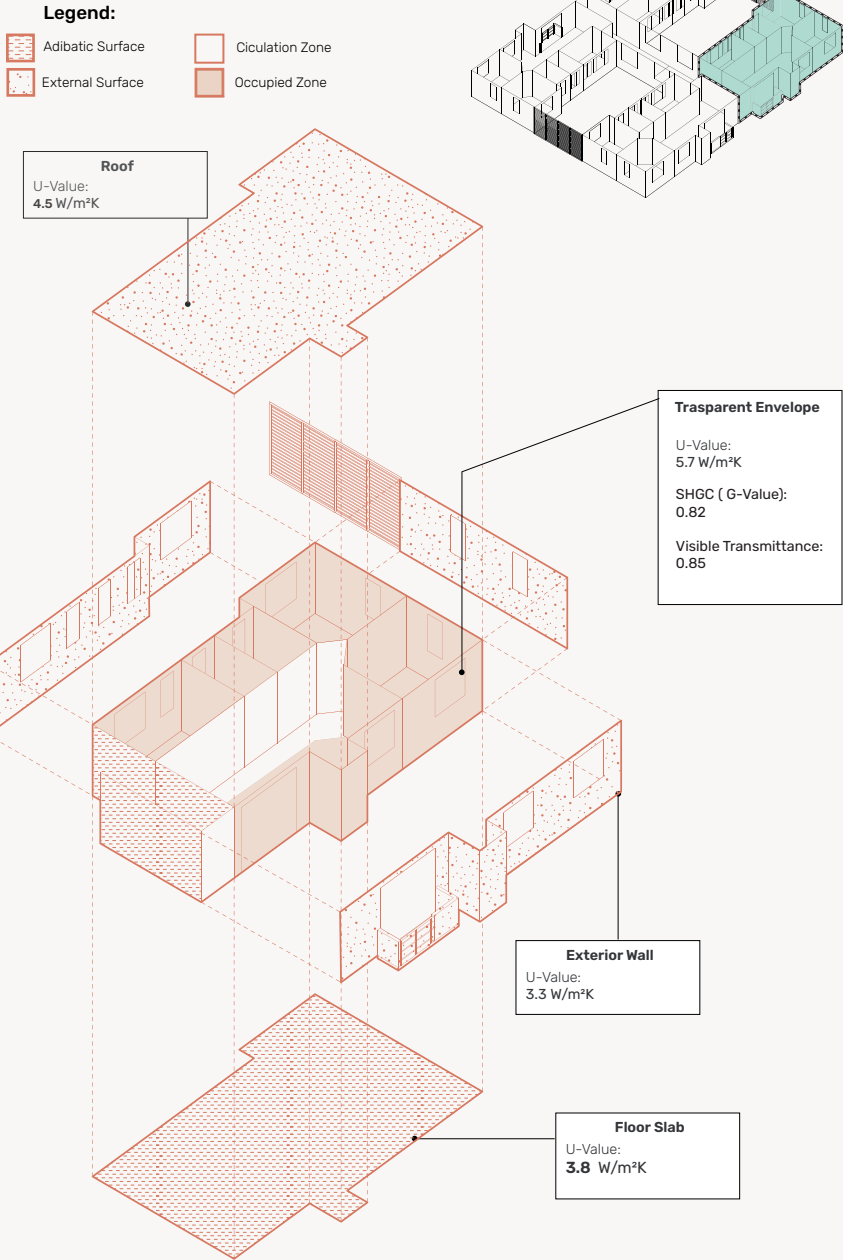
SHADING	Int. Comfort Model				
	Scenario	Cold (-1)	Comfort (0)	Heat (+1)	$\Delta\%$ Heat
					Δ Comfort (h)
	Balcony/shading 0.80 m	76	5686	2998	-28.4%
	Balcony/shading 1.20 m	83	5918	2759	-34.1%
	Balcony/shading 1.50 m	98	6069	2593	-38.1%
	Vertical Fins 0.80 m	131	6947	1361	-64.0%
	Vertical Fins 1.20 m	134	7198	1428	-62.2%
	Vertical Fins 1.50 m	142	6769	1361	-64.0%

OPAQUE ENVELOPE	Int. Comfort Model				
	Scenario	Cold (-1)	Comfort (0)	Heat (+1)	$\Delta\%$ Heat
					Δ Comfort (h)
	Wall paint $\alpha=0.25$	34	5126	3600	-14.0%
	Wall paint $\alpha=0.35$	N/A	N/A	N/A	N/A
	Wall paint $\alpha=0.45$	30	4840	3890	-7.1%
	Wall paint $\alpha=0.55$	N/A	N/A	N/A	N/A
	Isolated Wall $U=0.86$	1	2711	5772	52.7%
					-1833

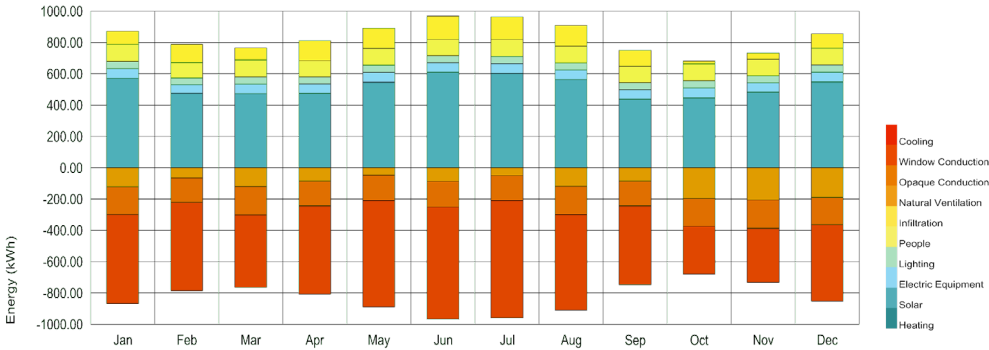
WWR	Int. Comfort Model				
	Scenario	Cold (-1)	Comfort (0)	Heat (+1)	$\Delta\%$ Heat
					Δ Comfort (h)
	WWR 15% + closed windows	N/A	N/A	N/A	N/A
	WWR 20% + closed windows	30	4527	4203	11.2%
	WWR 25% + closed windows	39	4226	4495	18.9%
	WWR 15% + Open windows	N/A	N/A	N/A	N/A
	WWR 20% + open windows	280	6439	2250	-46.2%
	WWR 25% + open windows	333	5931	2041	-46.0%

ENERGETIC MODEL

Before Refurbishment



THERMAL BALANCE



Archetype A03 is the most severe baseline case. Internal gains remain the same as in the intermediate unit, at approximately 2,547 kWh, so the increase in cooling demand is mainly caused by roof position and solar exposure.

Solar gain rises to 2,916.2 kWh, the highest value in the study, while infiltration increases to 939.3 kWh. At this level, solar radiation becomes the dominant heat source, representing more than half of the combined solar and internal gains.

Unlike A01 and A02, the problem is not mainly the collapse of the opaque heat sink. Opaque conduction only decreases from -1,324.7 to -997.0 kWh and remains the strongest roof-level sink among the archetypes. However, this sink is overwhelmed by the sharp increase in solar and infiltration gains. With ventilation inactive, residual cooling demand reaches -5,404.9 kWh, the highest of all cases.

This confirms that A03 is a source-driven problem rather than a sink-driven one. Controlled ventilation is necessary, but it cannot solve the imbalance alone because it acts after heat has already entered. For A03, shading and cool roof treatment must work together to reduce heat at the source, while WWR optimisation becomes essential in the Deep package to address the façade condition that admits the excess solar gain.

Main gains chart

Baseline Scenario	Total Main Gains (kWh)	Solar (kWh/year)	Infiltration (kWh/year)	Internal Loads (kWh/year)
	5492.4	2916.2	939.3	2,546.8

FROM SENSITIVITY ANALYSIS TO

RENOVATION PACKAGES

The sensitivity analysis reveals a consistent design logic for social housing in Cali's warm reveals a consistent design logic for social housing in Cali's warm, a logic that becomes even more relevant under the 2050 scenario. The strategies that improve thermal comfort are those that reduce solar heat gains, such as external shading and high-reflectance surfaces, and those that dissipate accumulated heat, such as controlled natural ventilation and cross-ventilation.

By contrast, strategies based on increasing thermal resistance are ineffective or even counterproductive in this context. Since the opaque envelope acts as a heat sink, with a negative conduction term that expels heat, insulating the wall or roof can trap heat under free-running conditions and increase overheating. This effect reaches up to +26% in A01 and +44% in A03. Therefore, the governing principle of the intervention strategy is clear: do not insulate; shade, reflect, and ventilate.

This logic also explains why no single measure is sufficient. Controlled ventilation is the strongest individual strategy, but its effectiveness decreases as the climate warms, from reductions of up to -96% in the present climate to

approximately -53% to -76% under the 2050 scenario.

It also leaves significant residual overheating, especially in the most exposed archetype. For this reason, combining measures is not optional but necessary, which justifies the evaluation of renovation packages rather than isolated interventions.

LEVELS OF INTERVENTION

The effective measures are organised into three renovation levels, and all of them are based exclusively on the mechanisms shown to improve performance as heat dissipation, external solar control, and surface reflectance.

Thermal insulation and uncontrolled increases in glazing are deliberately excluded, as the sensitivity analysis showed that they can be counterproductive in this type of climate.

1 | Low-intervention level

This level requires minimal cost and construction work, has high replicability, and operates mainly by improving heat dissipation.

Strategies such as controlled natural ventilation reflective wall paint added where it proves highly effective are included in this lever of intervention.

2 | Medium-intervention level

This package brings together heat dissipation and external solar control, making it the most cost-efficient and generally optimal option.

Combined strategies such as controlled natural ventilation, facade protection (overhangs or fins protection elements) and reflective wall paint where effective, are included.

3 | High-intervention level

It represents the maximum reasonable passive-performance package, with higher cost and construction complexity, but still excludes insulation.

This includes controlled natural ventilation, a deeper overhang, reflective wall paint, and cool roof treatment where useful.

The three renovation levels are assigned according to the baseline overheating severity of each archetype.

A01, which shows the lowest overheating hours, is associated with a low-intervention package focused on controlled natural ventilation.

A02, with intermediate severity and a strong response to reflective wall coating, is associated with a medium-intervention package combining ventilation, solar-grid shading and wall reflectance.

A03, the most critical archetype under the 2050 scenario, is associated with a high-intervention package that reinforces both heat dissipation and solar-gain reduction.

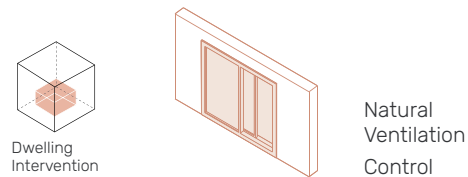
Archetype	Thermal Condition	Baseline overheating 2050 (Int / Roof Units)	Assigned Level of intervention
A01 Brisas de los Álamos	Best of the Three Archetypes	$\frac{3364}{8760}$ / $\frac{3115}{8760}$ h per year	Low-intervention level
A02 Edén de Comfandi	Intermediate	$\frac{3531}{8760}$ / $\frac{3584}{8760}$ h per year	Medium-intervention level
A03 Jardín de la Camelia	Worst of the Three Archetypes	$\frac{4186}{8760}$ / $\frac{3779}{8760}$ h per year	High-intervention level

PACKAGE COMPOSITION

PER ARCHETYPE

01

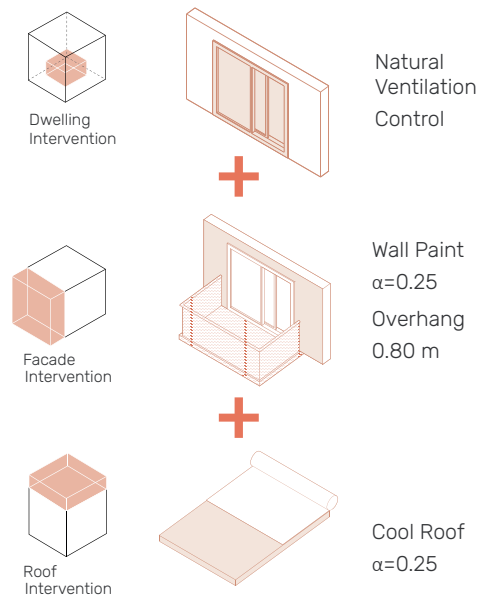
RENOVATION PACKAGE FOR A01 Low Intervention Level



In A01, overheating is not reduced by increasing thermal insulation or enlarging the window area; on the contrary, both measures worsen performance, increasing overheating by up to 26% and 46–60%, respectively. The most effective strategy is controlled natural ventilation, which alone reduces overheating by approximately 76%.

02

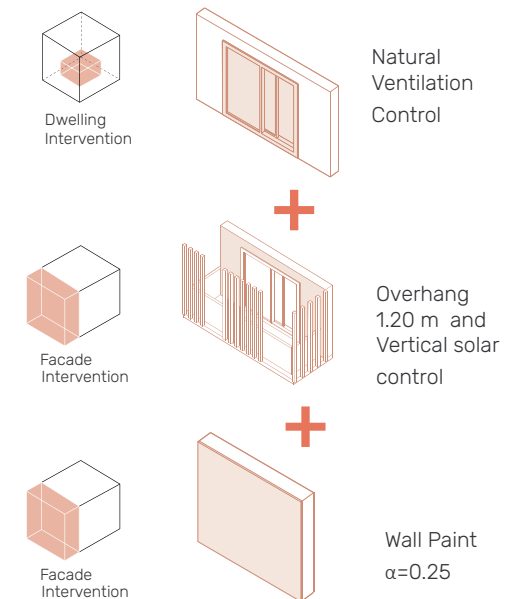
RENOVATION PACKAGE FOR A02 Medium Intervention Level



A02 is the archetype in which passive measures combine most effectively. Controlled ventilation reduces overheating by approximately 69%, while the 0.80 m solar grid achieves a reduction of around 60%. Reflective wall paint is also particularly effective in this case, reducing overheating by approximately 40%, because the high-U brick envelope responds strongly to a lighter exterior surface. The cool roof has a more limited but still positive effect, with a reduction of around 9%.

03

RENOVATION PACKAGE FOR A03 High Intervention Level



A03 is the most critical archetype under the 2050 scenario. Its linear morphology increases solar exposure, so ventilation alone reduces overheating by only about 53% and leaves a significant residual load. For this reason, the solar grid becomes essential and justifies the strongest package.

Insulation is excluded because it worsens performance (+44%), while cool roof treatment is omitted due to its negligible effect. Reflective wall paint is retained only as a complementary measure, with a limited reduction of around 14%.

The overheating reduction column shows the simulated range of variation in overheating hours across the three archetypes. This includes controlled natural ventilation, a deeper overhang, reflective wall paint, and cool roof treatment where useful. This should be understood as a thermal performance improvement, not as a reduction in the energy bill, since the analysis is based on free-running conditions.

The relative ROI is a preliminary qualitative relationship between thermal impact, implementation cost, and construction disruption. The highest-priority measures (controlled ventilation, the 0.80 m solar grid, and reflective paint for high-U envelopes) combine strong thermal impact with relatively low cost, making them particularly suitable for social housing.

A quantitative economic ROI calculation, understood as a monetary pay-back period, requires implementation cost data and is therefore reserved for the techno-economic evaluation.

This evaluation will be based on the Colombian Sustainable Construction Guide, Resolution 0549, which provides official reference values for energy savings, budget impact, and payback period for passive measures. These values are specifically provided for warm-humid multifamily social housing, which corresponds to the category analysed in this study.

The guide is based on the same methodological logic adopted along the thesis.

COST BENEFIT AND IMPLEMENTATION

Strategy	Thermal Impact	Cost	Overheating reduction	Relative ROI	Recommendation
Controlled Natural Ventilation	High	Low-Medium	-53% to -76%	Very high	Priority (all archetypes)
Solar grid and overhang 0.80 m	High	Medium	-43% to -60%	High	Priority
Solar grid and overhang 1.20 -1.50 m	Very High	Medium-High	-45% to -62%	Medium	Max performance (marginal gain beyond 0.80 m)
Reflective wall paint α 0.25	High (A02) / Medium (A01, A03)	Low	-14% to -40%	High (A02) / Medium	Priority
Cool Roof	Low	Low	-2% to -9%	Low-Medium	Complement (useful in A02, nil in A03)
Wall insulation	Low or negative	High	+26% to +44% (worsens)	Negative	Not recommended
Roof insulation	Negative	High	+3% to +10% (worsens)	Negative	Not recommended
Increased WWR (closed)	Risky	Medium	+46% to +88% (worsens)	Negative	Conditional (only with ventilation + shading)



This chapter translates the simulation evidence into architectural proposals for each archetype. It includes plan revision, the selective removal of non-structural partitions to enable cross-ventilation, and the application of the assigned renovation package. It is the bridge between numerical performance and architectural design.





LIGHT RENOVATION LEVEL

BRISAS DE LOS ALAMOS

DESIGN PRINCIPLES

A01 is a compact precast archetype with a low-U envelope and the smallest window-to-wall ratio (WWR 12.9%).

Since the low-U wall in A01 already limits conductive heat transfer, reflective wall treatment produces only a limited comfort benefit and is therefore not the main strategy for this archetype. Comfort improvement depends primarily on controlled air movement and **heat dissipation**. The existing small WWR is maintained as an advantage because it reduces solar exposure.

Reflective wall surfaces are not prioritised in this archetype, as the simulations indicate a limited and potentially counterproductive response when applied to the low-U envelope.

Additional thermal insulation is strictly excluded for A01 under free-running conditions, since it increases overheating by 26% by further reducing the envelope's capacity to dissipate heat.

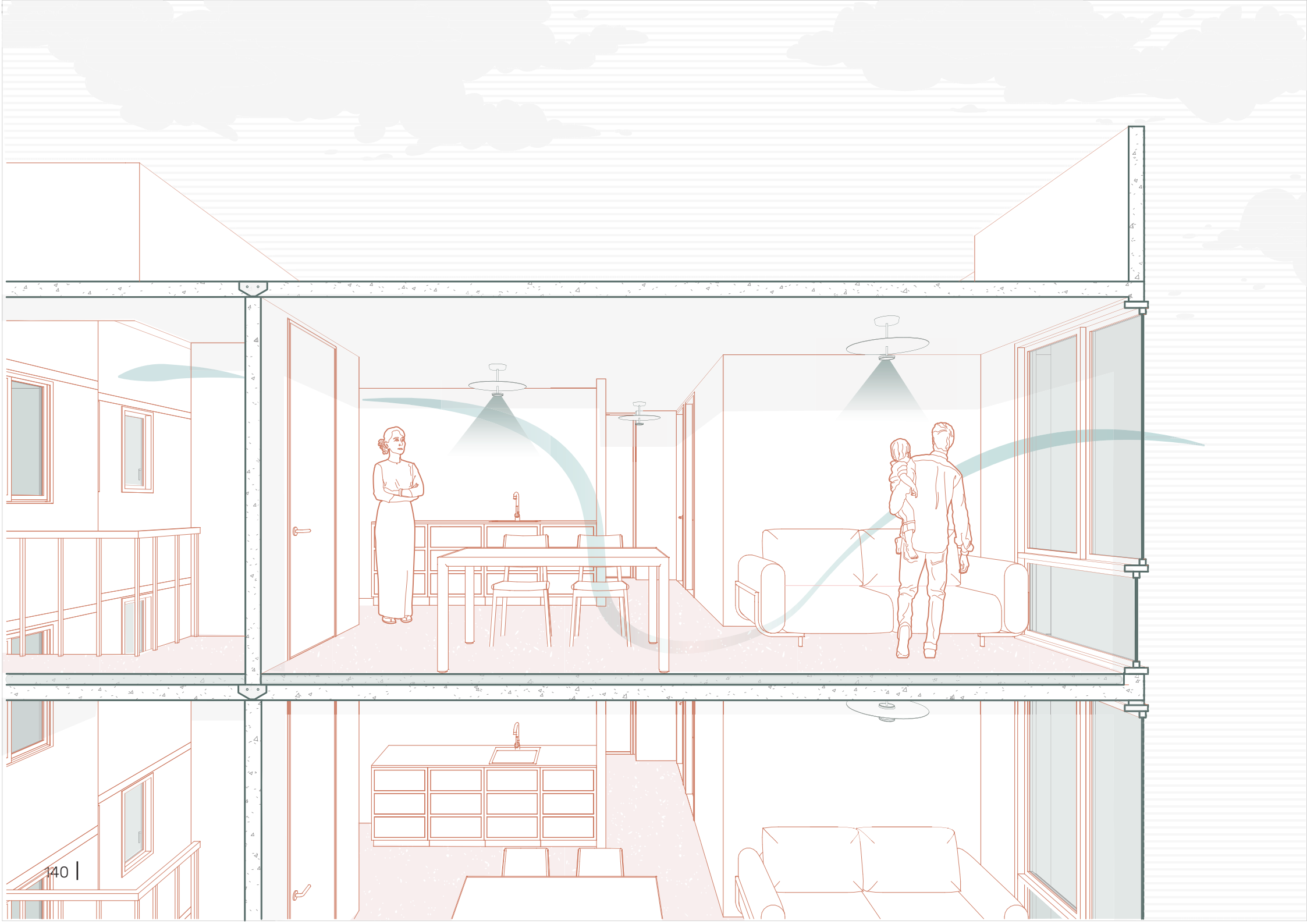
STRATEGIES

1 | Controlled natural ventilation:

Is the primary passive cooling mechanism of this thesis. Rather than relying only on occupant behaviour, the operable openings are governed by a control logic that admits outdoor air only when it can effectively remove heat: indoor air temperature above 23 °C, outdoor air temperature above 15 °C, and indoor temperature at least 2 °C higher than outdoor temperature.

In Cali, this strategy concentrates air exchange during the evening and night, when outdoor air becomes cooler than indoor air and can flush out the heat accumulated throughout the day.

Crucially, the proposal does not assume cross-ventilation as an automatic condition. The existing floor plan was reviewed according to its ventilation potential, and where the internal layout blocked a continuous air path between opposing façades, selected



non-structural partitions were removed to reopen that path and increase the achievable air changes per hour. The openings use locally available operable aluminium carpentry and a secure night-ventilation position. Under the simulated free-running conditions, controlled ventilation is by far the strongest single passive lever, reducing overheating by up to 76%.

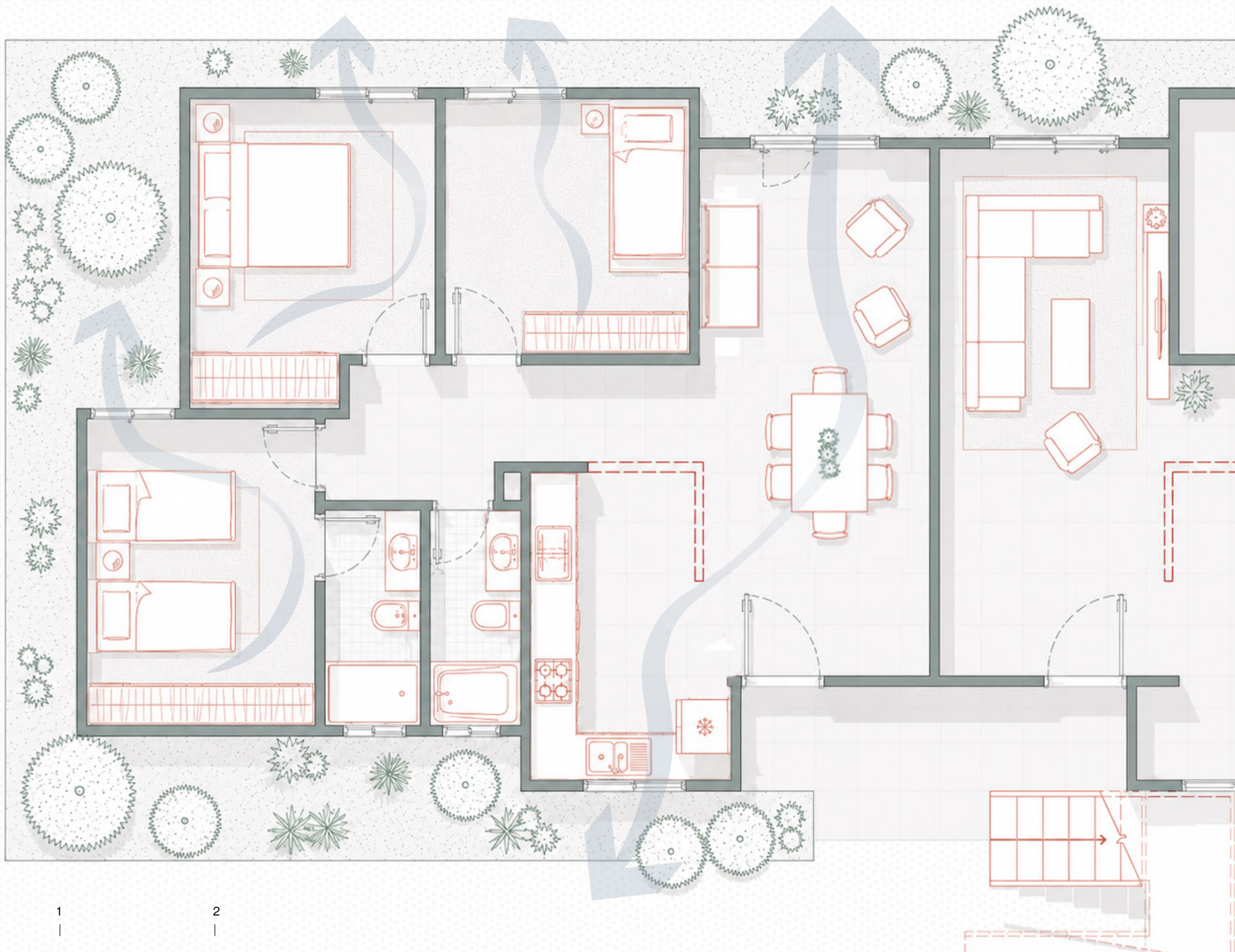
2| Excluded:

Additional insulation (+26% overheating), reflective wall finishes beyond $\alpha \leq 0.30$ due to a counterproductive U-shaped response, and WWR increase (+46–60% overheating).

REFURBISHMENT PROPOSAL

The proposal for A01 is the lightest of the three intervention packages. It recovers thermal comfort mainly by activating controlled cross-ventilation. The strategy therefore relies on heat dissipation rather than on increasing the thermal resistance or reflectance of the envelope.

Variable	Variable in the proposal	Notes
Controlled Natural Ventilation	On: $T_{in} \geq 23\text{ °C}$, $T_{out} \geq 15\text{ °C}$, and $T_{in} - T_{out} \geq 2\text{ °C}$	Enables night-time and cross-ventilation cooling
Cross-ventilation potential	Enabled through plan adjustment	Selected non-structural partitions are removed to increase achievable air changes per hour
Wall surface absorptance	0.70 (unchanged)	Two-directional solar control
Roof	Grey roof, unchanged	Cool roof is excluded because its effect is near-neutral or negative in this archetype
Roof solar absorptance (cool roof)	0.70	Roof heat absorption (top-floor unit only)
Opaque insulation	None	Counterproductive (+26% heat gains)
WWR	12.9% (kept)	Preserved as an asset

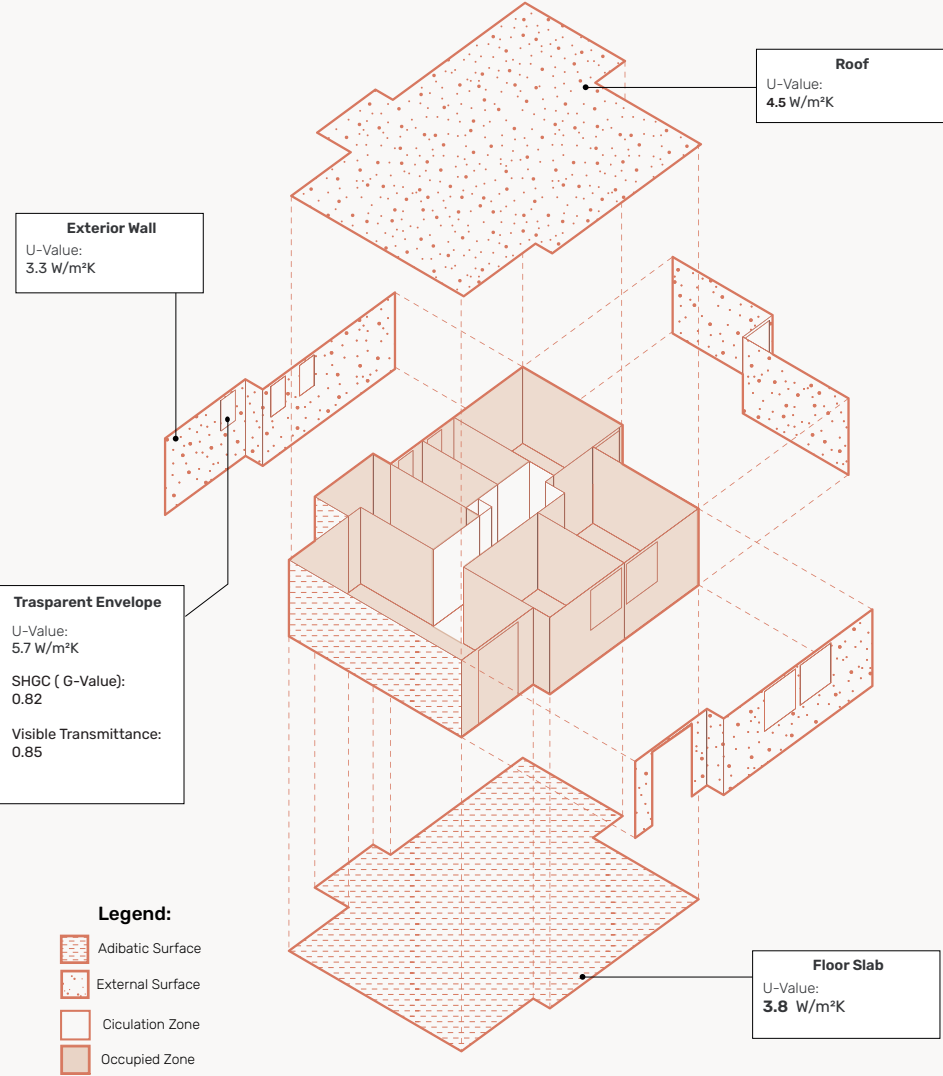




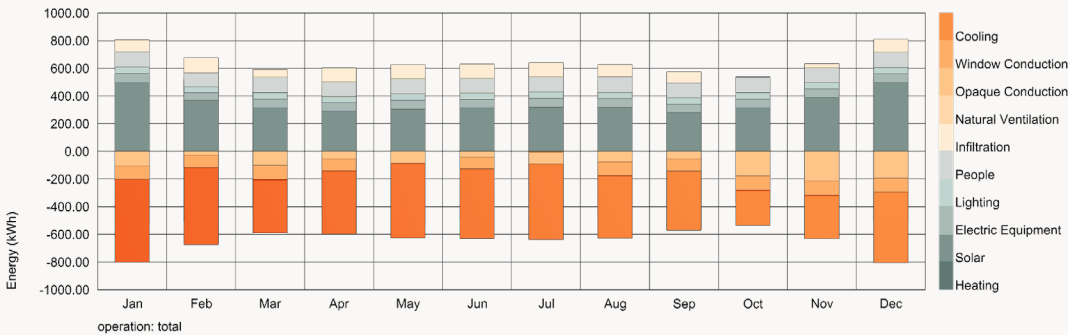
The future climate scenario in Cali shifts from a condition where heat can be balanced and dissipated to one where heat continuously accumulates over time.

PRE INTERVENTION

ENERGETIC MODEL



THERMAL BALANCE



The heat balance shows that overheating in A01 is primarily a problem of heat evacuation. Internal loads from occupants, lighting, and equipment dominate the input (+2,603 kWh), followed by solar gains through the glazing (+1,751 kWh) gains.

The only significant passive removal mechanism is the opaque wall, which acts as a heat sink (−1,147 kWh), but this is not enough to offset the accumulated with the windows closed, ventilation is inactive, leaving a large residual load (−3,690 kWh).

Under free-running conditions, this unresolved heat surplus translates into 3,364 overheating hours. In the 2050 scenario, this diagnosis becomes even more critical, as heat inputs increase while the wall's capacity to discharge heat remains limited.

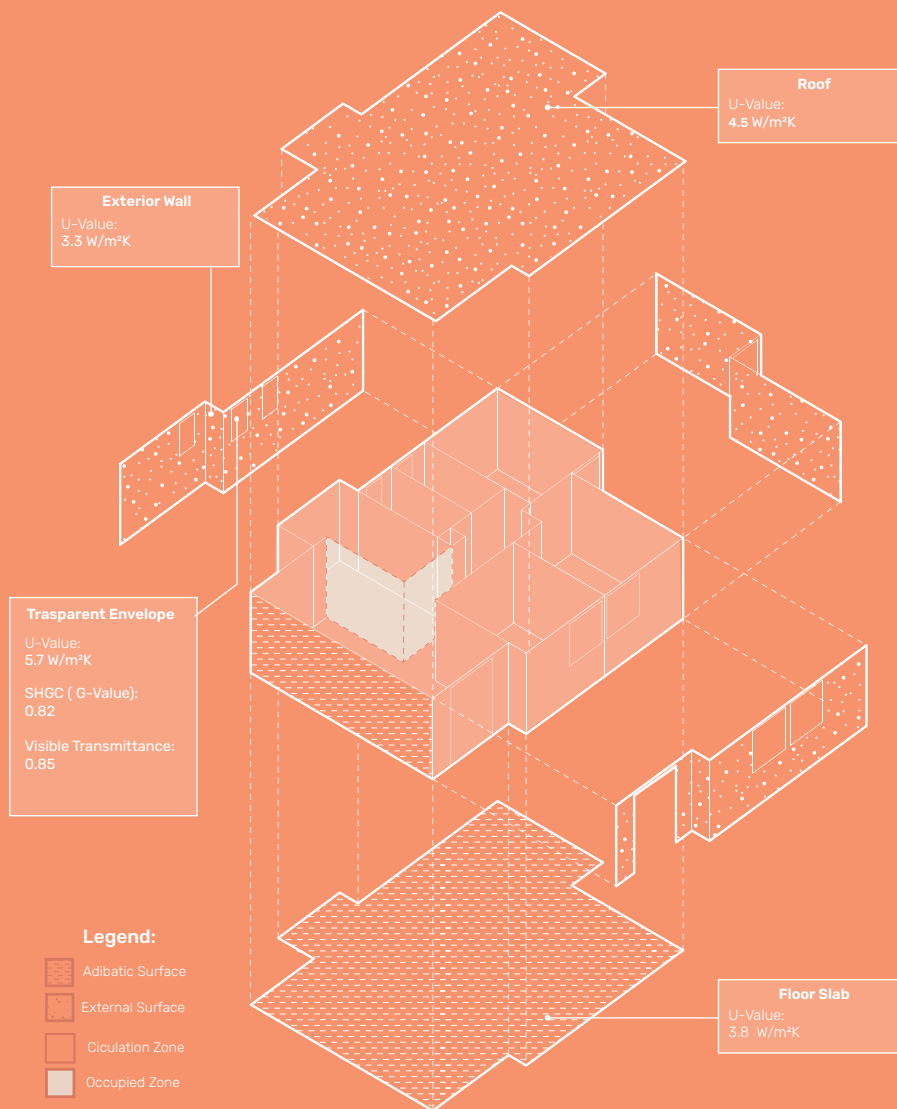
Component	Base 2050 Scenario
Solar (gain)	+1751
People + lighting + equipment	+2603
Infiltration	+426
Natural ventilation (removal)	0
Opaque conduction (wall as sink)	−1147
Window conduction	+73
Cooling residual	−3690

OVERHEATING HOURS
Baseline

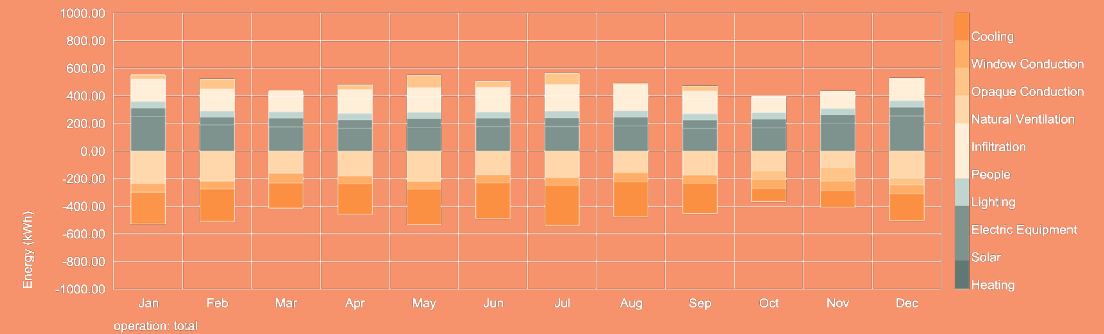
Intermediate Unit : 3364 hrs per year
Roof unit: 3115 hrs per year

POST INTERVENTION

ENERGETIC MODEL



THERMAL BALANCE



The heat balance shows that overheating in A01 is primarily a problem of heat evacuation. Internal loads from occupants, lighting, and equipment dominate the input (+2,603 kWh), followed by solar gains through the glazing (+1,751 kWh) gains.

The only significant passive removal mechanism is the opaque wall, which acts as a heat sink (−1,147 kWh), but this is not enough to offset the accumulated with the windows closed, ventilation is inactive, leaving a large residual load (−3,690 kWh).

Under free-running conditions, this unresolved heat surplus translates into 3,364 overheating hours. In the 2050 scenario, this diagnosis becomes even more critical, as heat inputs increase while the wall's capacity to discharge heat remains limited.

Component	Low Intervention Scenario
Solar (gain)	+1955
People + lighting + equipment	+2603
Infiltration	+318
Natural ventilation (removal)	−1999
Opaque conduction (wall as sink)	− 309
Window conduction	+627
Cooling residual	−1667

OVERHEATING HOURS

Light Refurbished Level

Intermediate Unit : 800 hrs per year
Δ% Heat : -76.2 %

Roof unit: 675 hrs per year
Δ% Heat : -78.3 %





MEDIUM RENOVATION LEVEL

EDEN DE CONFARDI

DESIGN PRINCIPLES

A02 is a compact brick-masonry archetype with a high-U envelope and a larger window-to-wall ratio (WWR 16.2%).

Unlike A01, it is the case where reflective surfaces become a leading design principle. Because the high-U envelope conducts a larger share of absorbed heat inward, reducing wall absorptance through reflective paint is highly effective, reducing overheating by approximately 40%.

The proposal for A02 is therefore governed by a balanced combination of reflectance, shading, and heat dissipation. Controlled ventilation remains the backbone of the strategy, while the 0.80 m grid acts as a co-primary measure to reduce solar gains. The existing glazing ratio is preserved, and insulation is excluded because its effect is negligible and it contradicts the heat-sink logic required in this climate.

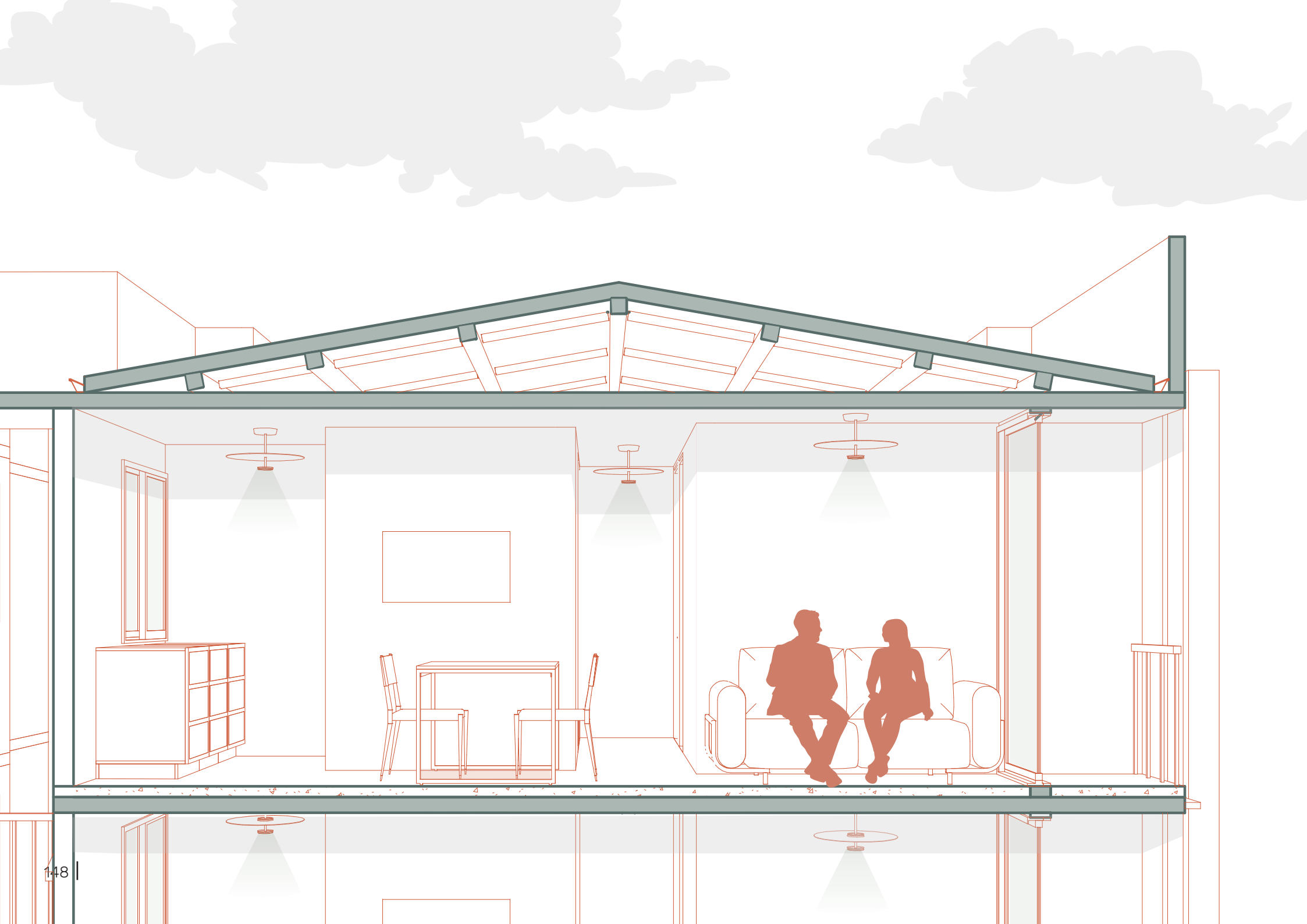
STRATEGIES

1 | Controlled natural ventilation: Operable openings are governed by the same

temperature difference control logic, allowing accumulated heat to be flushed out during cooler hours.

Cross-ventilation between opposing façades becomes the organising principle. As in the other archetypes, the plan was reviewed and selected non-structural partitions were removed to create a continuous air path and increase air changes per hour. On its own, controlled ventilation reduces overheating by approximately 69%.

2 | Solar control: The proposal incorporates a two-directional external shading layer, composed of horizontal and vertical members that form a grid in front of the glazed façade. Unlike a horizontal overhang, which mainly intercepts high-angle midday sun, the grid also blocks low-angle morning and afternoon radiation, which is particularly relevant near the equator. This explains why the grid performs better than the overhang at the same depth, reducing overheating by approximately 43% compared with 9%.



The grid is dimensioned at 0.80 m, the depth at which the solar-control effect begins to saturate. It is proposed as a precast concrete element, either integrated with the balcony structure or applied as a brise-soleil system.

3 | Reflective wall coating ($\alpha = 0.25$): A light-coloured elastomeric coating with low solar absorptance ($\alpha = 0.25$) is applied to reduce the amount of radiation absorbed by the façade and, consequently, the heat conducted inward. In A02, this is a primary measure rather than a complementary one: because the brick envelope has a high U-value, wall conduction plays a significant role in the heat balance, making reflective paint highly effective, with an overheating reduction of approximately 40%.

It is also the lowest-cost measure in the package, although periodic re-coating is required to maintain its reflective performance.

4 | Excluded measures: Thermal insulation is excluded because its effect is limited and contradicts the heat-sink logic of the envelope in this climate. Increasing WWR is also excluded, as the existing glazing ratio is already relatively high and additional window area would increase solar gains.

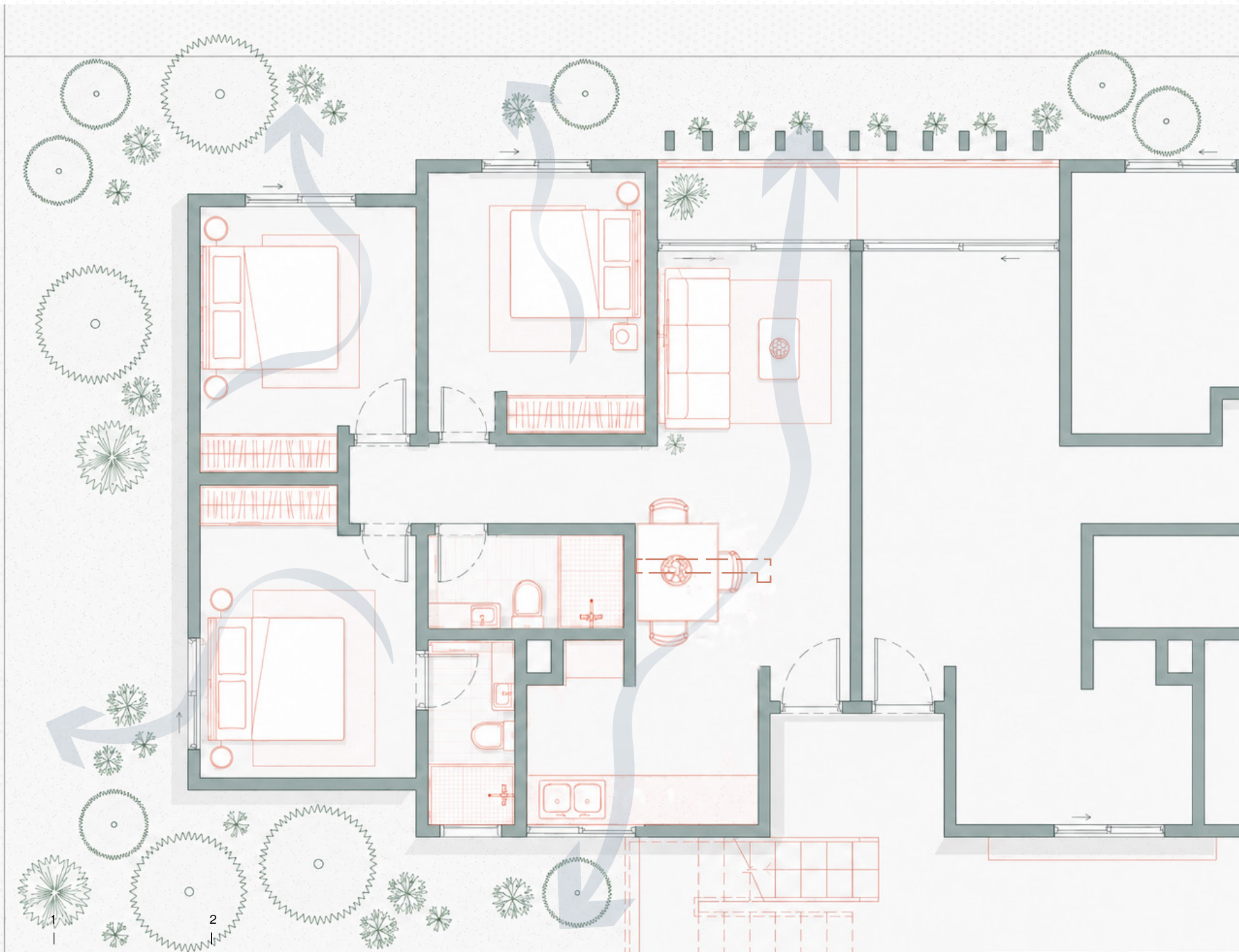
REFURBISHMENT PROPOSAL

The package distributes the thermal response across three mechanisms: ventilation removes

accumulated heat, the grid reduces solar gains through the glazing, and reflective paint limits heat absorption through the wall. Together, these measures produce the largest residual-load reduction of the three archetypes, around 65%.

For this reason, A02 is the least costly archetype to resolve, despite its larger windows: its overheating problem can be addressed effectively through low-cost, complementary passive measures.

Variable	Variable in the proposal	Notes
Controlled Natural Ventilation	On: $T_{in} \geq 23\text{ °C}$, $T_{out} \geq 15\text{ °C}$, and $T_{in} - T_{out} \geq 2\text{ °C}$	Enables night-time and cross-ventilation cooling
Cross-ventilation potential	Enabled through plan adjustment	Selected non-structural partitions are removed to increase achievable air changes per hour
Wall surface absorptance	0.25 (reflective paint)	Primary measure (high-U brick)
Roof	Grey roof, unchanged	Cool roof is excluded because its effect is near-neutral or negative in this archetype
Roof solar absorptance (cool roof)	0.70	Roof heat absorption (top-floor unit only)
Opaque insulation (wall and roof)	0.25 (reflective paint)	Surface reflectance of the opaque wall
WWR	16.2% (kept)	Preserved
External shading (overhangs and vertical elements)	0.80 m overhang and grid	Saturation depth



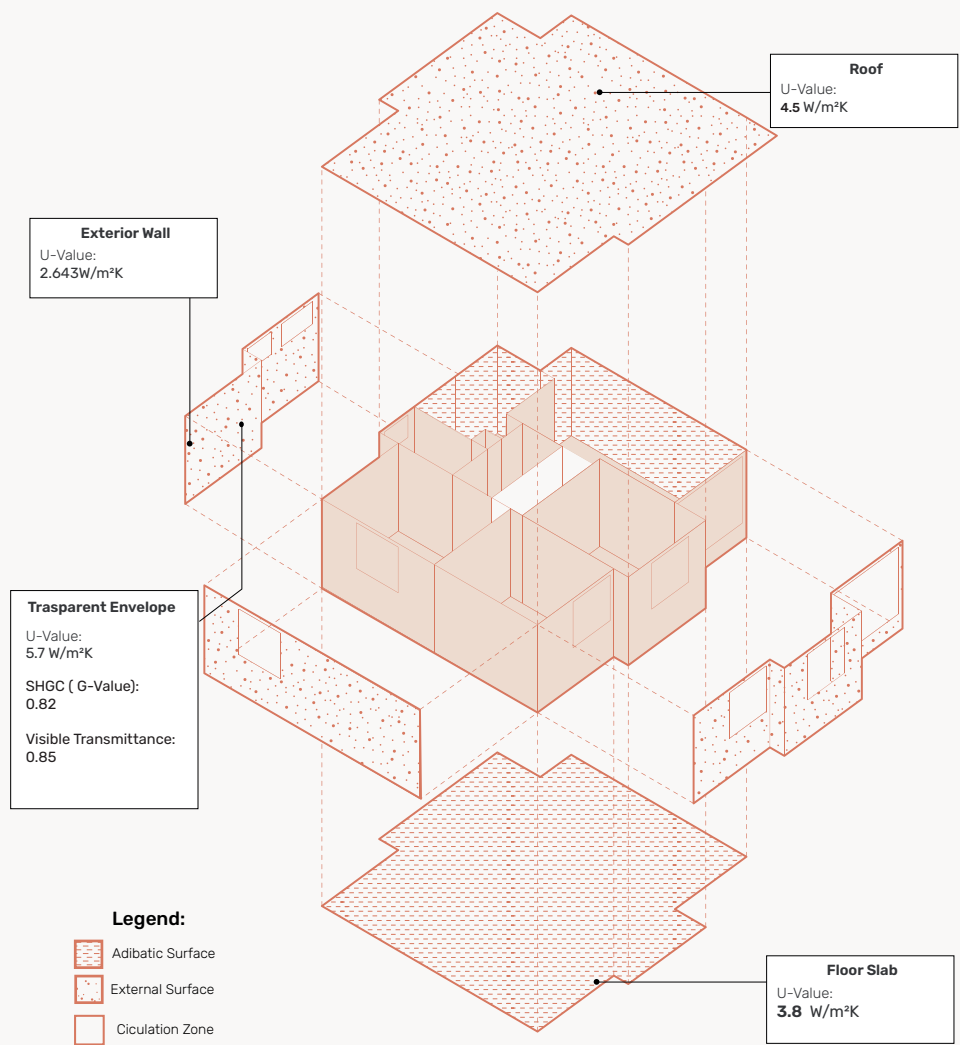
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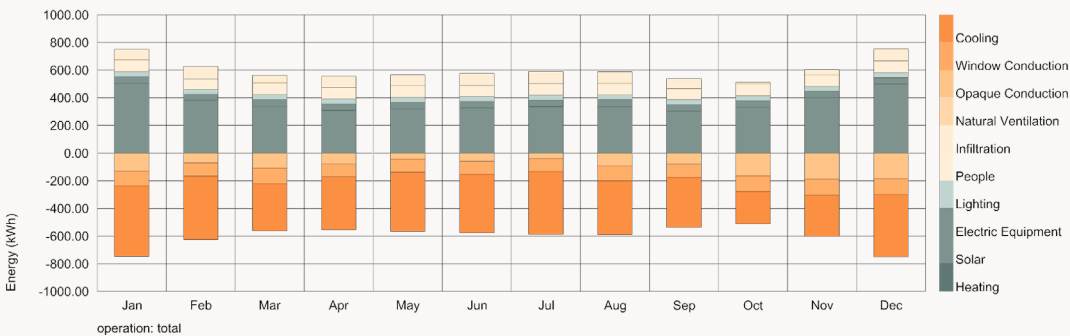
The future climate scenario in Cali shifts from a condition where heat can be balanced and dissipated to one where heat continuously accumulates over time.

PRE INTERVENTION

ENERGETIC MODEL



THERMAL BALANCE



The heat balance shows that overheating in A02 results from the combined effect of internal gains, solar gains, and heat transfer through the high-U masonry envelope. Internal loads account for approximately +1,987 kWh, while solar gains through the glazing add +1,513 kWh.

The opaque masonry envelope provides the main passive heat sink, releasing -1,256 kWh through conduction. Although this sink is stronger than in A01, it is still insufficient with the windows closed and ventilation inactive, leaving a residual load of -2,660 kWh.

Under free-running conditions, this surplus becomes overheating. However, because A02 starts with a stronger passive sink and a lower residual load, its retrofit response is more balanced: ventilation removes accumulated heat, the solar grid reduces glazing gains, and reflective paint limits heat absorption through the wall.

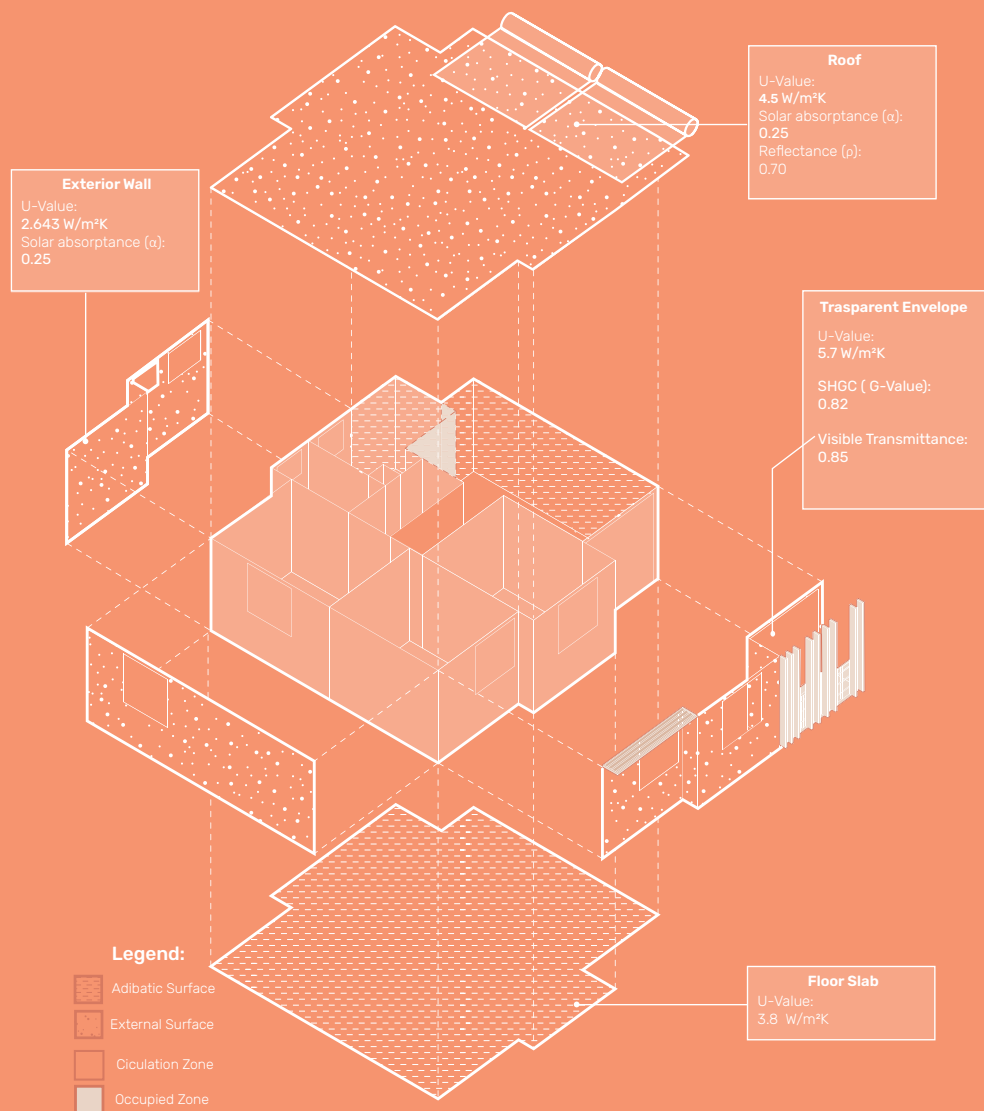
Component	Base 2050 Scenario
Solar (gain)	+1513
People + lighting + equipment	+1987
Infiltration	+299
Natural ventilation (removal)	0
Opaque conduction (wall as sink)	-1256
Window conduction	+129
Cooling residual	-2660

OVERHEATING HOURS
Baseline

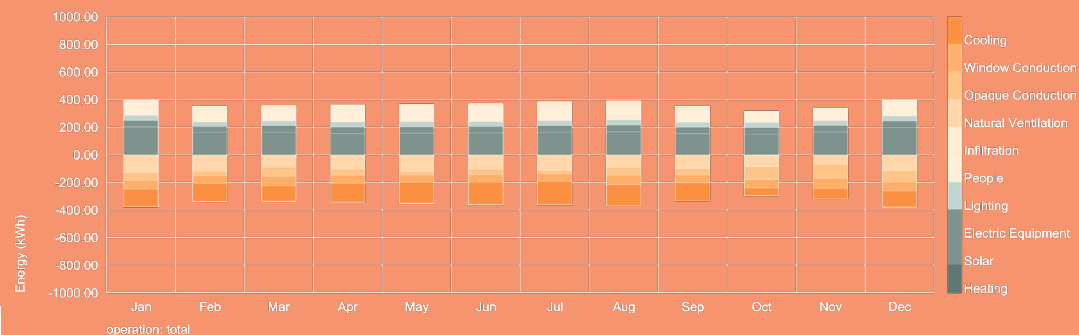
Intermediate Unit : 3531 hrs per year
Roof unit: 3584 hrs per year

POST INTERVENTION

ENERGETIC MODEL



THERMAL BALANCE



n A02, the medium package works because the correction is distributed across three mechanisms. The baseline residual load is approximately -2,660 kWh, driven by internal gains (+1,987 kWh), solar gains (+1,513 kWh), and heat transfer through the high-U masonry envelope.

The package combines controlled ventilation, the 0.80 m grid, and reflective wall coating. Individually, these measures reduce overheating by around 69%, 60%, and 40%, respectively. Together, they reduce the residual load by approximately 65%, from about -2,660 kWh to roughly -930 kWh.

This explains why A02 performs so well: ventilation removes accumulated heat, the grid limits solar gains, and reflective paint reduces wall heat absorption. No single measure is overloaded, which makes the package both effective and relatively low-cost.

Component	Med. Intervention Scenario
Solar (gain)	+1760
People + lighting + equipment	+1987
Infiltration	+192
Natural ventilation (removal)	-1085
Opaque conduction (wall as sink)	-1071
Window conduction	-607
Cooling residual	-924

OVERHEATING HOURS

Medium Refurbished Level

Intermediate Unit : 217 hrs per year
Δ% Heat : -93.9 %

Roof unit: 131 hrs per year
Δ% Heat : -96.3 %





HIGH RENOVATION LEVEL

JARDIN DE LAS CARMELIAS

DESIGN PRINCIPLES

A03 is the mixed, linear archetype and the most critical case under the 2050 scenario, with 4,186 and 3,779 baseline overheating hours.

It also shows the weakest response to ventilation, with a reduction of only 53%, because its linear morphology and orientation produce the highest solar exposure.

For this reason, its proposal is governed by intensive solar control through the external grid, which becomes almost as important as ventilation. Heat dissipation remains necessary, but it must be combined with shading and complemented by reflective wall treatment. Insulation is strictly excluded, as it increases overheating by up to 44%, while the existing glazing ratio is preserved. A03 is therefore the only archetype that requires the deepest intervention level.

STRATEGIES

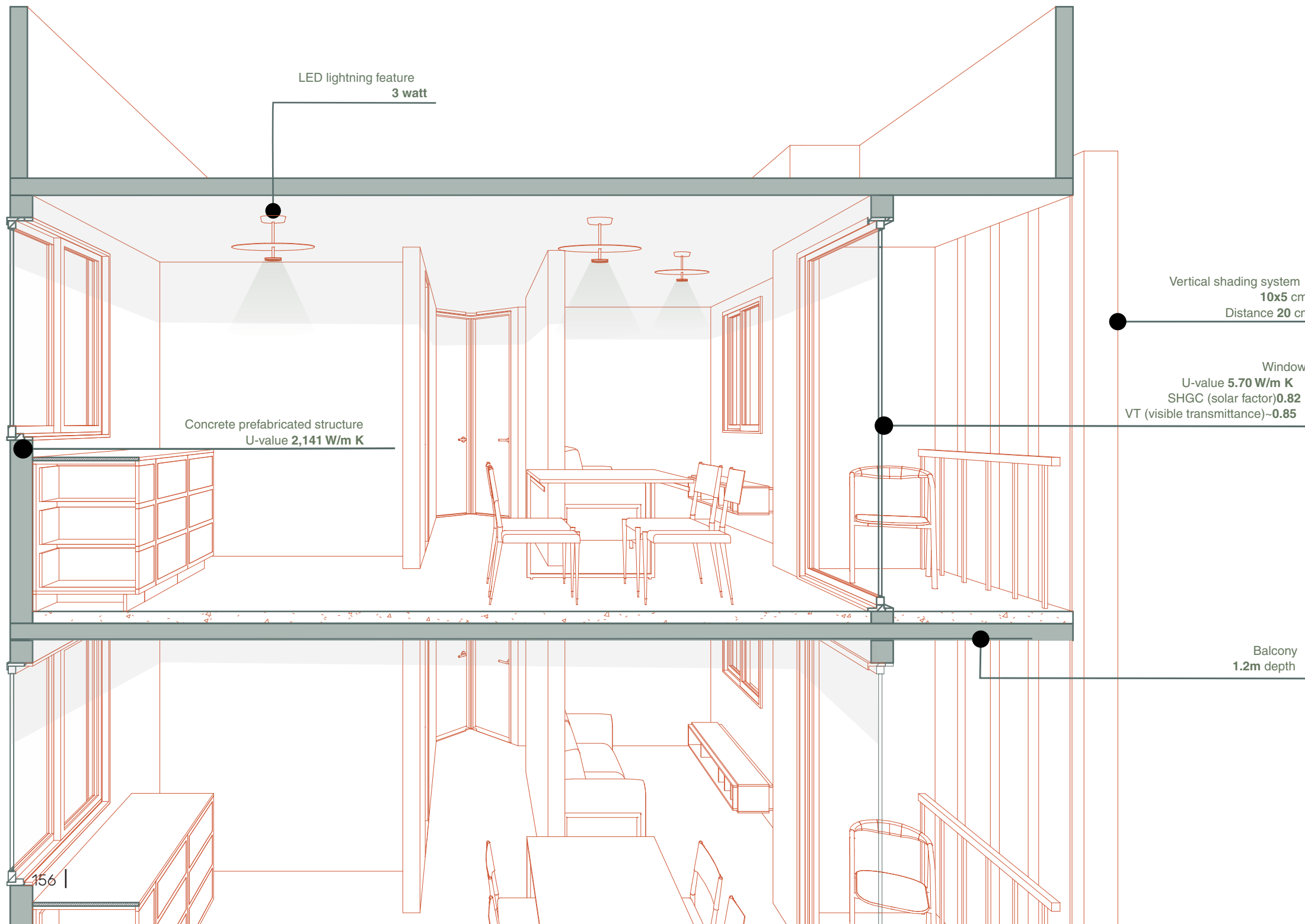
1 | Controlled natural ventilation: The same controlled operable-window system is applied in A03. As in the other archetypes, the plan is

reviewed and selected non-structural partitions are removed to ensure a continuous cross-ventilation path and improve air changes per hour.

However, in A03, ventilation is necessary but not sufficient. On its own, it reduces overheating by only 53%, leaving 1,963 overheating hours. This is why the shading grid must carry a larger share of the thermal correction, acting not only as a complement to ventilation but as a primary strategy for reducing solar gains before they enter the dwelling.

2 | Solar control: A two-directional external shading grid is applied to A03 and deepened to 1.20 m because this is the most solar-exposed archetype. In this case, the grid becomes almost as effective as controlled ventilation, so it is treated as a co-primary measure rather than as a secondary complement.

The deeper section is justified by the higher solar load of the linear form, unlike in the more compact archetypes where a 0.80 m grid is sufficient. The grid is proposed as a precast concrete element integrated with the façade,



LED lightning feature
3 watt

Concrete prefabricated structure
U-value 2,141 W/m K

Vertical shading system
10x5 cm
Distance 20 cm

Windows
U-value 5.70 W/m K
SHGC (solar factor) 0.82
VT (visible transmittance) ~0.85

Balcony
1.2m depth

reducing direct solar gains before they enter the dwelling.

3 | Reflective wall coating ($\alpha = 0.25$): A light elastomeric coating with low solar absorptance ($\alpha = 0.25$) is applied as a complementary measure. In A03, its individual effect is weaker than in the brick masonry archetype, reducing overheating by approximately 14%. However, within the combined high-performance package, it becomes decisive: it helps reduce overheating from 729 hours in the medium package to 301 hours in the high package.

For this reason, reflective wall coating is retained in A03, not because it is the strongest measure on its own, but because it provides the final performance gain needed to approach comfort in the most exposed archetype.

4 | Excluded measures: Thermal insulation is excluded because it significantly worsens performance in A03, increasing overheating by up to 44%. Cool roof treatment is also excluded, as its effect is near negligible in this archetype and does not justify its inclusion in the package.

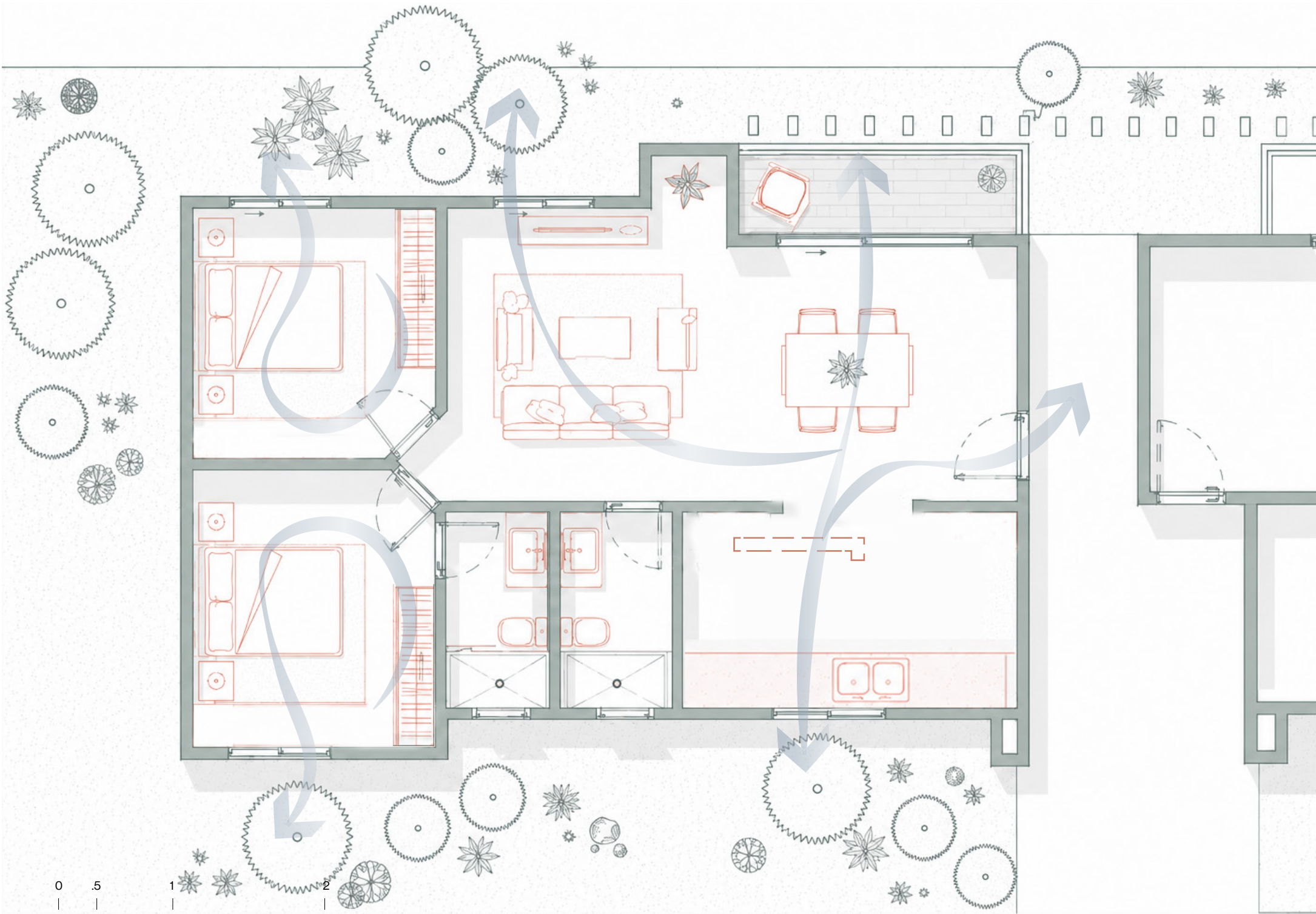
REFURBISHMENT PROPOSAL

The package combines a deep external grid across the exposed façade, reinforced cross-ventilation, and a reflective wall coating.

This higher level of intervention is justified by the results of the medium package: even after applying ventilation and solar control, A03 still retains a residual overheating level comparable to the baseline condition of the more compact archetypes.

In other words, the high package confirms the diagnosis that A03 is a structurally more exposed and solar-driven case. For this reason, the intervention must be escalated to the high package, where the deeper grid and reflective coating further reduce the remaining overheating load.

Variable	Variable in the proposal	Notes
Controlled Natural Ventilation	On: $T_{in} \geq 23\text{ °C}$, $T_{out} \geq 15\text{ °C}$, and $T_{in} - T_{out} \geq 2\text{ °C}$	Necessary but insufficient alone (–53%)
Cross-ventilation potential	Enabled through plan adjustment	Selected non-structural partitions are removed to increase achievable air changes per hour
Wall surface absorptance	0.25 (reflective paint)	Complement (–14% on mixed envelope)
Roof	Grey (cool roof excluded)	Near-nil effect here
Roof solar absorptance (cool roof)	None	None
Opaque insulation (wall and roof)	None	Strongly counterproductive (+44%)
WWR	15.6% (kept)	Preserved
External shading (overhangs and vertical elements)	1.20 m overhang and grid	Higher solar load of the linear form



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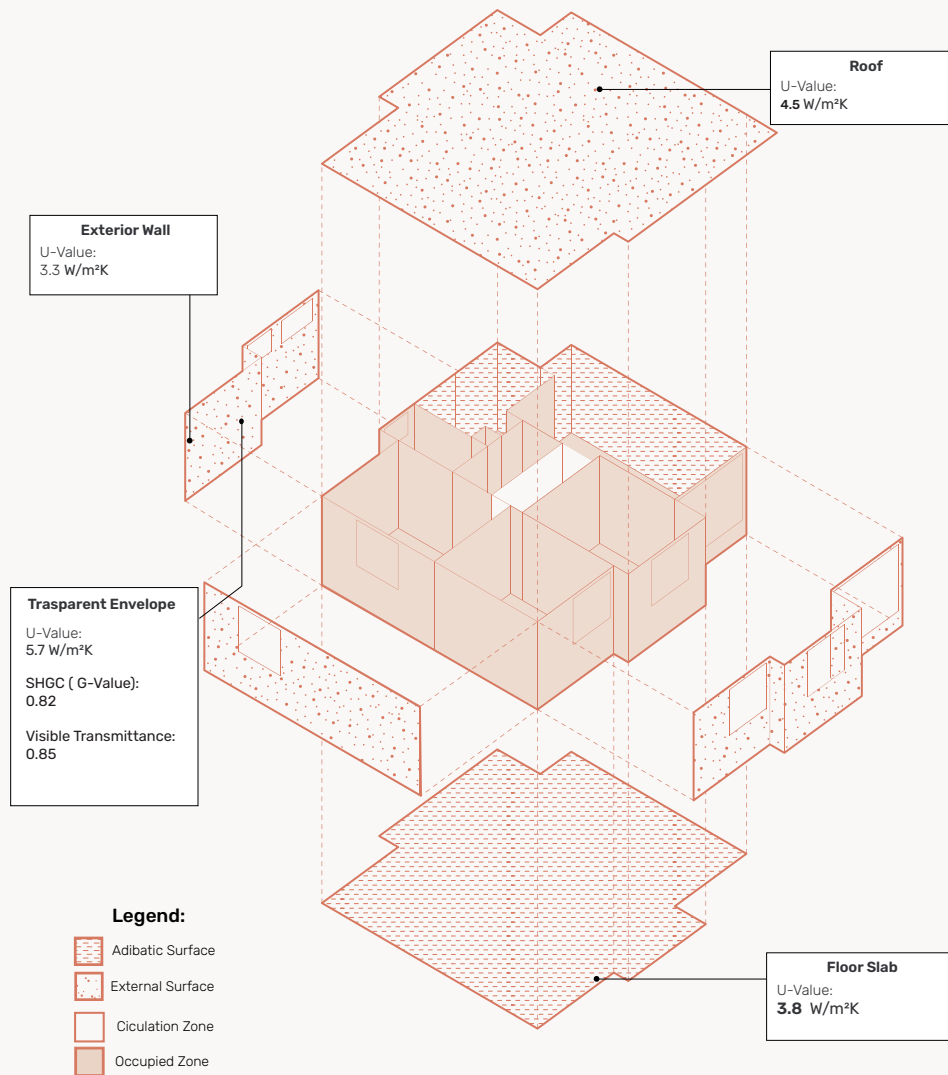
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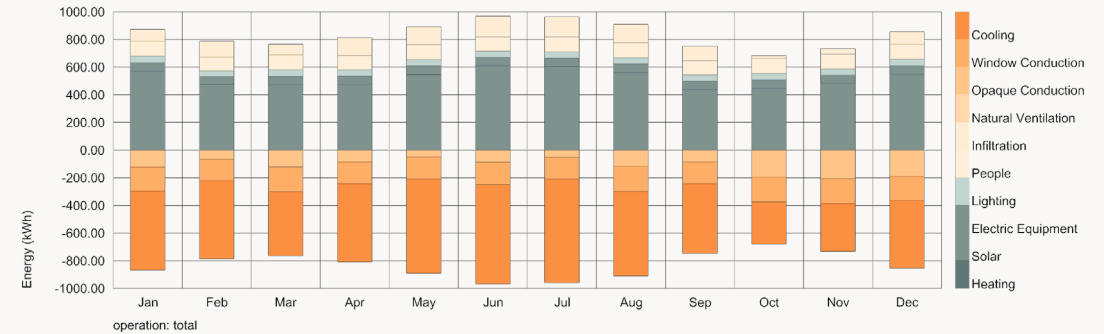


The future climate scenario in Cali shifts from a condition where heat can be balanced and dissipated to one where heat continuously accumulates over time.

PRE INTERVENTION ENERGETIC MODEL



THERMAL BALANCE



The heat balance identifies A03 as the most input-driven case, rather than a case limited by a weak envelope. In the roof unit, solar gains reach approximately +2,916 kWh, while internal gains remain high at around +2,547 kWh. This makes solar radiation the dominant source of heat, intensified by the exposed linear geometry and façade orientation.

Although the opaque envelope still acts as a passive sink, removing about -997 kWh through conduction, this discharge is not enough to compensate for the scale of the incoming heat. With ventilation inactive, the unresolved surplus appears as the highest residual cooling load of the baseline set, around -5,405 kWh.

The problem is therefore the excessive amount of heat entering the dwelling, not the absence of heat release. This explains why no single measure is sufficient in A03, and why the proposal requires a combined strategy of controlled ventilation, deep solar control, and reflective surface treatment.

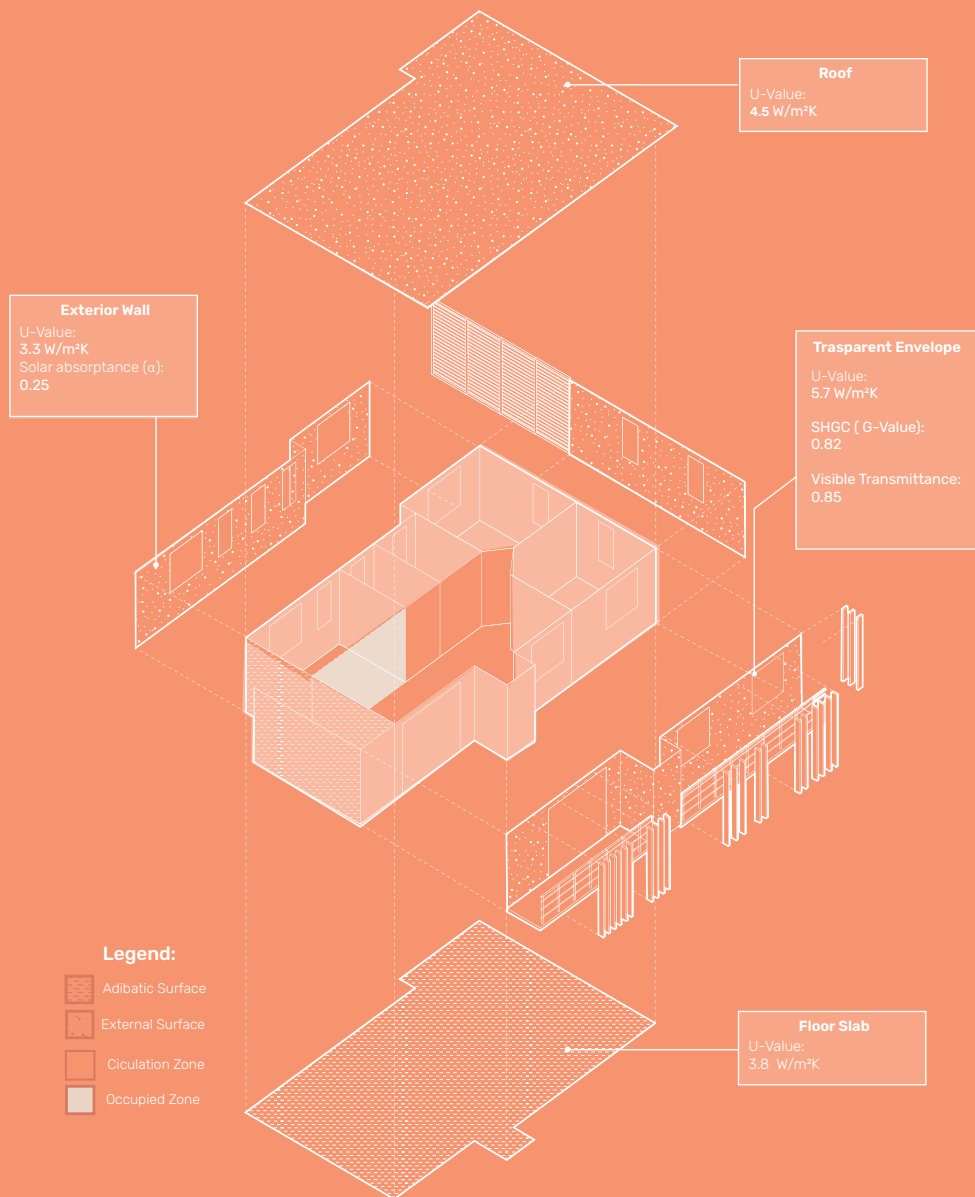
Component	Base 2050 Scenario
Solar (gain)	+2280
People + lighting + equipment	+2547
Infiltration	+505
Natural ventilation (removal)	0
Opaque conduction (wall as sink)	-1325
Window conduction	-42
Cooling residual	-3942

OVERHEATING HOURS
Baseline

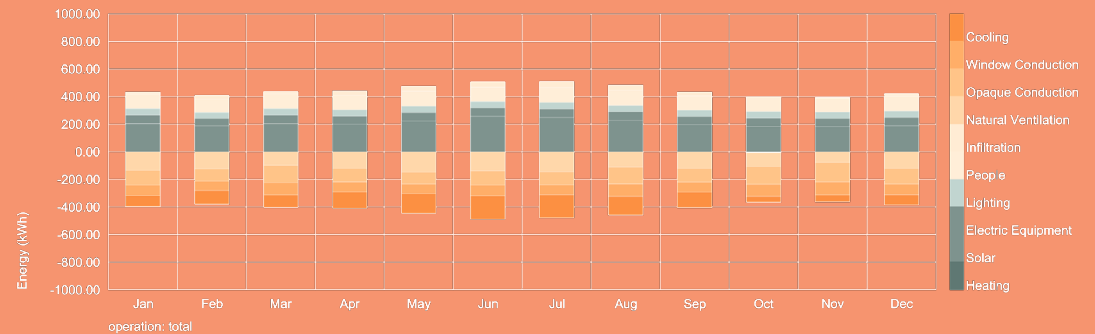
Intermediate Unit : 4186 hrs per year
Roof unit: 3779 hrs per year

POST INTERVENTION

ENERGETIC MODEL



THERMAL BALANCE



In A02, the medium package works because the correction is distributed across three mechanisms. The baseline residual load is approximately -2,660 kWh, driven by internal gains (+1,987 kWh), solar gains (+1,513 kWh), and heat transfer through the high-U masonry envelope.

The package combines controlled ventilation, the 0.80 m grid, and reflective wall coating. Individually, these measures reduce overheating by around 69%, 60%, and 40%, respectively. Together, they reduce the residual load by approximately 65%, from about -2,660 kWh to roughly -930 kWh.

This explains why A02 performs so well: ventilation removes accumulated heat, the grid limits solar gains, and reflective paint reduces wall heat absorption. No single measure is overloaded, which makes the package both effective and relatively low-cost.

Component	Med. Intervention Scenario
Solar (gain)	+2439
People + lighting + equipment	+2547
Infiltration	+440
Natural ventilation (removal)	-1670
Opaque conduction (wall as sink)	-541
Window conduction	-1018
Cooling residual	-1872

OVERHEATING HOURS

Medium Refurbished Level

Intermediate Unit : 301 hrs per year
Δ% Heat : -92.8 %

Roof unit: 236 hrs per year
Δ% Heat : -93.8 %



This chapter evaluates the proposed packages in terms of cost, feasibility, and regulatory alignment. It relates the thesis results to Colombia's Guía de Construcción Sostenible para el Ahorro de Agua y Energía under Resolution 0549, while clarifying the difference between the thesis metric, overheating hours under free-running conditions, and the national framework, which reports energy savings under conditioned assumptions.

TECNO-ECONOMICAL EVALUATION

(FOLLOWING THE COLOMBIAN SUSTAINABLE CONSTRUCTION GUIDE, RESOLUTION 0549)

REFERENCE FRAMEWORK AND METHODOLOGICAL ALIGNMENT

The techno-economic assessment is anchored in Colombia's Guía de Construcción Sostenible para el Ahorro de Agua y Energía, Annex 1 of Resolution 0549, which serves as the national reference framework for evaluating the cost-benefit performance of sustainable construction measures.

This guide follows a methodological structure that is consistent with the approach adopted in this thesis: the definition of a simulated baseline building, the evaluation of individual measures through sensitivity analysis, and the classification of each measure according to budget impact, energy savings, and payback period.

This alignment is significant for two reasons. First, it reinforces the methodological validity of the thesis by situating its simulation-based approach within an official national framework. Second, it allows the passive strategies evaluated in this research to be interpreted in relation to Colombian regulatory criteria, linking the proposed retrofit packages to the country's established standards for sustainable social housing.

BASE LINE

A point of coherence must be made explicit. This thesis characterises Cali as a warm-humid tropical climate, while Resolution 0549 classifies the city as Hot Dry according to its regulatory categories. In the guide, Cali is used as the representative city for the hot dry group.

For the relevant typology, VIS Multifamiliar, the reference baseline is 86.7 kWh/m² per year, against which the guide calculates percentage energy savings.

METRIC BRIDGE

The two frameworks measure different forms of performance and should not be equated directly. The guide reports energy savings in kWh under conditioned-building assumptions, while this thesis evaluates overheating hours under free-running conditions.

For this reason, the guide is used here only for what it can legitimately provide: a reference for cost, payback, budget impact, and regulatory energy-saving targets associated with comparable physical measures. It is not used as an external validation of the overheating results, since overheating hours have no direct equivalent in the national norm. from construction

system, morphology and the tested design variables, not from modelling resolution.

The following table cross-references the measures included in the thesis packages with their closest equivalent in the guide for VIS Multifamiliar. The values should be confirmed against the exact hot dry climate rows of the implementation matrix.

Two findings are especially relevant. First, the guide does not quantify controlled natural ventilation or night flushing for VIS Multifamiliar.

This means that the most effective strategy identified in this thesis is precisely the one left unquantified by the national reference matrix. Quantifying its thermal effect, with reductions between 53% and 76% in overheating hours, is therefore a direct contribution of this research.

Second, the measures that the Guía does evaluate economically, solar protection and reflective surfaces, correspond to the low- and medium-cost strategies recommended by this thesis. By contrast, insulation, which implies higher cost and limited value in warm climates, is rejected here on thermal-performance

grounds because it increases overheating under free-running conditions.

IMPLEMENTATION MATRIX

Thesis Measure	Guide item	Budget impact	Energy saving	Payback	Thesis thermal impact
Solar grid and overhang	Solar protection	Medium	Single-digit savings	> 3 years	–43% to –62% overheating
Reflective wall paint / cool roof	Reflective surfaces / colour	Low to very low	Low single-digit savings	Short	–8% to –40% overheating
Controlled ventilation / night flush	Natural ventilation / night flush	N/A	N/A	N/A	–53% to –76% overheating
Wall / roof insulation	Insulation	Medium to high	Low	> 5 years	+26% to +44% overheating
Increased glazing / WWR	Window-to-wall ratio	not mentioned	Marginal	not mentioned	Worsens performance

PER PACKAGE COST PROFILE

Because the dominant strategy is controlled natural ventilation, enabled through operable windows and selected internal adjustments, the proposed packages remain relatively affordable. This measure has low material cost and is not treated as a separate costed item in the guide.

A01 | Is based of controlled ventilation therefore represents a low-to-medium cost package, based on one operational measure

A02 | combines controlled ventilation, a 0.80 m solar grid, and reflective wall paint and cool roof. It offers the best cost-benefit relationship of the three archetypes, because the reflective coating is a low-cost and high-impact measure on the high-U brick envelope.

A03 | combines controlled ventilation, a deeper 1.20 m overhang, solar grid and reflective wall paint. It is the most expensive package of the three, mainly due to the deeper shading structure, but this higher cost is justified by the severity of its solar-driven overheating.

Nevertheless, the magnitude of the overheating reductions achieved and the low-cost nature of the proposed measures suggest that the packages are aligned with the regulatory objective of reducing energy demand through passive design strategies.



This chapter revisits the research question, summarises the main findings, discusses the limitations of the study, and proposes future lines of work. It closes by reaffirming the central message of the thesis and its transferability to other warm-climate social housing contexts

CONCLUSIONS

The thesis asked how the thermal comfort of multi-family social housing (VIS) in Cali can be improved through passive renovation under the warmer climatic conditions expected by mid-century. The question was addressed by deriving three archetypes from the existing VIS stock built between 1990 and 2015, simulating their thermal behaviour under a 2050 design climate, testing passive strategies through sensitivity analysis, and combining the most effective measures into archetype-specific renovation packages.

The result is a quantified, comparative account of which passive strategies reduce overheating most effectively, how their performance varies according to construction system and morphology, and how these findings can be translated into design principles for heat-resilient social housing.

The answer is clear and, in one respect, counterintuitive: in Cali's warm, free-running climate, comfort is recovered by evacuating and rejecting heat, not by resisting it. Strategies commonly prioritised in temperate-climate retrofits, especially thermal insulation, are not only ineffective here but can actively worsen overheating.

PRINCIPAL FINDINGS

The first finding is that overheating is primarily a problem of heat evacuation, rather than insufficient envelope resistance. The annual heat balances show that, under 2050 free-running conditions, the opaque envelope often behaves as a heat sink, discharging accumulated heat instead of simply admitting it. The main deficit is therefore the absence of an effective discharge path.

Controlled natural ventilation is the strongest individual strategy, reducing overheating by approximately 53% to 76% across the three archetypes. It becomes the backbone of every renovation package. However, its effectiveness decreases under warmer future conditions, meaning that ventilation alone is no longer sufficient and must be combined with solar-control strategies.

External solar control through a two-directional grid clearly outperforms a conventional horizontal overhang. In A01, for example, the grid reduces overheating by approximately 43%, compared with only 9% for an overhang of equal depth. This is because the grid intercepts both high-angle solar radiation and low-angle morning and afternoon sun, which is especially relevant near the equator. Its performance begins to saturate at around 0.80 m, beyond which additional depth produces diminishing returns.

Reflective surfaces are highly dependent on the construction system. Reflective wall treatment is particularly effective in A02, where the high-U brick envelope responds strongly to lower solar absorptance, reducing overheating by approximately 40%. In contrast, the same measure is much weaker in A01 and A03, where the lower-U or mixed envelopes limit its impact. Reflectance is therefore not a universal solution; it must be matched to the thermal behaviour of the envelope.

Thermal insulation and uncontrolled increases in glazing are counterproductive. Insulating the wall or roof traps heat under free-running conditions and increases overheating, reaching increases of up to 26% in A01 and 44% in A03. Similarly, increasing the window-to-wall ratio increases solar gains and penalises comfort. Both strategies are therefore excluded from the renovation packages.

Finally, the combined packages act non-linearly. Their performance is not simply the sum of individual measures, because ventilation, shading, and reflectance reinforce one another. The recommended packages reduce overheating from approximately 3,300–4,200 hours to around 200–415 hours, achieving reductions of about 88% to 94%.

More importantly, they bring the three archetypes to a comparable comfort range of approximately 91% to 93%, despite their different construction systems and morphologies.

MAIN PRINCIPLES AND DESIGN IMPLICATIONS

These findings crystallise into a single design principle: do not insulate; shade, reflect, and ventilate.

This principle structures the projective proposal. Controlled ventilation provides the main discharge path for accumulated heat and is enabled architecturally through operable windows, cross-ventilation, and the removal of selected non-structural partitions to secure continuous air movement. External shading reduces solar gains before they enter the dwelling, while reflective surfaces are applied selectively where the envelope can benefit from lower absorptance.

The renovation levels are assigned according to performance rather than intensity. The medium package is optimal for the two compact archetypes, A01 and A02, because it captures most of the achievable benefit with moderate cost and construction complexity.

A03, by contrast, requires escalation to the high package because its exposed linear morphology creates a solar-driven heat input that cannot be resolved through ventilation alone.

This produces three tailored but coherent proposals: A01 relies mainly on ventilation and moderate grid shading; A02 combines ventilation, grid shading, and reflective wall treatment as the most cost-efficient package; and A03 requires the deepest intervention, with reinforced ventilation, a deeper grid, and reflective coating. All three follow the same five principles: dissipate heat, shade with a grid, reflect selectively, avoid insulation, and keep glazing moderate.

CONTRIBUTIONS

Methodologically, it develops an archetype-based, simulation-informed workflow for passive renovation in social housing. This approach is aligned with the logic of Colombia's Sustainable construction guide under Resolution 0549, strengthening the institutional relevance of the method.

Empirically, it quantifies the performance of passive strategies under a future 2050 climate rather than only under present conditions. In doing so, it provides evidence for the role of controlled natural ventilation in multi-family VIS, a measure that the national framework does not fully quantify but that this research identifies as the dominant passive strategy.

Disciplinarily, the thesis establishes a climate-specific design principle that challenges the insulation-first logic often imported from temperate contexts. In Cali's warm climate, insulation is not simply suboptimal; under free-running conditions, it can be harmful. The thesis therefore reframes passive retrofit for warm-climate social housing around dissipation, solar control, and selective reflectance.

All the research demonstrates that heat resilience in Cali's social housing stock can be achieved through low-cost, locally buildable, passive strategies, provided that the intervention follows the logic of the climate rather than the reflexes of temperate-climate retrofit practice.

In a warming, warm-humid context, the envelope should not be sealed and insulated. It should be allowed to discharge heat. Solar radiation should be stopped before it enters the dwelling, and comfort should be recovered through air movement. The design principle is therefore clear: dissipate, shade, and reflect not insulate strategies.

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