The Tropical Climate Matrix: An Architectural Design Tool for the Tropics

Laura Rendón Gaviria, Daniela Borja Zuluaga, and Manuela Yepes Ocampo

Abstract Currently, one of the main causes of environmental deterioration is the increasing rates of power consumption that, at the same time, are a consequence of numerous actions in all sectors. In the architecture and design field, the lack of good environmental comfort conditions in buildings is the main cause behind increased power consumption, because improperly ventilated and illuminated buildings, require mechanical strategies to regulate indoor environmental conditions. This is the reason why it is fundamental to develop tools that allow designers to incorporate environmental control strategies into design processes, to guarantee optimal indoor bioclimatic conditions. Thus, the objective of this chapter is to develop a tool that defines bioclimatic strategies for the first stages of building design and to generate good comfort conditions inside buildings. First, an analysis of climatic conditions in different climates was made in two Colombian cities: Medellin and Barranquilla, and then monthly comfort indexes were defined with their corresponding climatic correction strategies to guarantee comfort conditions, before finally proposing architectural and building strategies to achieve these climatic corrections. As a result, a highly usable tool is created, that can be used in the first stages of the design process by bioclimate experts and also users with little experience.

Keywords Andean tropics · Environmental comfort · Architectural design · Bioclimatic strategies · Design tool

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L. Rendón Gaviria (✉) · D. Borja Zuluaga · M. Yepes Ocampo
Faculty of Architecture and Engineering, Institución Universitaria Colegio Mayor de Antioquia, Medellín, Colombia
e-mail: laura.rendon@colmayor.edu.co

D. Borja Zuluaga
e-mail: dborja@est.colmayor.edu.co

M. Yepes Ocampo
e-mail: myepeso@est.colmayor.edu.co

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1 Introduction

Power consumption has increased globally by more than 50% in recent decades due to factors such as demographic growth, urban migration, and accelerated economic development [1]. Moreover, the lack of good environmental comfort conditions inside buildings directly affects their power efficiency, so it becomes fundamental to include bioclimatic and environmental control strategies in the building design process. Such strategies should generate optimal thermal, lighting, and acoustics conditions in those buildings. Additionally, it is important, especially in developing countries such as Colombia, to establish more regulations and standards to incorporate these strategies. Furthermore, most design processes do not include insights on environmental comfort or only add them in the project's last stages. However, there is still no clear and complete regulatory framework in Colombia that looks to improve indoor environmental comfort conditions. According to Parra Correa [2], only 63% of surveyed Colombian professionals, specialists in bioclimatic design, construction, or consulting, have included bioclimatic strategies in their design processes.

Paradoxically, nowadays, there are innumerable analog and digital tools, at every level of complexity, that aim at defining bioclimatic strategies to optimize environmental conditions in buildings [3–6]. But as has been previously mentioned, their use is limited or included in less suitable stages of the design process. There are few comfort indexes developed for tropical climates, especially for Colombia [7]. Additionally, the existing indexes have been developed for specific climates, and/or they do not simultaneously consider the three variables of Temperature, Relative Humidity, and Ventilation. In this way, most of these tools focus on a single aspect of environmental behavior, making it almost impossible to analyze them all and integrate the indicated criteria within projects [8]. These are the reasons why it is essential to develop tools that may provide applicable guidelines for the first stages of the project. These guidelines should only require general information about the project, and at the same time, should be simple enough to be used by most professionals without them needing to be experts. By doing so, it would contribute to removing environmental comfort barriers in the Global South and improving the habitability conditions of buildings in these areas where environmental comfort analysis is not within the scope of the projects.

Given this, the objective of this chapter is to develop a user-friendly tool that allows defining applicable bioclimatic strategies for the first stages of building design in the tropics, to guarantee good habitability and comfort conditions inside buildings. This tool is based on the Grille Climatique developed by the architect Le Corbusier in the 1950s.

2 Environmental Comfort in the Andean Tropics

In the tropical climatic context, the main variations of environmental conditions appear thanks to changes in the height above sea level, instead of experiencing seasonal changes during the year. In this zone of the planet, prevailing climates are between warm–dry and warm–humid, the latter being a climate that has high temperatures and relative humidity throughout most of the year. Specifically, the representative Andean Tropic climatic contexts used here, have an Af—Tropical rainforest climate without a dry season (Medellin), and Aw—Tropical savanna climate with a short dry season (Barranquilla), under the Köppen–Geiger climatic classification.

Several authors define solar control and radiation protection, as well as rain management, as the key factors for Andean tropical architecture. According to Olgyay [9], in the Tropics, the roof is the main barrier to a building's environmental defense. This considering that in places near the Equator, solar radiation has an intense and almost perpendicular impact on the land and buildings, practically making solar and shading design necessary in any construction [10]. In this vein, Saldarriaga [11] defines tropical architecture as "shaded and permeable," which considering its climatic and social surroundings must mitigate the building's thermal gains, in the best way possible. Also, according to Stagno [12], preparing spaces passively, not only improves the energy efficiency of the building but also benefits the people inside who may have a greater capacity to self-regulate their temperature and better adapt to climatic conditions.

Considering that the fundamental factors of environmental comfort in the Andean tropical strip revolve around the thermal environment of buildings, it can be concluded that this is one of the main topics to evaluate the first stages of architectural design. This is especially relevant, bearing in mind that aspects such as orientation and building shape have a profound effect on the internal thermal comfort of spaces.

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) defines thermal comfort in its standards as "the condition of mind that expresses satisfaction with the thermal environments" [13]. Although the evaluation of thermal comfort is subjective and personal, over the years several simple mathematical methods have been developed, and they manage to define the environmental conditions a space must have for most of its occupants to consider it comfortable, with Olgyay's Bioclimatic chart [14, 15], Givoni's Bioclimatic chart or Psychrometric chart, Comfort triangles [16], and the Climatic Grille of Le Corbusier [17] standing out.

3 Methodology

The methodology of this research project consisted of two general stages: (i) Weather identification where climatic conditions were identified in two representative cities of the Andean tropical climatic context: Medellin (Lat. 6° 15′ N; Long. 75° 34′ W) and Barranquilla (Lat. 10° 58′ N; Long. 74° 48′W), to analyze the main atmospheric conditions that affect the environmental comfort of people inside buildings in the tropics; and, (ii) Development of a tool which included comfort zone identification, the definition of climatic correction strategies to outline appropriate indoor comfort conditions as per the climatic context of the location, and finally, the definition of architectural and constructive strategies to achieve these climatic corrections.

3.1 Documentary Review

Apart from research on the specific tool of Le Corbusier's Grille Climatique, a review of issues related to thermal comfort, different analogous tools to calculate the comfort zone or its definition, as well as the specific environmental needs of the architecture found in the tropical zone was carried out.

3.2 Identification of Le Corbusier's Climatic Grid

> It is necessary to regulate and usefully rectify the overflowing of excessive climates, and to do so make architectonic devices with conditions able to guarantee well-being and comfort [18]

A complete investigation was made on the Grille Climatique of Le Corbusier. This is a graphical methodological tool, that summarized the rules to create an architecture that is universal and adaptable to a place considering its environmental conditions. Mainly the matrix origin, creation year, and context were analyzed, (See Fig. 1). Thus, it was evident that a large swathe of Le Corbusier's professional work focused on standardizing the project process, more than the product itself, which was proven with the invention of different tools that helped him to apply bioclimatic, environmental, or technical criteria when designing projects [17].

Le Corbusier's Grille Climatique includes three vertical sections, each one divided into 12 columns corresponding to the months of the year. The first vertical section, Part A, (données climatiques) contains the climate information of the place being

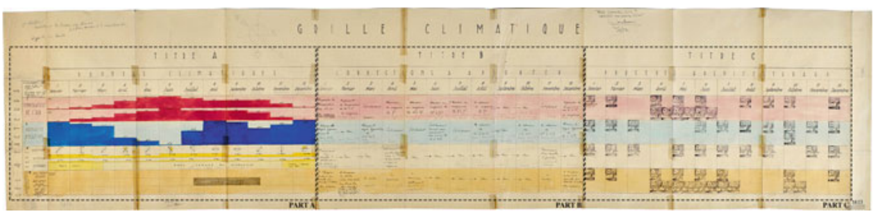


Fig. 1 Grille Climatique of Le Corbusier. Adapted from [15]

intervened. Horizontally, the matrix is divided into four rows, corresponding to the variables to consider air temperature, relative humidity, wind, and radiation, and each row into one, two, or three sub-rows based on the data displayed on each variable. In addition, the table has an extra space indicating the geographic information of the place corresponding to the table and the project involved.

Part B (corrections á to apporter) consists of the necessary modifications or corrections to apply to climatic variables to reach the optimal comfort conditions of a person inside the space. The information displayed in this section is the number of degrees or humidity percentages that would have to be increased or decreased to achieve a comfort zone. It also recommends air speed or periods at which ventilation must be completely blocked, and periods, when radiation must be avoided or attracted, are identified. For months when corrections are not required, the "satisfactory" legend appears. It is important to point out that Le Corbusier, to define these corrections, defined the following ideal or recommended internal climatic conditions to guarantee a comfortable space (See Table 1).

The third section, or Part C (procédés architecturaux), consists of the architectural processes that allow obtaining these optimal conditions within the specific climatic context of each zone. Different stamps indicate the code, the name of the solution applied, and the location of the section where all the graphic solutions are annexed.

It is worth mentioning that, because the information is shown by month and not by season, this tool can be used in seasonal climatic contexts, as well as in the tropical strip.

3.3 Adaptation of Le Corbusier's Climatic Grid to Develop the Tropical Climatic Matrix (MCT, in Spanish)

After thoroughly analyzing the information in the previous stage, two pilot matrices were run with information from the cities of Medellin and Barranquilla, to simplify the verification process and analyze the coherence of the results obtained. This information proved that it is possible to use the tool for any other city or territory if the necessary climatic information is available.

The information collected was reviewed and data entry began in the Tropical Climatic Matrix (MCT), of climatic data, climatic corrections, and project strategies in 4 horizontal strips divided into Sections A, B1, B2, and C (See Fig. 2).

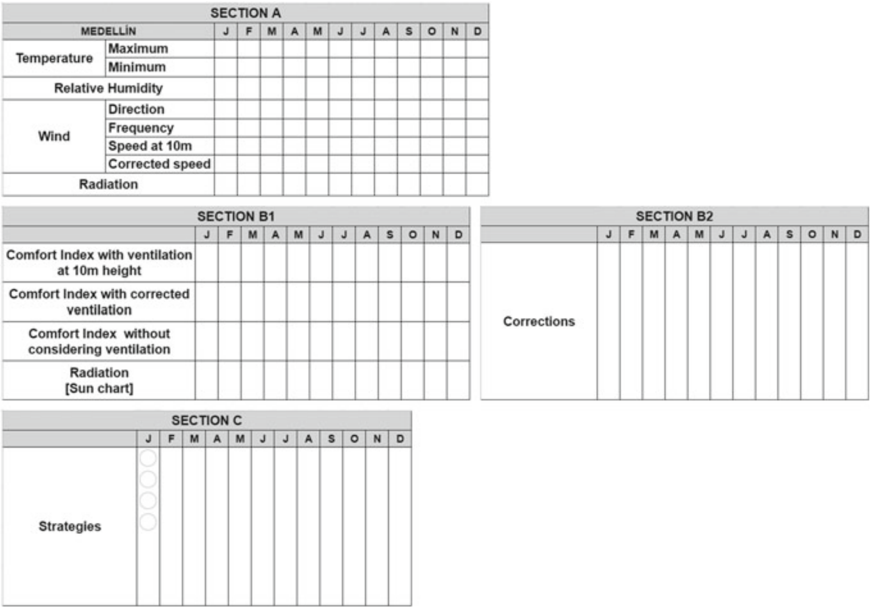
3.3.1 Section A

In the first section, the information displayed in the Tropical Climatic Matrix (MCT) is just as in the original: maximum and minimum monthly air temperatures (°C), average monthly relative humidity (%), and graphical information of both variables. Wind directions, frequencies (% of the time), and speed (m/s) also appear, as well

Table 1 Comfort conditions to calculate "climatic corrections" in Le Corbusier's Grille Climatique, by month. Calculated from Le Corbusier's Grille Climatique

	J	F	M	A	M	J	J	A	S	O	N	D
T_{max}	21°C	21°C	21°C	21°C	25°C	25°C	25°C	21°C	21°C	22°C	19°C	21°C
T_{min}	15°C	16°C	12°C	19°C	16°C	15°C	16°C	22°C	22°C	19°C	12°C	13°C
RH_{max}	55%	52%	54%	53%	50%	60%	62%	56%	53%	60%	60%	55%
RH_{min}	50%	47%	49%	53%	50%	55%	62%	51%	48%	55%	55%	50%
Vent.	Avoid sensitive wind			Sensitive wind between 1.0 and 1.5 m/s							Avoid all wind	
Solar Radiation	Harvest all	Harvest some, avoid on hot hours	Avoid	Prohibit all	Prohibit all	Prohibit all	Prohibit all	Prohibit all *Cloudy sky	Prohibit all *Cloudy sky	Prohibit all	Avoid	Harvest all

T_{max}: Maximum Temperature
T_{min}: Minimum Temperature
RH_{max}: Maximum Relative Humidity
RH_{min}: Minimum Relative Humidity
Vent: Ventilation
Solar Rad: Solar radiation



SECTION A													
MEDELLÍN		J	F	M	A	M	J	J	A	S	O	N	D
Temperature	Maximum												
	Minimum												
Relative Humidity													
Wind	Direction												
	Frequency												
	Speed at 10m												
	Corrected speed												
Radiation													

SECTION B1												
	J	F	M	A	M	J	J	A	S	O	N	D
Comfort Index with ventilation at 10m height												
Comfort Index with corrected ventilation												
Comfort Index without considering ventilation												
Radiation [Sun chart]												

SECTION B2												
	J	F	M	A	M	J	J	A	S	O	N	D
Corrections												

SECTION C												
	J	F	M	A	M	J	J	A	S	O	N	D
Strategies												

Fig. 2 Sections A, B1, B2, and C of the Tropical Climatic Matrix (MCT)

as an additional row, indicating the corrected wind speed (m/s), considering the roughness level of areas in urban surroundings, following the Hellmann Exponent Law (a Hellmann exponent of 0.4, corresponding to densely populated areas). All the ventilation information is also graphically shown in the schematic wind rose diagrams. Finally, the bottom row contains the global horizontal irradiance available every month (Wh/m^2), with its respective graphical reference indicating maximum and minimum azimuth and altitude angles.

Climatic data were extracted from the climatic file (.epw) of both cities, from Climate.OneBuilding.Org, and analyzed in Climate Consultant software version 6.0.

As mentioned above, one of the modifications is the way to display information. This is done with more images demonstrating numerical data, icons, and floor plans, to allow easier and more practical reading of the compiled information.

3.3.2 Section B

This section is divided into two parts, B1 and B2. The first part contains one of the main modifications made to Section B, the one that generates the greatest contribution and innovation of the tool: the combination of climatic factors to define the Comfort Index of spaces. This is a significant improvement over the original version because it considers the environmental factors together (as they appear) and shows how their combination impacts the comfort sensation of human beings, instead of defining corrections to each factor (e.g., temperature and humidity) without considering the effect of some factors on the others.

To do so, equations to calculate climatic comfort are used (equations 2, 3, 4, and 5), developed by González [19], which are specifically designed considering the climatic conditions of Colombia (defining a different equation for each city according to its height above sea level). This method uses the main climatic parameters: air temperature, relative humidity, and wind speed, given that relative humidity and temperature data are included without considering solar radiation. After applying the defined equation, the result is a value representing the Comfort Index (CI) of the people. This index is a numerical value between zero and 15, representing different comfort states such as 0–3—Very hot; 3.1–5—Hot; 5.1–7—Warm; 7.1–11—Comfortable; 11.1–13— Somewhat cold; 13.1–15—Cold; and >15: Very cold [19]. Although numerous comfort indexes have been developed, they are designed for only one type of building (e.g., office building, hospital, school, etc.), and/or work for a specific climate, which would limit the usage of the MTC tool, because it would not allow its use for any type of space in any climatic context. The index proposed by González [19] is designed for any of the Andean tropic climates and considers the height above sea level as a key factor for climatic conditions in this part of the planet. It also makes the calculation possible with or without wind (depending on data availability).

As mentioned before, this investigation uses two equation types considering the availability of wind speed information. This is important because there are cases where it is not easy to calculate or obtain wind speed data. CI calculations for both situations are as follows: with wind (corrected) and without wind.

For altitudes between 0 and 1,000 m above sea level, considering wind speed (1)

$$CI = (36.5 - T_s)(0.05 + 0.04\sqrt{s} + h/250) \tag{1}$$

For altitudes between 0 and 1,000 m above sea level, without considering wind speed (2)

$$CI = (36.5 - T_s)(0.05 + h/250) \tag{2}$$

For altitudes between 1,000 and 2,000 m above sea level, considering wind speed (3)

$$CI = (34.5 - T_s)(0.05 + 0.06\sqrt{s} + h/180) \tag{3}$$

For altitudes between 1,000 and 2,000 m above sea level, without considering wind speed (4)

$$CI = (36.5 - T_s)(0.05 + h/180) \tag{4}$$

Where:
CI = comfort index
T_s = air temperature (°C)
h = relative humidity (%)
s = wind speed (m/s)

Additionally, Section B2 contains similar modifications to those considered by Le Corbusier regarding temperature, relative humidity, radiation, and ventilation, to achieve comfortable indoor conditions. However, they are comprehensively shown as general recommendations (e.g., solar protection and natural ventilation). These recommendations are taken from the psychrometric chart following the criteria from ASHRAE 55 Standard and Current Handbook of Fundamentals Model [13].

3.3.3 Section C

According to the climatic corrections defined in Sections B1 and B2, some general architectural strategies were laid down based on the graphic representation of Le Corbusier for the floor plan and elevation according to each category. The main difference with the reference tool is that the strategies appear individually for each "correction" so that the user can analyze its suitability, relevance, and hierarchy level, as well as how to apply the tool in each project depending on its requirements. The strategies are classified in the Tropical Climatic Matrix in three categories, as indicated in the following table (Table 2):

These solutions are the climatic corrections to be applied to the building and location. This will allow providing basic applicable design guidelines in the first stages of the design process, that should not compromise the building's style or structure, but have flexible enough guidelines so that the architect applies as they deem fit. Thus, the user will be able to analyze the climatic conditions in Section A, to understand which environmental requirements or climatic corrections must be implemented to obtain a good Comfort Index (Sections B1 and B2) and, finally, obtain bioclimatic design guidelines aiming at improving the indoor environmental conditions, these guidelines applying to any project without prior project information (Section C).

To define the recommended strategies, in addition to the specific corrections laid out in Section B2, the combination of environmental variables in every month was considered, for example: If in January the climatic corrections are solar protection, cooling by evaporation, and natural ventilation, it is recommended to protect the eastern and western facades (East and West) and especially the southern facade that receives solar radiation all the day at this time of the year. It is also recommended to open the northern and eastern facades to allow the entrance of predominant ventilation and humidity.

4 Results

> The desirable procedure will be to work with and not against natural forces and to make use of their potentialities to create better living conditions...The procedure for building a climatically balanced house is divided into four steps, of which the last is the architec-

Table 2 Classification of architectural strategies

Strategy	Description	Code
Humidity: H Stamps	Humidification by bodies of water	H1–H2–H3
	Humidification by vegetation	H4–H5–H6
	Green walls	H7–H8–H9
Ventilation: V Stamps	Cross-ventilation through Windows	V1–V2–V3
	Ventilation through openwork surfaces	V4–V5–V6–V8
	Ventilation with wind-conducting elements at the edge of the facade	V4–V5–V6
	Ventilation through raised roofs	V7
	High ceilings	V9
	Chimney effect	V10
Solar protection: R Stamps	Solar protection with vertical elements on eastern and western facades and predominantly on the southern facade with a horizontal element	R1
	Solar protection with vertical elements on eastern and western facades and predominantly on the northern facade with a horizontal element	R2
	Solar shading with horizontal elements on eastern and western facades	R3
	Solar protection with vertical elements on eastern and western facades	R4
	Solar shading with vegetation on eastern and western facades	R5
	Recessed windows	R6

> tural expression. The expression must be preceded by the study of climatic, biological, and technological variables... [14]

The following are the four sections of the Tropical Climatic Matrix tool, with data and results corresponding to both types of climates analyzed (See Figs. 3–6).

It is important to consider that the available climatic information depends on current databases. Analyzing the climatic data available for places within the scope, it was identified that some of the information is not updated or is inaccurate compared with the climate perception in these cities. Thus, it is necessary to gather updated climatic information to improve the accuracy of the results obtained using the tool. Despite the previous statement, it was verified that this dynamic tool is completely customizable to the environmental conditions of any territory with sufficient climatic information, especially in the Andean tropics.

As mentioned above, on reviewing the literature, it was possible to verify that there are few comfort indexes for tropical climates, especially for Colombia [7]. Addition-

SECTION A		JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER
TEMP	MAXIMUM	29°	30°	30°	31°	32°	30°	30°	31°	31°	29°	29°	29°
	MINIMUM	14°	14°	15°	14°	14°	14°	13°	14°	14°	14°	14°	11°
RELATIVE HUMIDITY		59%	62%	62%	77%	73%	61%	57%	57%	62%	69%	74%	68%
WIND	DIRECTION												
	FREQUENCY	15%	15%	8%	9%	6%	12%	10%	12%	15%	7%	9%	15%
	SPEED AT 10m HEIGHT	2.0 m/s	1.0 m/s	1.0 m/s	3.0 m/s	1.0 m/s	2.0 m/s	2.0 m/s	1.0 m/s	1.0 m/s	2.0 m/s	2.0 m/s	2.0 m/s
	CORRECTED SPEED	1.2 m/s	0.6 m/s	0.6 m/s	1.9 m/s	0.6 m/s	1.2 m/s	1.2 m/s	0.6 m/s	0.6 m/s	1.2 m/s	1.2 m/s	1.2 m/s
RADIATION		5336 Wh/sq.m	5269 Wh/sq.m	5161 Wh/sq.m	5198 Wh/sq.m	5192 Wh/sq.m	5659 Wh/sq.m	5784 Wh/sq.m	5988 Wh/sq.m	5675 Wh/sq.m	4894 Wh/sq.m	4795 Wh/sq.m	5090 Wh/sq.m

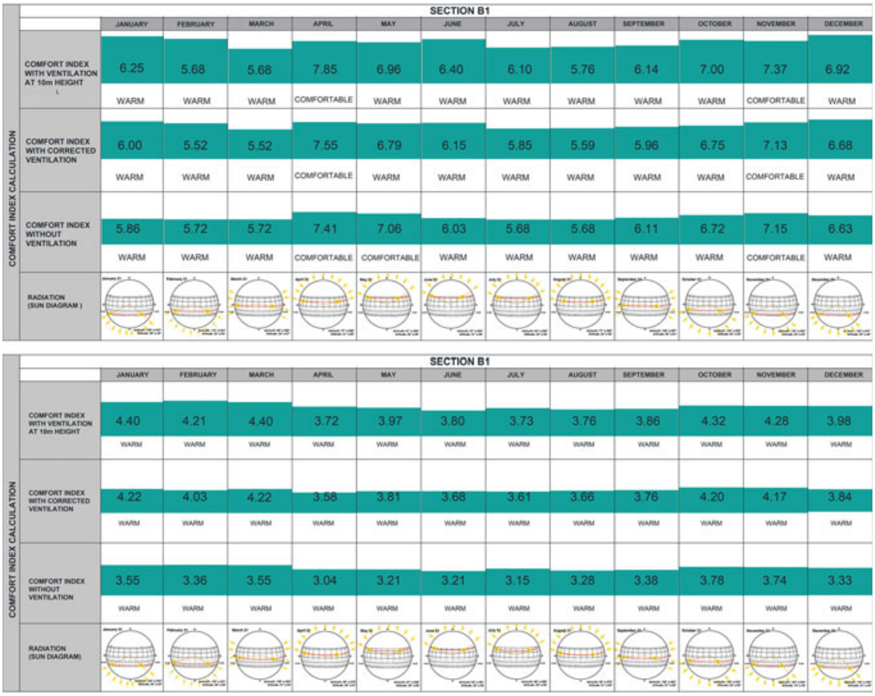
SECTION A		JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST			NOVEMBER	DECEMBER
TEMP	MAXIMUM	32°	33°	33°	34°	34°	35°	33°	34°	35°	33°	33°	33°
	MINIMUM	23°	22°	23°	22°	24°	23°	22°	23°	22°	22°	23°	22°
RELATIVE HUMIDITY		81%	76%	81%	77%	82%	82%	80%	84%	87%	87%	86%	75%
WIND	DIRECTION												
	FREQUENCY	24%	22%	24%	20%	18%	8%	11%	10%	14%	7%	8%	19%
	SPEED AT 10m HEIGHT	5.0 m/s	5.0 m/s	5.0 m/s	4.0 m/s	5.0 m/s	3.0 m/s	3.0 m/s	2.0 m/s	2.0 m/s	2.0 m/s	2.0 m/s	3.0 m/s
	CORRECTED SPEDD	3.1 m/s	3.1 m/s	3.1 m/s	2.5 m/s	3.1 m/s	1.9 m/s	1.9 m/s	1.2 m/s	1.2 m/s	1.2 m/s	1.2 m/s	1.9 m/s
RADIATION		5871 Wh/sq.m	6302 Wh/sq.m	6467 Wh/sq.m	5802 Wh/sq.m	5589 Wh/sq.m	5698 Wh/sq.m	5774 Wh/sq.m	5990 Wh/sq.m	5500 Wh/sq.m	4673 Wh/sq.m	4713 Wh/sq.m	5426 Wh/sq.m

Fig. 3 Section A of the Tropical Climatic Matrix: Climatic characterization. On the top Medellín, on the bottom Barranquilla

ally, the indexes there are, have been developed for specific climates, and/or they do not simultaneously consider the three variables of temperature, relative humidity, and ventilation. It is important to mention that Section C of the MCT displays the CI calculation considering these three variables and, it does not consider the effect of solar radiation for its calculation. Therefore, it is possible to expect overheating in spaces that are more exposed to this solar radiation. Detailed information regarding sunlight is also displayed.

The stamps from Section C of the MCT, correspond to architectural layouts suggested in each specific case considering the featured climatic conditions and the necessary corrections. Each strategy suggested considers the most efficient façade to apply it on. If several stamps on the same topic appear in the same month, it means that there are different options to choose from. For example, in Medellín, several humidification strategies are recommended every month, due to the relative humidity levels and wind speed and direction. Therefore, the user can choose from humidification by bodies of water, humidification by vegetation, or installing a green wall, depending on the project.

Figures 6–8, show all the layouts of those strategies mentioned in the MCT of both cities.



SECTION B1 (Medellín)

COMFORT INDEX CALCULATION	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER
COMFORT INDEX WITH VENTILATION AT 10m HEIGHT	6.25	5.68	5.68	7.85	6.96	6.40	6.10	5.76	6.14	7.00	7.37	6.92
	WARM	WARM	WARM	COMFORTABLE	WARM	WARM	WARM	WARM	WARM	WARM	COMFORTABLE	WARM
COMFORT INDEX WITH CORRECTED VENTILATION	6.00	5.52	5.52	7.55	6.79	6.15	5.85	5.59	5.96	6.75	7.13	6.68
	WARM	WARM	WARM	COMFORTABLE	WARM	WARM	WARM	WARM	WARM	WARM	COMFORTABLE	WARM
COMFORT INDEX WITHOUT VENTILATION	5.86	5.72	5.72	7.41	7.06	6.03	5.68	5.68	6.11	6.72	7.15	6.63
	WARM	WARM	WARM	COMFORTABLE	COMFORTABLE	WARM	WARM	WARM	WARM	WARM	COMFORTABLE	WARM
RADIATION (SUN DIAGRAM)												

SECTION B1 (Barranquilla)

COMFORT INDEX CALCULATION	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER
COMFORT INDEX WITH VENTILATION AT 10m HEIGHT	4.40	4.21	4.40	3.72	3.97	3.80	3.73	3.76	3.86	4.32	4.28	3.98
	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM
COMFORT INDEX WITH CORRECTED VENTILATION	4.22	4.03	4.22	3.58	3.81	3.68	3.61	3.66	3.76	4.20	4.17	3.84
	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM
COMFORT INDEX WITHOUT VENTILATION	3.55	3.36	3.55	3.04	3.21	3.21	3.15	3.28	3.38	3.78	3.74	3.33
	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM
RADIATION (SUN DIAGRAM)												

Fig. 4 Section B1 of the Tropical Climatic Matrix: Calculation of comfort indexes and sunlight angles. On the top Medellín, on the bottom Barranquilla

SECTION B2 (Medellín)

	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER
CORRECTIONS	Solar protection Evaporative cooling Natural ventilation	Solar protection Evaporative cooling Natural ventilation	Solar protection Evaporative cooling Natural ventilation	Solar protection Evaporative cooling Natural ventilation	Solar protection Evaporative cooling Natural ventilation	Solar protection Evaporative cooling Natural ventilation	Solar protection Evaporative cooling Natural ventilation	Solar protection Evaporative cooling Natural ventilation	Solar protection Evaporative cooling Natural ventilation	Solar protection Evaporative cooling Natural ventilation	Solar protection Evaporative cooling Natural ventilation	Solar protection Evaporative cooling Natural ventilation

SECTION B2 (Barranquilla)

	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER
CORRECTIONS	Solar protection Natural ventilation cooling	Solar protection Natural ventilation cooling	Solar protection Natural ventilation cooling	Solar protection Natural ventilation cooling	Solar protection Natural ventilation cooling	Solar protection Natural ventilation cooling Air conditioning Dehumidifier	Solar protection Natural ventilation cooling	Solar protection Natural ventilation cooling Air conditioning Dehumidifier	Solar protection Natural ventilation cooling Air conditioning Dehumidifier	Solar protection Natural ventilation cooling	Solar protection Natural ventilation cooling	Solar protection Natural ventilation cooling

Fig. 5 Section B2 of the Tropical Climatic Matrix: Definition of recommended general climatic strategies. On the top Medellín, on the bottom Barranquilla

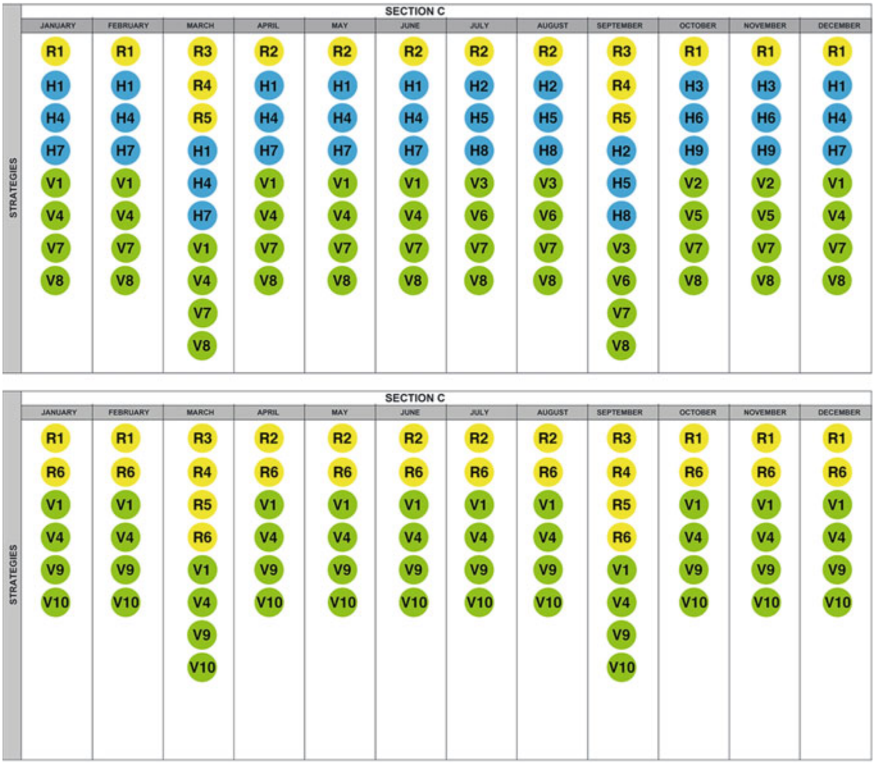


Fig. 6 Section C of the Tropical Climatic Matrix: Definition of specific architectural strategies (each stamp matches the specific architectural strategy diagram. V: Ventilation strategies, H: Humidification strategies, and R: Solar radiation strategies). On the top Medellín, on the bottom Barranquilla

Subsequently, there is an additional list of precautions or recommendations to obtain better results or not affect other environmental factors when applying the strategies.

How to prioritize:

- To promote comfort in months with a Comfort Index other than Comfortable, it is recommended to comply with the strategies of the months that registered the CI results furthest from Comfort.
- If the strategy type is prioritized, where ventilation is preferred, it is recommended to apply the strategies defined for those months with greater average wind speeds and those that represent the recommendations for most of the year.
- If the priority is relative humidity, it is recommended to prefer those strategies defined for months with a lower average relative humidity.
- If it is necessary to choose a single radiation strategy, it is recommended to choose the one corresponding to months with a higher average solar radiation.

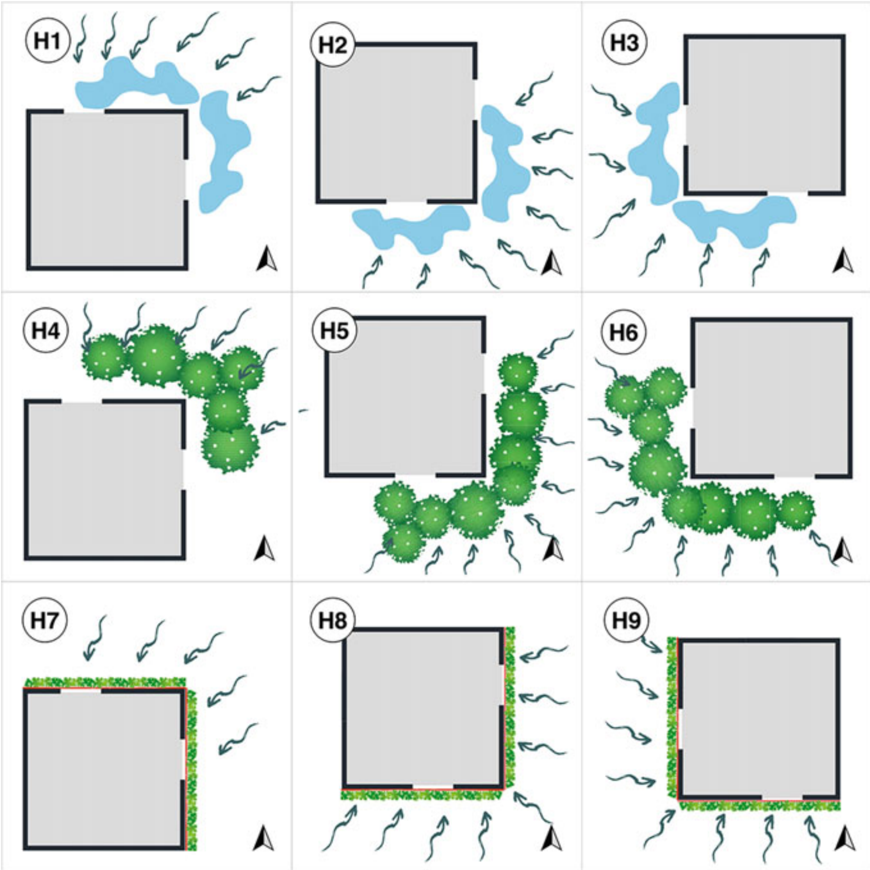


Fig. 7 Relative humidity strategies. H1, H2, and H3: Humidification by bodies of water on the northeastern, southeastern, and southwestern facades. H4, H5, and H6: Humidification by vegetation on the northeastern, southeastern, and southwestern facades. H7, H8, and H9: Green walls on the northeastern, southeastern, and southwestern facades

Please consider:

- When applying solar protection on facades, the amount of indoor daylight will also be reduced. Verification of the amount of sky blocked by these solar protections is recommended, as well as their colors and materials to favor light reflection that improves indoor daylighting availability.
- It is important to consider the risk of rain entering due to ventilation solutions such as openwork walls, high ceilings, and other façade perforations. It is recommended to plan these strategies in spaces that can get wet, using additional protections like eaves or complementing these openings with systems that can be closed.
- To increase indoor thermal comfort in warm climates, it is recommended to complement the tool's strategies, with a selection of low transmittance materials

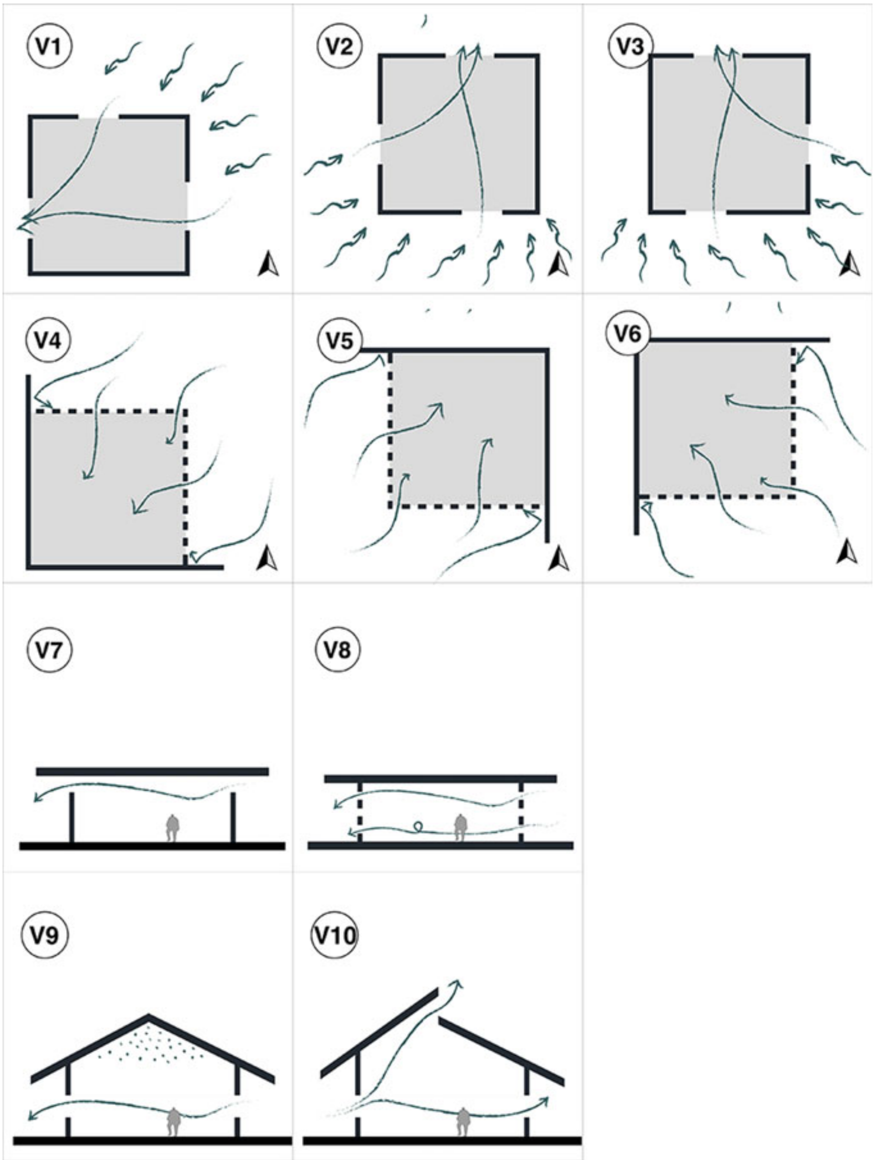


Fig. 8 Ventilation strategies. V1, V2, and V3: Cross ventilation through windows on the northeastern, southeastern, and southwestern facades. V4, V5, V6, and V8: Ventilation through openwork surfaces on the northeastern, southeastern, and southwestern facades. V4, V5, and V6: Ventilation with wind-conducting elements at the edge of the facade. V7: Ventilation through raised roofs. V9: High ceilings. V10: Chimney effect

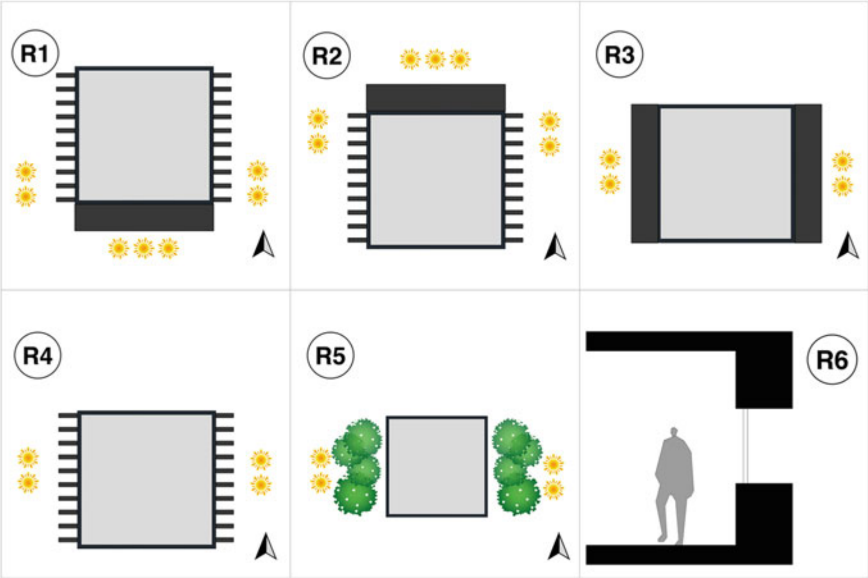


Fig. 9 Solar radiation strategies. R1: Solar protection with vertical elements on eastern and western facades and predominantly on the southern facade with a horizontal element. R2: Solar protection with vertical elements on eastern and western facades and predominantly on the northern facade with a horizontal element. R3: Solar shading with horizontal elements on eastern and western facades. R4: Solar protection with vertical elements on eastern and western facades. R5: Solar shading with vegetation on eastern and western facades. R6: Recessed windows

(U value) especially on the roof, that help to isolate heat transference due to the great amount of solar radiation these surfaces are exposed to.

- It is important to consider the shadows cast by neighboring buildings. It is recommended to analyze the shading of surrounding constructions to verify whether there are periods of the year or facades that do not need their own shading. If this is the case, R strategies must be discarded for those facades where shading is no longer necessary.

5 Discussion and Conclusions

One of the main contributions of this investigation is the fact that the tool has a very good relationship between its simplicity and potential. In other words, it is a tool that, despite being simple to use and not requiring in-depth technical knowledge on bioclimatic aspects, can provide relevant information for the environmental improvement of spaces being designed. As was already mentioned, the high level of usability is remarkable: this tool can be used by non-expert bioclimatic users. It can even be stated that it mainly targets them, which fulfills the objective of closing the gap still present in the area, because only a few people technically manage the bioclimatic concepts and tools, or they are not properly applied to the projects. Moreover, it is a tool that aims at improving habitability conditions for buildings in countries where environmental control and comfort are not yet high-priority or inherent subjects in architectural design. This is relevant because it helps remove barriers to environmental comfort in the Global South and at the same time, provides design and construction professionals with elements so that they include environmental optimization strategies in buildings, thus providing better habitability conditions, better performance of people in their indoor activities, improvement in health conditions, and reduction of building's power dependency, among others.

It is important to mention that the MCT can also be applied (with its necessary modifications) to other types of spaces that require environmental controls, such as farms, greenhouses, production plants, etc., which diversify and extend the influence of the MCT to an interdisciplinary field. In addition, this tool is conceived to be applied in the first stages of a project, a feature that provides another great strength: It requires the definition of little information on the project as an input, to generate the architectural guidelines. In this regard, there is a significant difference between this and other tools, given the fact that most of them require some building characteristics to be defined beforehand to generate the recommended strategies.

The Tropical Climatic Matrix displays more graphical information, and this is an innovation for a reference tool. Specifically, for radiation information, there are schematic solar diagrams that precisely indicate the maximum and minimum azimuth and altitude angles, which allows choosing one solar protection strategy or another. The user can also calculate, with a good level of detail, the size and rhythm of these elements, considering the angles of solar rays impacting the facades. Another distinguishable contribution made by the tool compared to other tools of its class is that strategies and recommendations appear individually by façade, according to the needs and influence of each climatic variable on them. This allows the MCT user, to decide which strategies to use considering their formal needs, esthetic taste, topography, and budgetary or technical aspects, among others.

Similarly, the MCT is sufficiently flexible so it can be applied to any building regardless of its use or typology, considering that the designer will apply the strategies in the best possible way depending on the project's needs.

Especially in cities with noticeable topographies such as Medellín (so common in the Andean tropic zone), it is important to consider the major climatic changes generated by differences in heights above sea level, which creates climatic information that does not represent the entire territory. Also, the need to gather updated climatic information about the Andean tropic cities is evident, to improve the accuracy of the results obtained using the tool.

References

1. Omrani S, Garcia-Hansen V, Capra B, Drogemuller R (2017) Natural ventilation in multi-storey buildings: Design process and review of evaluation tools. Build Environ 116:182–194. https://doi.org/10.1016/j.buildenv.2017.02.012
2. Parra Correa E (2020) Propuesta de una metodología para la optimización multi-objetivo de estrategias bioclimáticas en edificaciones a través de modelos paramétricos. Master's thesis, Universidad de San Buenaventura, Medellín, Colombia
3. Wagdy A, Fathy F (2015) A parametric approach for achieving optimum daylighting performance through solar screens in desert climates. J Build Eng 3:155–170. https://doi.org/10.1016/j.jobe.2015.07.007
4. Negendahl K, Nielsen TR (2015) Building energy optimization in the early design stages: A simplified method. Energy Build 105:88–99. https://doi.org/10.1016/j.enbuild.2015.06.087
5. El Daly H (2014) Automated fenestration allocation as complying with leed rating system. Alexandria Eng J 53:883–890. https://doi.org/10.1016/j.aej.2014.09.011
6. Toutou A, Fikry M, Mohamed W (2018) The parametric based optimization framework daylighting and energy performance in residential buildings in hot arid zone. Alexandria Eng J 57:3595–3608. https://doi.org/10.1016/j.aej.2018.04.006
7. García A, Olivieri F, Larrumbide E, Ávila P (2019) Thermal comfort assessment in naturally ventilated offices located in a cold tropical climate, Bogotá. Build Environ 158:237–247. https://doi.org/10.1016/j.buildenv.2019.05.013
8. Mackey C, Roudsari M (2018) The tool(s) versus the toolkit. In: Humanizing digital reality, vol 9. Springer, Singapore, pp 93–101. https://doi.org/10.1007/978-981-10-6611-5-9
9. Olgyay V (1968) Clima y arquitectura en Colombia. Facultad de Arquitectura. Universidad del Valle, Cali, Colombia
10. Salazar J (2003) Protección solar en edificaciones. Fundamentos teóricos. In: VII Encuentro nacional de estudiantes de arquitectura, Universidad Nacional de Colombia, sede Medellín, Grupo EMAT, Medellín, Colombia
11. Saldarriaga D (2019) La influencia del balcón abierto en la reducción de la carga térmica y en el comportamiento de la ventilación natural para edificios residenciales en altura. Caso de estudio Medellín. Master's thesis, Universidad de San Buenaventura, Colombia
12. Stagno B (2004) Climatizando con el clima. In: A TI (ed) III Encuentro de arquitectura, urbanismo y paisajismo tropical. Instituto de Arquitectura Tropical, San José, Costa Rica, p 22
13. ASHRAE (2017) ANSI/ASHRAE standard 55-2017 thermal environmental conditions for human occupancy
14. Olgyay V (1963) Interpretación Climática
15. Arauza Franco M (2009) Adecuación de los triángulos de confort, para la condiciones climatológicas dominantes en la República Mexicana. Master's thesis, Universidad Autónoma Metropolitana, Mexico
16. Evans JM (2007) The comfort triangles: A new tool for bioclimatic design. PhD thesis, Technological University of Delft, Netherlands
17. Martín Fuentes D (2016) Le Corbusier y la Grille climatique: Herramientas para la inclusión de variables termodinámicas y sensoriales en el proyecto arquitectónico. PhD thesis, Universitat Politècnica de València, España
18. Corbusier Le (1985) Oeuvre complète 1952–1957. Les Editions d'Architecture, Zurich, Switzerland
19. González OC (1998) Metodología para el calculo del confort climático en Colombia. IDEAM 47