A Pathway to Comfort by Natural Conditioning: Selecting Bioclimatic Design Resources

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Abstract Passive building design and construction modifies outdoor environmental conditions, improving comfort and reducing dependence on artificial conditioning and conventional energy. This chapter presents an analysis of bioclimatic design resources and selection methods developed over the last 50 years and presents a new approach based on the response to typical external conditions with special emphasis on the control of temperature swings and modification of indoor average temperatures. This is based on the dynamic variations of periodic heat flow using bioclimatic design resources such as thermal inertia that affects the indoor conditions over the daily cycle. The method aims at promoting appropriate combinations and levels of bioclimatic strategies, to guide the designer at the initial design stage before definitive decisions. The graphic tool allows the designer to use climate data and comfort limits to select and visualize alternative design resources, promoting participation in the development of bioclimatic approaches to near-zero energy buildings.

Keywords Natural conditioning · Climate · Bioclimatic design · Thermal comfort · Passive strategies

1 Introduction

The latest report of the Intergovernmental Panel on Climate Change [1] emphasizes the need to reduce greenhouse gas emissions and avoid potentially catastrophic environmental impacts. This is especially important in the building sector due to the long-term impacts and conventional energy demand of permanent structures [2, 3]. Much of the

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region below the Tropic of Cancer has also suffered from a severe housing deficit in quantity and quality with a demand for more and better solutions [2].

However, many designers and builders do not have the knowledge and tools to respond to this new challenge with appropriate sustainable solutions. This chapter therefore emphasizes the need to identify suitable bioclimatic strategies at an early design stage, presenting a new approach to select passive solutions that reduce or avoid dependence on air conditioning and heating with the inevitable impacts, promote near-zero energy-building solutions, and overcome the barriers to environmental comfort.

This new approach allows the identification of design strategies to promote low-impact and improved social housing, offering comfort and energy efficiency, and responding to local climatic, technological, and social conditions. Passive solutions incorporating natural conditioning are especially appropriate in temperate climates and warmer regions with significant temperature swings and good solar radiation; conditions that are typical of many countries in the region. The conventional approach to comfort is based on a simple energy balance, using artificial heating and cooling to provide adequate conditions when the building fails to provide them. Traditional bioclimatic methodologies, based on the charts of Olgyay [4, 5] and Givoni [6], identify key strategies but have two drawbacks. On one hand, they consider each strategy individually, and although several strategies are usually used simultaneously, some work well together, while others may be incompatible. They also analyze conditions at a specific point in time, while indoor conditions will often depend on strategies that affect future conditions, such as thermal inertia and time lag. So, following an evaluation of traditional bioclimatic procedures, this chapter presents a new design approach to select suitable combinations of design strategies and evaluate their effectiveness in achieving comfort by building designs for natural conditioning.

2 Traditional Bioclimatic Methodologies

This section reviews different approaches to the bioclimatic design process that have evolved over the last 50 years with an emphasis on graphic tools developed for architects, and their application in the range of climates found in the southern hemisphere. They all follow a similar process that compares the existing outdoor temperature and humidity with the indoor conditions needed to ensure thermal comfort. The difference between the existing and required conditions is used to detect the appropriate design strategies. In this framework, four methods are considered, starting with the characteristic response for each basic climatic type.

It should be noted that the whole concept of bioclimatic design and changes of strategies needed in different climates have been known since Greek and Roman times when large empires started to spread over different climatic regions and regional building variations were recognized. Up to seven climatic regions were identified by early geographers such as de Sacrobosco [7], ranging from uninhabitable cold northern climates to excessively hot climates. These differences became more important in the colonial period when British, French, German, Dutch, Spanish, and Portuguese territories extended over widely different climatic regions.

This required a deeper knowledge of the design strategies and bioclimatic resources needed for the design of government buildings and housing in each zone, in the era before air conditioning was available. Systematic research undertaken into comfort conditions and building performance intensified because of military requirements during both world wars, leading to the development of thermal stress research, comfort studies, and bioclimatic methodologies. These are presented in the following four subsections.

2.1 Solutions for Different Climate Types

The standard texts on bioclimatic design describe the typical climates and the corresponding architectural design solutions that have been developed in response to these environmental conditions. The tropical climates are often divided into warm humid equatorial, hot dry desert, monsoon, or transition climates. Additionally, this classification can include cooler upland climates, humid maritime desert climates, and continental climates found in regions between the tropics. In sub-tropical and higher latitudes, the classification can include the climate of the Mediterranean Region with hot dry summers and cool wet winters, cool mid-latitude, and cold Arctic and Antarctic climates. An initial design solution is suggested for each of these climates, often derived from vernacular responses. Early references include Maxwell Fry and Jane Drew [8, 9]. Many standard texts such as [4, 5, Chap. 2] and [10, Chap. 6] start with this sequence before presenting more detailed methods. This approach can provide an initial indication of architectural solutions that respond to the local climate but have limitations. They usually indicate a single solution, though there may be equally effective alternatives. Also, they do not consider the transitions between different climate types. Another relevant factor is the difference between building types, as housing requires day and night comfort, while schools and offices are normally used by day.

2.2 Olgyay's Bioclimatic Chart

Victor Olgyay's Bioclimatic Chart [4, 5] relates the external climate conditions of temperature and humidity to the range of conditions that fall within the comfort zone. The chart also proposes a variation in the comfort zone for winter and summer seasons, an early recognition of "adaptive comfort". When external conditions of temperature and humidity are outside the comfort zone, the chart indicates the favorable modifications that can be achieved using three mechanisms: air movement, humidification, and solar radiation. The chart shows the intensity of solar radiation,

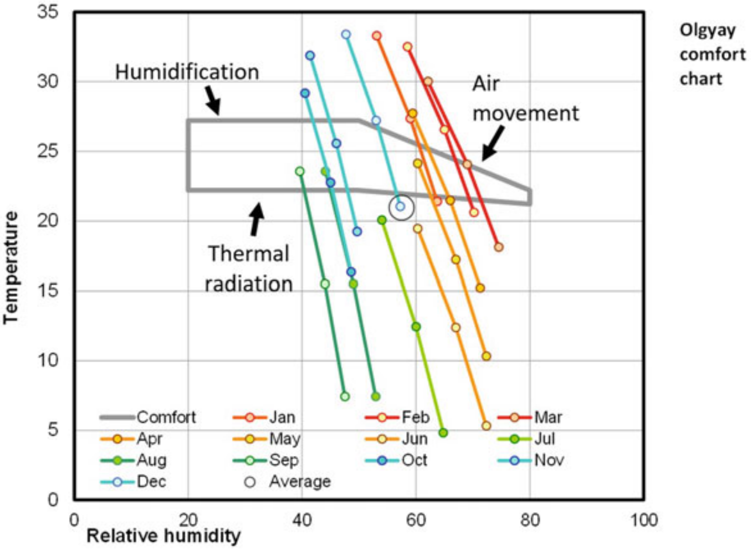

Fig. 1 Adaption of the Olgyay Bioclimatic Chart [4, 5] with SI units, with average monthly temperature and relative humidity for Catamarca, Argentina

the velocity of air movement, or the amount of water evaporated that is needed to achieve comfort.

These mechanisms only include direct impacts on the occupants (see Fig. 1). For example, the chart considers solar radiation on the body, but does not indicate the indirect effect of passive solar systems. These include the direct cooling effect of cross ventilation with air movement over the body but do not include the night cooling achieved with selective ventilation.

The text includes a clear recognition that, in addition to the strategies included, other resources are needed to achieve comfort. Olgyay's book [4, 5] provides extensive guidance on the use of thermal inertia though this bioclimatic design resource does not appear in the chart. The book is influential, and even after 60 years, it is still in print.

2.3 Givoni's Bioclimatic Chart

Givoni [6] developed an update on Olgyay's Chart, incorporating three new strategies based on building performance rather than just direct physiological responses (see Fig. 2): thermal inertia, passive solar strategies, and selective ventilation.

Thermal inertia will reduce indoor temperature variation, which is especially useful in climates with a high diurnal range.

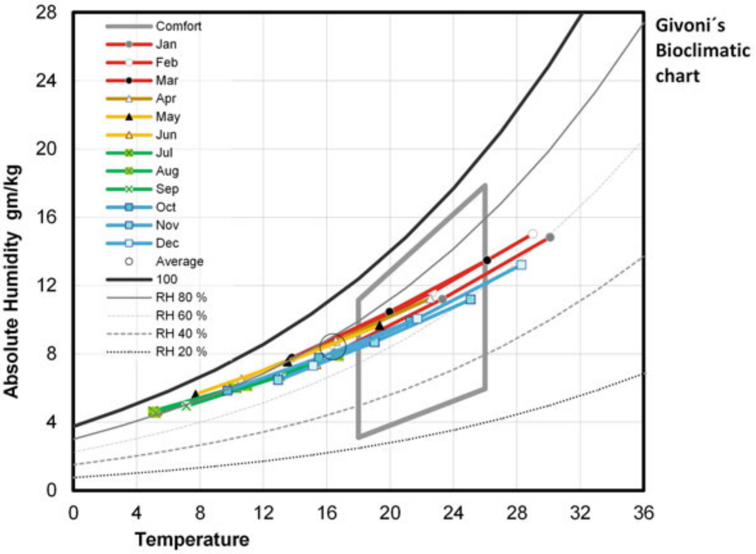

Fig. 2 Adaptation of Givoni's Bioclimatic Chart

The chart emphasizes the resources for hot climates though it is also effective in cool climates. Passive strategies such as direct solar gain increase indoor temperatures, though thermal inertia and insulation are needed to control temperature swings and conserve heat gains. The strategy of selective ventilation uses the favorable difference between indoor and outdoor air temperatures to improve indoor comfort, by opening and closing windows. When indoor temperatures are cool and outdoor temperatures are comfortable or warm, increased ventilation can warm the interior. Conversely, when indoor temperatures are hot at night but the outdoor temperature is comfortable or cool, ventilation can also improve comfort. Therefore, the psychrometric chart is used as a base for the analysis of climate concerning comfort and appropriate bioclimatic strategies applying a format with a horizontal temperature axis and a vertical absolute humidity axis, widely understood and used for air conditioning. The basic chart shows 16 strategies, although 5 are active systems: conventional heating, cooling, fan-assisted air movement, two-stage evaporative cooling, and dehumidification. Most of the strategies combine bioclimatic design resources.

2.4 Mahoney Tables

The Mahoney Tables [10, 11] were developed in response to one of the limitations of the basic climatic classification. This is illustrated by the case of West Africa where the climate varies gradually from a tropical warm humid equatorial climate on the coast to the fringe of the Sahara Desert to the north. In the two extremes, design solutions are clear with different bioclimatic strategies, but the problem remains of defining the changing design responses to the slow climatic variations as the latitude increases. Where is it necessary to change from a lightweight construction to components with high thermal inertia? Where is a change required from effective cross ventilation to limited air movement and protection from hot dusty winds? Where is the change needed from an open urban layout that promotes cooling breezes to a compact urban form to achieve protection from the sun and wind?

The Mahoney Tables offer a menu of design options that correspond to climate conditions based on the following analysis. Firstly, the annual average temperature is used to determine the comfort zone, directly responding to the adaptive comfort studies by [12] and [13]. The introduction of comfort limits for day and night is another innovation, recognizing that the daytime maximum requires a different range from the nighttime minimums. The average monthly maximum and minimum temperatures are then compared with these comfort zones, establishing the average comfort sensation, warm, cool, or neutral for night and day in each month. These comfort conditions are then compared to the climate, identifying the strategies needed for each month, called “Indicators”.

- Cross ventilation: essential if conditions are warm, relative humidity is high, and temperature swings are low.
- Cross ventilation: desirable if conditions are warm and humidity is high.
- Thermal inertia: needed when temperature swings are over 10 degrees.
- Thermal insulation: needed if day temperatures are cold.

Two additional indicators are used for situations where protection from heavy rain is needed, and where outdoor sleeping on the roof provides comfortable conditions in desert buildings with high inertia. The total number of months with each indicator is used to obtain the appropriate design recommendations in the final tables. The first table of recommendations provides initial design guidance for project layout, orientation, and spaces between buildings, the second provides detailed guidance on the thermal properties of walls and roofs and window design.

The systematic application of the Mahoney Tables can use spreadsheets or simple programs to transform the initial climatic data into a design guide. This automatic process avoids possible errors in the application to tell the designer *what* to do but does not allow the designer to follow the sequence and understand *why*. However, some limitations of the Mahoney Tables should be noted. They were developed in 1975 when computers were very limited for simulating alternatives and test results. They provide one design solution for each location but, in many cases, alternative bioclimatic resources can provide equally comfortable results.

2.5 *Climate Consultant*

Milne et al. [14] developed a tool based on Givoni's bioclimatic chart, presenting an advance, with additional bioclimatic strategies, using daily or hourly climate data rather than monthly means. Version 4 adds features such as graphic screens and an explanation of the psychrometric chart. It also automatically creates a list of design guidelines based on the attributes of each unique climate and then displays a sketch illustrating how each guideline applies. The chart indicates the percentage of time each design strategy can be used to improve comfort, providing the designer with a clear guide to the importance of each strategy.

3 Current Trends

In the half-century since the introduction of bioclimatic design methods with a systematic and scientific base, there have been several developments, some of which favor more energy-efficient and thermally comfortable projects and others that do not promote low-impact architecture. This section presents the most important of these influences.

3.1 *Rising Expectations*

Although poverty and the lack of physical and economic resources are still critical limitations in many regions of the world, large proportions of the population have benefited from improved conditions and expect continuing improvements in the quality of life. This includes better, larger, and more comfortable homes, easier travel, access to technology, and better diets, implying larger environmental impacts. In the residential sector, expectations of improved comfort may lead to an important increase in energy demand. Improved indoor conditions, better building envelopes, and more efficient environmental control installations will also further increase comfort expectations, narrowing the temperature range of acceptable conditions.

3.2 *Air Conditioning*

Modern air conditioning, introduced by Carrier in 1923 [15], was beginning to be used in the pre-war period in offices and industries where climate control was essential for productivity. In the post-war period, the use of air conditioning spread to the tropics in offices, clothing, and electronic industries, allowing Singapore, Hong Kong, Japan, and Korea to compete in world markets.

Rising expectations in the residential sector have also led to an increased and widespread demand for air conditioning in recent decades. This trend is a result of three factors: reduction in the cost of small A/C units, improvements in energy efficiency, and better access to electricity networks over the years, combined with the aforementioned rising expectations. However, the wider distribution of air conditioning units has additional consequences. As designers, users, and producers of buildings recognize the possibility of achieving comfort through artificial conditioning, there is less incentive to plan energy-efficient buildings through improved architectural design and construction.

3.3 Architectural Trends

Another factor related to rising expectations and increased dependence on air conditioning is the current trends in architectural design. These include the tendency to use larger glazed openings and reduce solar protection. The increased use of air conditioning also allows designers to ignore the consequences of undesirable orientations and less efficient building shapes. This is also related to the training of building professionals which still requires an additional emphasis on sustainable and energy-efficient design.

3.4 New Materials

Over the decades, there has also been progress in developing new materials and improvements for existing components. In this context, new technologies in glass production have introduced the possibility of lower costs and larger windows. At the same time, new technological advances allow glass with lower heat transfer, through low transmission and heat-reflecting glass. However, in many regions, the adoption of double-glazing and heat-reflecting treatments have been slow. New and improved insulating materials have also been developed such as glass wool, mineral wool, and plastic foam in sheets or sprayed.

These low-density materials allow very low thermal transmission at accessible prices, allowing a sustained improvement in thermal performance over time with stricter building regulations in many developed countries, though in most of Latin America and other warmer climates, thermal performance standards are still not mandatory.

Another development is the tendency toward lightweight building systems with limited thermal inertia. Even when improved thermal insulation is incorporated, in many cases, these low-heat capacity buildings will need artificial conditioning for thermal comfort, especially in climates with significant outdoor daily temperature swings.

3.5 Simulation and Computer Tools

The use of computers allows new tools to evaluate building performance, dimension heating and cooling installations, and simulate thermal comfort. These tools include highly complex programs to simulate energy performance, thermal comfort, and environmental impacts over a typical year, using detailed virtual building models and hourly climate data. However, these programs do not provide useful output at the early stages of the design process. Another advance is the availability of detailed climatic data for most cities of the world, often with hourly measurements. Where ground-based meteorological data is not available, for example, solar radiation intensity and remote sensing provide design data [16, 17].

4 Comfort Triangles

Comfort Triangles [18] were developed as a bioclimatic design tool to overcome some of the limitations of the existing graphic and numerical methods presented in previous sections. The bioclimatic design resources and techniques modify the external environment to obtain more favorable indoor conditions. These are the result of three changes in the outdoor temperature variations shown in Fig. 3.

- The incorporation of thermal mass in the building envelope tends to reduce the indoor temperature variation (1) as a proportion of the outdoor temperature swing (2).
- It also produces a time lag or delays in the indoor peak temperature with respect to the outdoor maximum (3).
- The internal heat sources and solar gains combined with thermal insulation produce an increase in the indoor average temperature compared to the outdoor average (4).

The result of this combination can often achieve indoor comfort without the need for heating or cooling using conventional energy.

These modifications depend on complex combinations of thermal insulation, thermal mass, selective and cross ventilation, internal and solar heat gains, and other bioclimatic design resources. The indoor conditions usually depend on the modification of external conditions several hours beforehand. For example, the thermal inertia of a roof delays the peak outdoor impact on indoor conditions for several hours. A passive solar system such as direct gain or an unventilated mass wall stores solar heat received during the day to provide indoor comfort at night up to 8 hours later, while night ventilation cools the interior to improve comfort the following morning.

However, conventional tools compare the external environmental conditions with comfort requirements at the same time, without considering the time delay induced by the building. Another limitation of the charts is the impact of internal gains and metabolic heat of the occupants which will modify the indoor climate. The Comfort

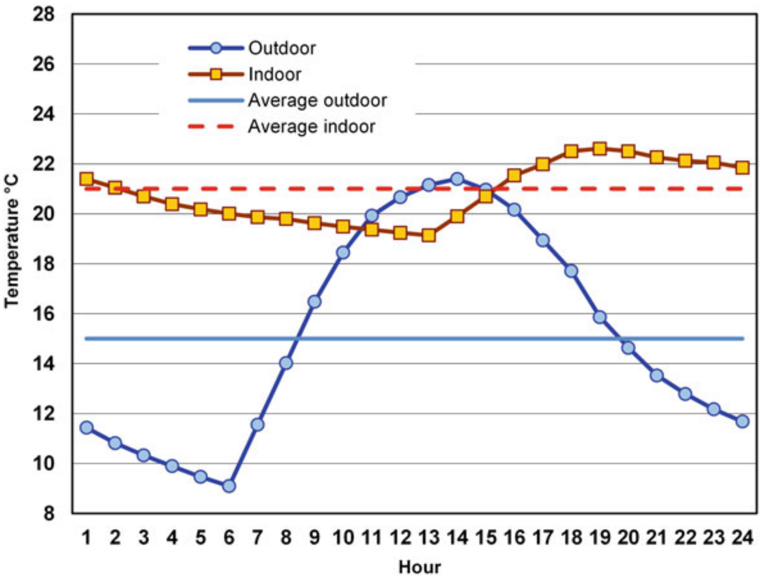

Fig. 3 Indoor and outdoor temperatures showing the modification achieved by bioclimatic design resources, (1) and (2) show reductions in temperature swing, (3) shows the difference between average outdoor and indoor temperature, while (4) shows the time lag or delay between outdoor and indoor peaks

Triangles, therefore, analyze daily outdoor temperature swings and average daily temperatures, comparing these with the range of conditions that provide comfort, assisting in the selection of appropriate bioclimatic design resources, Table 1.

The dynamic daily variations of indoor and outdoor temperatures are defined on the triangle chart by the average temperature and the range, the difference between the maximum and minimum daily temperature. The average temperature is shown on the horizontal scale, while the range is shown on the vertical scale. A point on the scale corresponding to these two values represents the daily temperature variation. This is compared to the triangle which shows the combinations of conditions for thermal comfort. The truncated triangle shows that, as average temperatures reach the maximum and minimum comfort limit, the comfort range is reduced. The basic triangle is for typical sedentary activity, but alternative triangles indicate comfort conditions for higher levels of metabolic activity, outdoor comfort (where expectations are different), and rest at night.

An example explains the tool, using selected temperature measurements from records made every 15 min over 1 year in a living room and outdoors in the shade, made in Buenos Aires. Figure 4 shows the average of hourly temperature measurements over a 5-day period, comparing an indoor space with passive bioclimatic strategies with simultaneous outdoor measurements, and presents the comfort triangles for the same data, showing the modifications due to building design, materi-

Table 1 Bioclimatic strategies and their effect on average indoor temperature and range

N°	Code	Bioclimatic strategies	Impact on average indoor temperature	Impact on the indoor temperature range	Type of strategy
1	VC	Cross ventilation	Lower temperature	No change in range	Design, adjustable
2	IT	Thermal inertia	No change	Reduce indoor range	Design, fixed
3	GD	Internal gains by day	Higher average	Increase range	User control
4	GN	Internal gains by night	Lower average	Reduce range	User control
5	GS	Solar gains	Higher average	Higher indoor range	Design
6	VD	Daytime ventilation	Higher average	Higher range	Adjustable
7	VN	Nighttime ventilation	Lower average	Lower range	Adjustable
8	AT	Thermal insulation	Increase in average	No change in range	Design, fixed
9	SP	Solar protection	Average unchanged	Without change	Design, adjustable
10	HU	Humidification	Lower temperature	Reduction in range	Adjustable

Average: Daily average of hourly temperatures
Range: Temperature swing: difference between the maximum and minimum daily temperatures
Strategy: Adjustable or constant, all require building design responses
GD: Internal gains by day: for example, classrooms, offices
GN: Internal gains by night: for example, bedrooms

als, and user adjustments such as changes in ventilation and resulting improvements in indoor comfort. The naturally conditioned room was occupied without artificial heating or cooling.

The impact of bioclimatic design strategies changes when they are combined in the same building [19, 20]. The following examples show some of the key combinations:

- Solar gains will increase the internal temperature range as well as the average indoor temperature, so thermal inertia must be incorporated to control the indoor temperature range. Improved thermal insulation in the building envelope will also enhance the effect of solar gains.
- Selective ventilation by day will take advantage of higher midday temperatures to warm the interior when the difference is favorable, enhanced by thermal inertia and insulation. Similarly, night ventilation will lower the indoor temperature, but thermal inertia will maintain cooler indoor conditions till the next day.
- Humidification will lower the temperature, but the increased humidity can reduce the temperature range. This strategy will be more effective when the temperature range is higher, as high-temperature ranges are usually associated with low humidity. Moderate ventilation may also be required to avoid an accumulation of humid air.

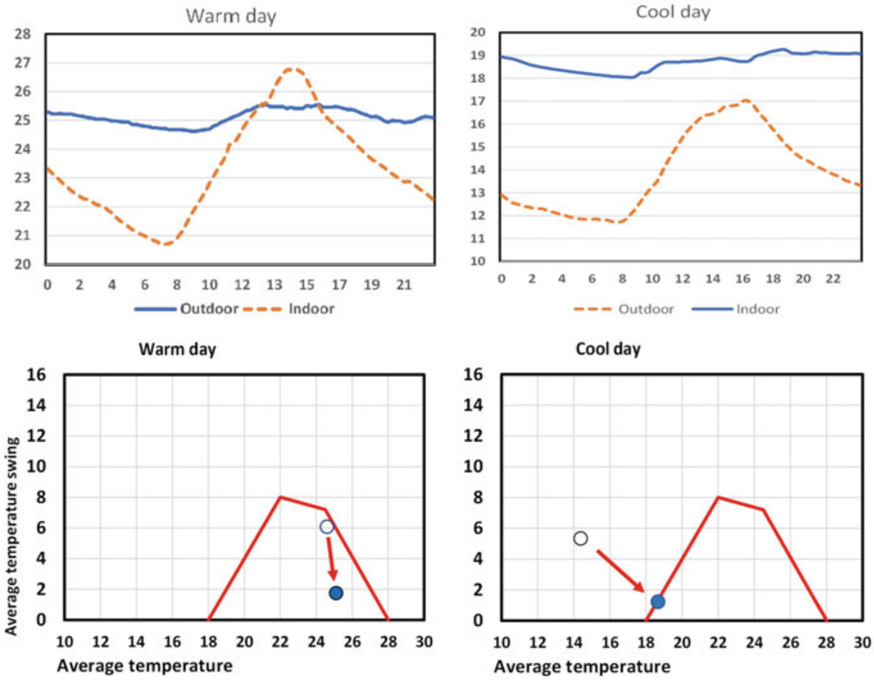

Fig. 4 Indoor and outdoor temperatures on warm and cool days in the same space, average hourly values (above), and average daily swings with average temperatures in the comfort triangles (below)

The application of different strategies may also vary in different months of the year as temperatures change. For example, cross ventilation needs openings in opposing facades, a permanent design feature, but it is assumed that openings will be closed as temperatures drop below 26°C. Solar gains will be useful when temperatures drop below 20°C, but protection will be needed as temperatures increase. In both cases, the fixed design and construction can facilitate the effectiveness of these bioclimatic strategies, but occupants will operate windows and adjust shading to avoid discomfort according to the changing conditions.

Other strategies may remain constant depending on the building type. For example, there will be limited internal gains by day and night in housing in all months of the year, while in schools and offices, higher internal gains will correspond to daytime hours. Figure 5 shows the modification achieved with different bioclimatic design strategies to improve comfort, and the actual modification in practice as a result of a combination of strategies.

The Comfort Triangles have been incorporated into an electronic spreadsheet, with results for three different climates shown in Figs. 6, 7, and 8. The spreadsheet has the following characteristics:

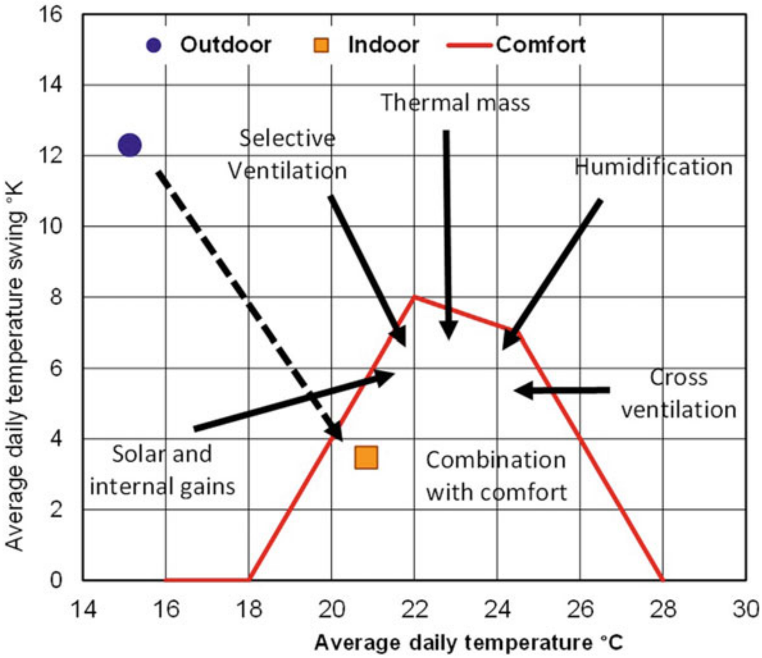

Fig. 5 The comfort triangle in red shows the combination of average temperature and daily swing that provides comfort. The black arrows show a modification of the external conditions to approach or achieve comfort, while the dotted arrow shows the actual modification with a combination of strategies, with the same data as Fig. 2

- The spreadsheet includes a climatic database of over 600 locations in Latin America and selected cities from other regions of the world.
- Once the location is selected from pull-down lists, the Comfort Triangle is shown according to country and region, and the activity level is chosen.
- The bioclimatic design resources can then be shown and the level of application is selected with different levels. For example, cross ventilation can be "high", "medium", "low", or "without movement", and solar gains can be "without sun", "limited", "average", or "high".
- The spreadsheet also calculates the number of months within or close to the comfort zone.

The impact of each bioclimatic design strategy can be changed, increased, or moderated when it is combined with others in the same building. The application of different strategies may also vary in different months of the year as temperatures change. For example, cross ventilation needs openings in opposing facades, a permanent design feature, but it is assumed that openings will be closed as temperatures drop below 25°C. Solar gains will be useful when temperatures drop below 20°C, but protection may be needed as temperatures increase above 25°C, especially with

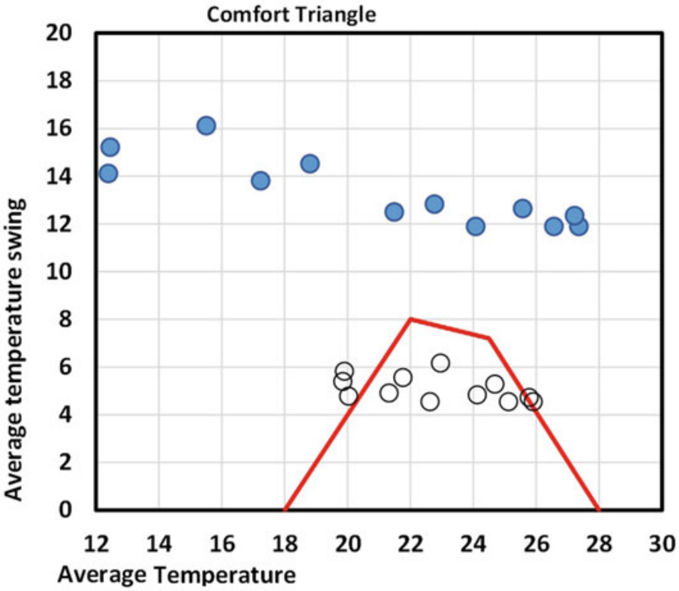

Fig. 6 Comfort Triangle and strategies in a hot dry climate: Catamarca, Argentina, latitude 28°S. Strategies include thermal inertia, limited internal gains, winter solar gains, and summer night ventilation, with good thermal insulation. An appropriate combination of strategies achieves comfort without heating or cooling for average conditions for 9 months of the year

larger glazed openings. In both cases, the fixed design and construction will allow the implementation of bioclimatic strategies, but occupants will operate windows for ventilation and adjustable shading to achieve comfort according to changing conditions.

The incorporation of the Comfort Triangles in an electronic spreadsheet demonstrates the following characteristics and advantages:

- At the initial stages of the design process, basic monthly climate data can be used to select and test design resources. Over 600 locations in Latin America and selected cities from other regions of the world have been incorporated into the database and tested.
- Comfort conditions are also variable depending on activity level and the time of day.
- The bioclimatic design resources have different levels or scales of application, for example, cross ventilation can be “high”, “medium”, “low”, or “without movement”, and solar gains can be “without sun”, “limited”, “average”, or “high”.
- The visualization also shows the number of months within or close to the comfort zone. This shows the contribution of design to achieving very low energy demand and zero emissions.

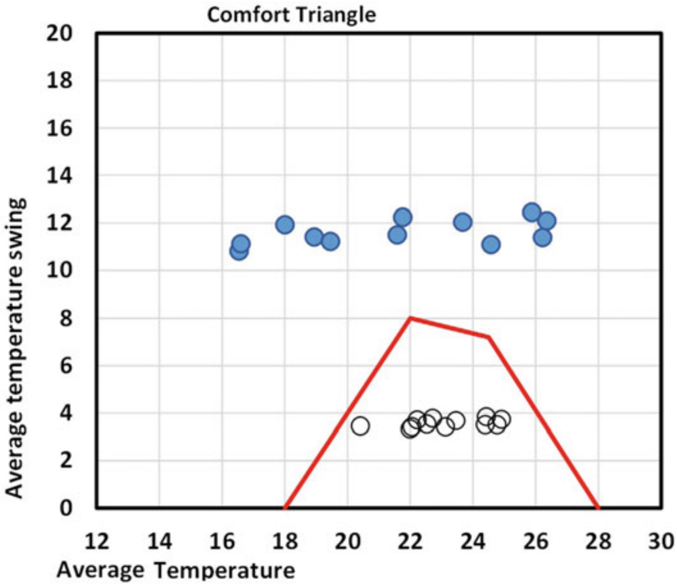

Fig. 7 Comfort Triangle and strategies in a sub-tropical warm humid: Posadas, Argentina, latitude 27°S. Strategies include cross ventilation, limited solar and internal gains, moderate thermal mass, and good thermal insulation

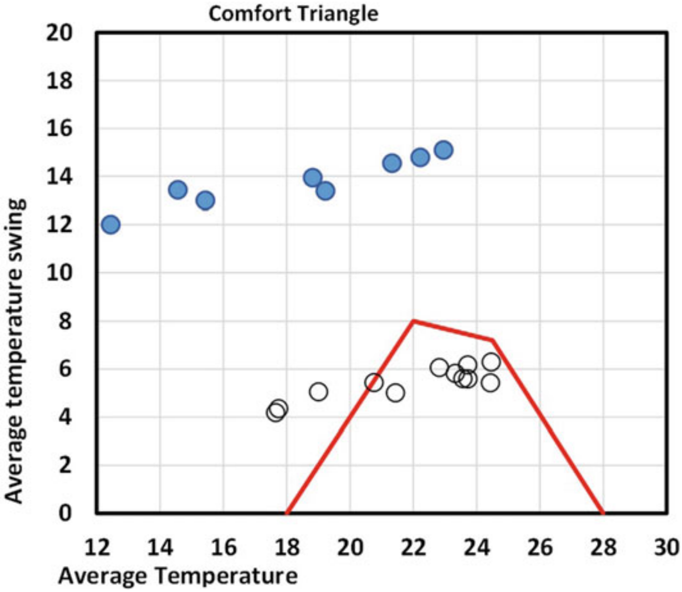

Fig. 8 Comfort Triangle and strategies in a cool mid-latitude climate: Bahia Blanca, latitude 38°S. Strategies include high thermal mass, solar gains, and very good thermal insulation. Partial heating required in 3–4 months

The modifications achieved in naturally conditioned buildings in different climates were measured in Ecuador, Mexico, Costa Rica, Chile, and Argentina and plotted the Comfort Triangles, to show the effect of different bioclimatic design resources on the urban and architectural scale [21]. Examples include lightweight and heavyweight construction, houses with passive solar systems, earth construction, and different levels of thermal insulation. The measured modifications were also compared with simulations of indoor temperature.

The application of Comfort Triangles in the design process was also tested in a wide range of climates in postgraduate courses in Argentina, Ecuador, Mexico, and Paraguay, with measurements to confirm the effective modification of indoor conditions in existing naturally conditioned buildings. An evaluation in Mexico [22] analyzes the application in different regions of the country with comparisons with the Mahoney Tables and Givoni's Bioclimatic Chart. The spreadsheet [23] includes the Olgyay and Givoni graphs, as well as adaptive comfort charts.

5 Conclusions

The Comfort Triangles offer a different way to visualize the favorable modification of external conditions using passive bioclimatic strategies. They emphasize the importance of variable thermal performance with heat flows in and out of the building envelope. This relates to many bioclimatic strategies which modify the temperature over time:

- Passive solar design uses solar absorption by day, the transmission of heat for storage in the materials, and restitution of heat to indoor spaces as temperatures decline in the evening and night.
- Daytime ventilation can increase indoor temperatures, taking advantage of warmer midday conditions, while night ventilation can be used for cooling.
- Variable internal gains during the daily cycle also contribute to temperature variations over time that can contribute to improving indoor comfort.

In cold climates, with heat losses for many months of the year, the design strategies of compact form, well-insulated building envelopes, and the incorporation of solar gains are easy to understand and incorporate in the design. The management of variable and dynamically changing conditions, typical of cool, temperate, and warmer climates are more difficult for designers to understand and apply during the design process.

This parallels other new challenges that designers face, such as mitigation and response to climate change, global warming, and low-impact materials. This change requires the development of new capacities and tools in a rapidly changing world both in education and in professional practice. The Comfort Triangles were developed to contribute to this challenge.

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