Application of a bioclimatic tool for the hygrothermal analysis of a historic building in Lima-Peru

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Abstract. The main objective of this paper is to know and analyze the bioclimatic strategies that would be present in colonial residential architecture in Lima. The knowledge and use of systems to achieve certain climate conditions in ancient buildings made of sun-dried bricks and thatch, both in open and closed spaces. We consider that through trial-and-error approaches, techniques would have been developed to obtain indoor comfort considering local climate conditions, available materials and other cultural conditions. Temperature, humidity and air speed measurements were taken three times a day during four days in some places of the building. Givoni’s building bioclimatic chart is used to analyze the performance of the places measured. On the one hand, different climate conditions were recorded in each patio and would be the result of its physical characteristics. In addition, differences between the performance of social spaces and private rooms were observed due to different ventilation strategies.

1. Introduction
Several authors [1, 2] argue that traditional or vernacular architecture responds to the climate of its surroundings. Based on this premise, some research studies bioclimatic design techniques in vernacular architecture in countries such as Spain [1] Brazil [3] and India [4] in order to learn and rescue the bioclimatic strategies used. In our local environment, there is the study on Las teatinas de Lima, where the author seeks to rescue their possibilities of use in contemporary architecture, through their energetic-environmental analysis [5]. The usefulness of the analysis of Lima’s colonial buildings is based on the need to apply passive design strategies to contribute to the reduction of the ever-increasing energy consumption by achieving an adequate level of thermal comfort. It is worth mentioning that we refer to traditional architecture, which is the one that has been produced by the old builders and not the one produced by the population in a spontaneous way, i.e., vernacular architecture. In this paper we will analyze the Casa de Aliaga, which was built in the 16th century, rebuilt after the earthquake of 1746 and partially remodeled in the 19th century.

As previously stated, the techniques and materials used in Lima’s architecture were “the result of a process of adaptation and response to the environment” [6]. It would have responded not only to the technical possibilities and materials available but also to the presence of earthquakes, user needs, among others. We consider that Lima’s colonial residential architecture has included some bioclimatic strategies as part of its design. Although it may be difficult to speak of a comprehensive system, it is
possible that some aspects that contribute to thermal comfort have been successfully managed.

2. Methodology
The field work consisted in collecting graphic information of the building, as well as the materials used in its construction. On the other hand, temperature, humidity and air speed measurements were taken three times a day for 4 days, in March, September and October 2017 (table 1).

| Table 1. Dates on which measurements were taken. |
|-----------------------------------------------|
| Day 1 | Day 2 | Day 3 | Day 4 |
| Summer | Mar-23 | Mar-24 | Mar-25 | Mar-26 |
| Winter | Sep-24 | Set-30 | Oct-01 | Oct-07 |

An anemometer with a humidity and air speed sensor was used. A temperature sensor was added by placing it inside a black sphere to measure operating temperature. Measurements were taken at approximately 7:00, 15:00 and 19:00. Points were chosen to cover different types of spaces. The first group corresponds to open and intermediate spaces such as patios and the gallery in the second patio and a second group corresponds to the indoor spaces such as rooms inside the house. With the information from the measurements and from SENAMHI’s Campo de Marte station, the building bioclimatic charts (BBCC) are prepared on the basis of the psychometric chart and using Excel, in order to know the behavior of the building in both seasons. Here it has been recognized in which zones the environmental conditions of the measured spaces are located and their behavior throughout the three measurements taken. By using the BBCC as a framework, we observe what bioclimatic strategies should be considered in the design to compensate for those moments in which the environmental conditions are not in the comfort zone. From this, and after having enough planimetric information of each building, we can analyze and evaluate if there are any bioclimatic considerations present in the design.

3. Climate diagnosis and thermal comfort
The comfort zone is that zone defined by the range of climate conditions within which most people do not feel thermal discomfort, neither hot nor cold [7]. Among the different tools developed to analyze climate conditions, Givoni’s psychrometric chart has been chosen for this case as it provides more alternatives to obtain thermal comfort in the design of buildings [8].

We have considered the corrections made for buildings designed to be naturally ventilated (our case) and in a warm country where users tend to accept ranges of daily climate variation greater than users accustomed to air-conditioned buildings. At this point Givoni makes the distinction between developed and developing countries [7]. Although we consider this distinction to be very general and elementary, we rescue it for being consistent with the notions of adaptive comfort considered more recently by Bragger [9]. Therefore, we assume it for our analysis.

3.1. Climate in the city of Lima
Lima has its historic center about 7 km from the coast, it is 110 m above sea level and 12° south latitude. In the Köppen classification, Lima’s climate is considered arid warm BKh (B=dry climate, W=desert and h=hot). The graphs of temperature and relative humidity in 2017 (figure 1) show that the average temperature that year ranged from 16°C to 25°C, reaching a maximum of 30.7 °C and a minimum of 14 °C. In March, the temperature averaged 25°C although it reached a maximum of 31°C. In the months of September and October, the average temperature is 15°C and 16 °C, dropping to a minimum of 14 °C. The average relative humidity in March is 77% with a maximum of 96%, while in September and October it averages 87% and 85%, reaching 96% and 95%, respectively. Figure 2 shows that the predominant annual wind direction comes from the south with maximum speeds from 5.5 to 7.9 m/s. A second direction with that same intensity but with less presence is the SSE direction. These data have been worked with an online climate tool from the University of Berkeley [10]. The climate tool also
shows that in March the wind direction is mainly from the south, with greater strength in the afternoons (5.5 to 7.9 m/s). At 15:00 (as in the morning), there is a second direction of moderate and strong winds (3.3 to 5.5 m/s) from the SSW and at 18:00 strong winds (5.5 to 7.9 m/s) from the SSE. Therefore, the south direction is the most predominant wind direction in summer. In the cold months all three hours have strong winds (5.5 to 7.9 m/s). September shows some particularities: hours the strong winds from the south prevail and then moderate winds from the west; at the end of the afternoon the strong winds from the south prevail and the wind from the SSE is less present. In October, the wind from the south prevails at all times.

**Figure 1.** Graphs of the maximum, mean maximum, mean, mean minimum, and minimum monthly averages of temperature and relative humidity in Lima in 2017.

**Figure 2.** Graph of the annual wind direction [10].

We can conclude from the graphs that the wind from the south prevails in Lima. The climate data presented correspond to 2017 for temperature and relative humidity and from 1961 to 2017 for winds (the Center for the Built Environment Climate Tool Web processes data from those years taken from the Jorge Chavez Airport station). Lima has grown and has also become densified presenting conditions different from those existing centuries ago when the house under study was built. Undoubtedly, this may have generated changes in wind speed.

Fortunately, the climate in Lima in earlier times has been the subject of historical research.
Meteorological records date back to 1753, carried out by cosmographer. Later, from 1791 to 1794, the *Mercurio Peruano* published daily records of temperature measurements made at 12:00 in degrees Reaumur and Fahrenheit with a mercury thermometer [11]. Likewise, Hipólito Unanue made measurements at the end of the 18th century and published them [12].

Figure 3 (left) show climate information for the years 1791, 1799 and 2017 with data from 12:00. Data corresponding to 1791 are already presented in °C [11], while data corresponding to 1799 are published in degrees Reaumur and have been converted to Celsius scale with the conversion factor 1.25. From both cases, the highest and the lowest measurement of each month has been considered. For the year 2017, data published online by SENAHMI have been used, taking the highest and the lowest measurement among those taken at 12:00 of each month. Minimum and maximum temperatures at 12:00 in the summer months have increased in the last centuries. Today, midday summer temperatures are 3.1 °C higher than those in the 18th century. In addition, temperature at 12:00 is not the highest of the day. Even the current summer minimum temperatures are also up to 1.8 °C above the minimum temperatures of other years. On the other hand, in winter the curve of the 2017 measurements is up to approximately 2 °C below the minimum temperatures of the curves of the 18th century. Therefore, when the house was built in colonial times, Lima had a milder climate; less hot in summer and less cold in winter. In addition to these differences in temperatures, other differences must be taken into account:

- Environmental conditions have changed: The presence of cars can create heat islands, there is less water in the Rímac River, there are more buildings in the area which presence can change the wind behavior, etc.
- The change of use from housing to museums and offices leads to the use of work equipment that produces heat. Likewise, doors and windows are not used in the same way and frequency as they should at the beginning.
- The SENAMHI station from which data were obtained, is 3.1 km away from the Main Square.
- 2017 was an exceptionally hot year due to the El Niño phenomenon.

### 3.2. Picture of Givoni’s building bioclimatic chart (BBCC)

Temperature and relative humidity data are plotted on the BBCC. The dry bulb temperature on the X-axis and the absolute humidity on the Y-axis. The relative humidity expressed as the percentage of humidity with respect to the maximum humidity that the air can support for a given temperature is represented by the curves. A total of fourteen zones organized around the comfort and permissible comfort zone ranging from 20 °C to 27 °C and from 20% to 80% relative humidity are established.

However, assuming Givoni’s proposal, a first extension of the upper limit to 29 °C after adding 2 °C is considered to evaluate our summer. For the winter, we accept from 18 °C with calm wind. Thus, figure 3 (right) shows the comfort zone (CZ) which includes what some authors also call the permissible comfort zone, the comfort zones accepted for our case for the winter and summer months (WCZ - SCZ). In addition to the summer and winter comfort zones, we are interested in the three neighboring zones where temperature and relative humidity values of Lima are located. These zones are:

- The internal heat gain zone (IHGZ) in red. This is a zone of moderate cold in which the energy missing to achieve comfort can be obtained by heat generated by occupants, lighting and equipment.
- The zone that achieves comfort with cooling high thermal mass (CHTMZ) is yellow.
- The zone that achieves comfort with cooling natural or mechanical ventilation (CNMVZ) is green.

The psychrometric diagram shows in March, climate conditions are partially located in the summer comfort zone and also in the zone that requires natural or mechanical ventilation. In September and October, the climate conditions are mainly located in the zone that needs internal gains to reach the comfort zone. It is therefore of interest to determine whether the design of the house considers bioclimatic strategies for optimal ventilation to reduce the high and constant relative humidity and the sensation of heat in summer. The health problems caused by humidity were already known in the past, as Hipólito Unanue mentioned in the early 19th century [12]. Moreover, the World Health Organization recognizes that relative humidities with very high (as in the case of Lima) or very low percentages are harmful to health [13].
3.3. Typology of colonial residence in Lima: Casa de Aliaga

It is located half a block from the Main Square on the side street of the Government Palace. Its construction dates from the 16th century. Following the techniques and materials used during the colony, stone is used for the foundation, sun-dried brick walls on the first level and thatch on the second level, both coated with mortar, wooden roofs and mud cake. It was rebuilt after the earthquake of 1746 and also intervened in the 19th century. It is partially located on archaeological remains and, therefore, its main rooms are developed on a second level. This particularity produces an alteration to the usual typology of Lima’s colonial patio house, placing its first patio on the second level. The front of the house forms an approximate angle of 50 °C with the NS axis and would be favorable for wind catchment if we keep in mind that Givoni refers that when the angle formed by the wind direction and the front of the house does not exceed 60°, there is an appropriate wind catchment (figure 4).

3.3.1 Open and intermediate spaces

Here we have two open spaces: patio 1 and patio 2, and an intermediate space: the gallery in patio 2. patio 1 is located near the entrance. It is rectangular in shape, approximately 14 m long by 4.65 m wide and has 5 m high walls. It does not have galleries. Patio 2 has galleries on all its fronts. Almost square in shape, it is approximately 7.87 m long by 5.60 m wide and 8.70 m high. This is a space with a green area, a tree and a fountain. The gallery is a roofed space, it is approximately 2.50 m wide and 4.65 m high and is located on a higher level than patio 2.

3.3.2 Indoor spaces

Measurements were taken in four rooms: the French Room and the Hallway, the social area of the house, and the Blue Room and the Bedroom, both more private spaces. The French Room, the living room of the house is 13 m x 6 m; the Hallway is a longitudinal space 2.90 m wide; the private rooms are 5 m and 6 m on each side with no low windows and ventilation through teatinas (high windows located on the roof of houses to provide light and ventilation to inner rooms). The Blue Room has a SO facing teatina and the Bedroom has a SE facing teatina. The rooms of the house are approximately 4.70 m high, the teatinas reach 5.80 m of inner height and the farola (a type of skylight, polygonal in shape, which horizontal surfaces are usually opaque, and the vertical surfaces are translucent and versatile) of the Hallway reaches 6.70 m of inner height.

4. Results and analyses of Casa de Aliaga

4.1. Results at open and intermediate spaces

Graphs in figure 5 show the patios and delimit in magenta color the area that receives sun at 12:00, at the solstices and equinoxes. Patio 1 receives more hours of sunlight than patio 2 which only receives
partial sunlight at midday and always in a smaller percentage of its area than patio 1 and therefore can store less heat. Our measurements show that both patios and the gallery have higher temperatures than those made by SENAMHI. The graphs show the behavior of these spaces in both summer and winter (figure 6). In summer, climate conditions in open and intermediate spaces are located far from the comfort zone. They are located in the cooling natural and mechanical ventilation zone (CNMVZ) to achieve the comfort zone. The relative humidity in these spaces is always below 70% and decreases as

Figure 4. Plan and sectional drawings of patio 1 (above) and patio 2 (below). In yellow the open spaces, in green the intermediate space and in light blue the indoor spaces.

Figure 5. Plan drawing plotting in magenta boxes the area with sunlight in the patios at 12:00 at solstices and equinoxes.
the temperature rises during the day, with patio 1 having the lowest relative humidity and it shows a higher temperature than the other two spaces (patio 2 and gallery) that have a similar behavior. The temperature in these spaces reaches up to 4 °C higher than that recorded by SENAMHI. Air currents have only been recorded in patio 1 with speeds reaching up to 1 m/s at the end of the afternoon. With the recorded speeds we could not say that the CZ is achieved. Givoni refers that in previous studies it was accepted that with air speeds of 1.6 m/s and temperatures up to 31 °C it was considered that the CZ was achieved; however, in our case the speeds are lower.

In winter, the building has a favorable performance. SENAMHI data are located in the IHGZ (internal heat gain zone) and only in the afternoon it is located on the limit with the winter (WCZ) comfort zone (CZ). However, the patios and gallery achieve the comfort zone for several hours. Patio 1 is warmer than patio 2; it is located in the CZ more hours of the day and only early in the day and late in the afternoon in the WCZ. While patio 2 and the gallery have a similar behavior, being located for more time in the winter CZ and for less time in the CZ. Patio 1 can have 1.9 °C in the first measurement more than patio 2, up to 1.5 °C more in the second measurement and 0.8 °C more in the third measurement. Also, either due to its lower height and/or its proximity to the front, only patio 1 records air currents. In summer it reaches 0.6 m/s and in winter 0.9 m/s.

Figure 6. Building bioclimatic chart (BBCC) with data from patio 1, patio 2 and gallery in summer. Only one day is shown but the graphs are representative of the four days.

4.2. Results at indoor spaces

Figure 7 shows the climate behavior in hot days. The indoor spaces replicate indoors what we have outdoors in both seasons. However, we have found a behavior with some differences between social and private spaces. In summer, at the beginning of the day, the climate conditions are located at the upper limit of the SCZ. During most of the day they are in the zone requiring cooling natural and mechanical ventilation and air currents were only recorded in the French Room and the Blue Room. The French
Room gains more heat during the morning, but also loses it more quickly during the afternoon. Only in the late afternoon it records air currents with speeds ranging from 1 to 1.3 m/s. Towards the end of the afternoon and at night, the French Room would be located in the CZ. The Hallway shows varied behavior, but has less temperature variation during the day than the French Room. Air currents were not recorded in any of the days. The Blue Room and the Bedroom have similar behaviors and keep the heat gained better. Air currents were only recorded in the Blue Room, which reached 1.3 m/s by the end of the afternoon. This contributes to improve the climate conditions and the space approaches the CZ. No air currents were recorded in the Bedroom.

In the cold months, Casa de Aliaga has a favorable performance, being located several hours of the day in the CZ. SENAHMI data are located in the IHGZ, but the data from the measurements made in the indoor spaces are located in the WCZ and in the CZ with indoor temperatures 3 °C above the outdoor temperature. The private spaces are 1 °C warmer than the social spaces at the end of the afternoon. This is favorable for private spaces that need to be warm at night during the cold months. This will be favored by the absence of low windows and for having teatinas. Their results are similar, although the French Room at the end of the afternoon is less comfortable than the other three spaces. This Room has cross ventilation and wind currents of 0.3 m/s were recorded in the second measurement and 0.4 m/s in the third measurement. The Blue Room records air currents of lower speed than in summer, which is favorable. The Bedroom also recorded calm and weak air currents that would not alter the comfort recorded.

![Building bioclimatic chart (BBCC) of indoor spaces in summer. Only one day is shown, but the graphs represent the four days measured.](image)

**Figure 7.** Building bioclimatic chart (BBCC) of indoor spaces in summer. Only one day is shown, but the graphs represent the four days measured.

It is noted that the walls of the house largely meet the national standard EM.110 [15]. The 40 cm wall is made of two 15 cm panels made of thatch each with plastering on the sides of 4 cm of mud with straw and 1 cm of gypsum plaster. The thermal transmittance (U) of the wall is calculated using the data
in table 2. It shows the thermal resistances: $R_{si}$ for the inner surface and $R_{so}$ for the outer surface, as well as wall materials data.

| Table 2. Data on conductivity coefficient (k) and thickness of the materials that make up the wall [15, 16]. |
|----------------------------------|----------------------------------|----------------------------------|
| k (W/m°C) | THICKNESS (m) | W/m²°C |
| Rsi | 0.06 | |
| Gypsum plaster | 0.40 | 0.01 |
| Mud with straw | 0.09 | 0.04 |
| Thatch panel | 0.17 | 0.15 |
| Rs | 0.11 | |

The U of the walls of the house is 0.348 W/m²°C, while the standard allows a maximum of 2.36 W/m²°C. The U of the roof and floor has not been worked to avoid inaccuracies since there is no exact data available. On the one hand, in the last decades, reinforcement beams have been added to the roof and its covering has varied cement layers in some areas. On the other hand, the existence of archaeological remains means that the house museum sometimes has only one level and sometimes two levels. In this way, the house is partially located on the second level and partially on the archaeological remains and the first level cannot be accessed.

5. Conclusions

Different climate conditions observed in each patio would correspond to their different physical characteristics. Patio 1, with smaller height and no galleries, receives more solar exposure not only on the floor but on the walls too. It therefore manages to gain and store more heat during the day and then return it at night so it is a comfortable place in winter. It is hardly comfortable during a summer day since it records air currents only in the afternoons. Patio 2 has less floor area with solar exposure and its walls are protected by the galleries. It does not present air currents, but it gains less heat due to its spatial configuration. Some additional elements contribute to cool the space such as vegetation, a tree that provides shade and a fountain. It is a comfortable place in summer.

No major difference is found in the performance of the gallery and patio 2. The indoor spaces of the house show one criterion for the organization of the social area and another criterion for the private area. The social area is located between the two patios and receives ventilation directly from them. In the private zone, on the other hand, the rooms are grouped together and do not have a free area nearby, capturing air through their teatinas. Thus, there are different ventilation strategies: the social area has cross ventilation and farolas for hot air evacuation (chimney effect) while the private area has zenithal ventilation through its teatinas. These different strategies give rise to differences in the climate conditions of the private and social areas, contributing to their comfort in winter.

The lack of comfort in summer can be attributed to factors such as the change of use of the house to a museum that restricts and limits the use of doors and windows. On the other hand, the strategies used previously corresponded to a different climate than the current one. Also, in order to have an actual reading of the behavior of the house with respect to the outdoor climate, it would be optimal to have the outdoor climate conditions close to the house. The analysis of the house shows the knowledge of the importance of having cross ventilation. This has been proposed either with openings on opposite sides of a room or capturing air through teatinas located in complementary directions. The latter may suggest a joint work of the teatinas for constant wind capture. Farolas are also used for hot air evacuation.

On the other hand, there are issues that need to be investigated, such as the comfort range that allows us to set our own limits for the psychrometric diagram.

Finally, the idea of having in the same building free spaces that provide in one case the optimal conditions for its use in summer and in the other case the conditions for its use in winter could be
appropriate for contemporary collective housing buildings where more than one open space is available.

Acknowledgment
This work was sponsored by the Peruvian National Council for Science and Technology (CONCYTEC) under the contract No. 04-2018-FONDECYT-BM-IADT-MU.

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