Learning from the Past
Environmental aspects of the traditional architecture of Arequipa, Peru

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ABSTRACT: Arequipa, an UNESCO World Cultural Heritage site, is a good example of how the harmonious interaction between climate, local materials, construction techniques and traditions can generate architectural solutions with positive values in terms of quality of life and cultural identity. The paper discusses under an environmental prism and with the help of scientific instruments the architectural patterns of the city. On-site measurements and energy computer simulations have been used to study the effect of climate factors on the adaptation process of the European models to a new natural surroundings and cultural context. The research has been focused on the study of traditional typologies by using a methodology in which environmental and technological aspects are related. The traditional architecture of Arequipa had never been analyzed before using real measures and computer science technologies. The research contributes objective and novel data about the advantages of vernacular solutions in light of a modern environmentally aware evaluation.

Keywords: traditional architecture, ecological concept, design strategies, comfort, Arequipa

INTRODUCTION
What we perceive around us as cities with cultural or historical interest are not simply a group of picturesque buildings that create a more or less colourful environment. They are a set of systems with which the buildings interact with the environment around them using the limited resources available in a specific moment or geographic place [1].

Traditional architecture has offered numerous solutions of urban planning and architectonical composition perfectly adapted to the natural surrounding due to a secular wisdom and an accumulated experience [2]. Nevertheless, most of the studies on architectural and urban heritage have been focused in formal or compositional aspects. In limited occasions references to the relation with the environmental had been explored.

Fortunately, this tendency has been changing in the last years. More and more studies have been done about traditional architecture in many places of the world that try to determine energy performance and integration to their environment, while techniques and modern equipments are used [3]. Currently, traditional concepts and techniques are being considered by many architects and city planners as a source of knowledge and inspiration to design more energy efficient solutions and to conserve land-surface resources and natural environments [4].

Research has been published about Arequipa’s urban pattern and building typologies [5], but the relationships between Arequipa’s buildings and climate have barely been studied. Furthermore, the few references to the environment mainly focus on qualitative descriptions. A lack of quantitative analysis and on site measurements make difficult to produce an accurate evaluation of the supposed benefits of its vernacular models. This paper seeks to contribute new data about the traditional dwellings in light of a modern environmental evaluation.

METHODOLOGY
Site characteristics such as climate and geographical factors have been studied to understand the natural surroundings. Taking into account these aspects, the urban form and constructive elements have been analysed to evaluate their physical behaviour (thermal mass, illumination, etc.) and psychological interpretation (comfort, indoor-outdoor relationship, etc.).

Two different procedures have been used, on site measurements of the environmental parameters and computer programs for energy modelling. We focused on a typological study, analysing the inner structure of the traditional dwellings and its connections and modes of operation. Once these data were obtained and properly analyzed, we established possible interrelations to determine conditions of habitability and comfort.
CLIMATE DATA
The values used in the climate analysis have been obtained from a TMY data file for Arequipa and processed with Ecotect. The city is located at a high altitude, 2329 m above sea level, and a low latitude 16º 24' 10'' South. These two geographical variables have opposite effects in the climate of the city. Due to the altitude, the temperature quickly descends after sunset to values near 0º C. Nevertheless, the proximity to the Equator produces high levels of solar radiation and as a consequence, the temperature quickly ascends after sunrise. As a result, the daily temperature swing is frequently above 15º, but the annual variation of the monthly averages is very low, less than 2º C (Fig. 1).

Most of the rainfall takes place between February and March. The rest of the year the relative humidity is below 40% and the sky cloudless.

GEOGRAPHICAL FACTORS
Arequipa is located in a fertile valley, in the western side of the Andes mountain range. Next to this area, there is an immense desert that extends by the Pacific coast. During the Spanish colonization Arequipa was an important food production and communications center. Currently it also occupies a strategic location with the bordering countries of Bolivia and Chile.

It is located in a very seismic zone due to the tectonic interaction of the South American and Nazca plates. The city is surrounded by three volcanoes, the Chachani 6096 m high, the Misti 5853 m high and Pichu Pichu, 5425 m high. The Misti is still active and has erupted several times in the last 600 years.

The history of the city has been affected by the processes of destruction and urban renovation caused by terrible earthquakes that has encouraged the progressive adaptation of the European models to the local environment. As a consequence, Arequipa as we know today has some elements of XVIIIth century and most of them from the XIXth century.

URBAN LAYOUT
The Spanish city was founded in 1540 by mandate of Francisco Pizarro. The city follows the urban model proposed by the Laws of the Indies that basically consists of a reticular pattern articulated from a main square. Following this model, 911 cities were constructed in America until 1810 [6].

The original layout consists of a grid formed by 7x7 blocks that occupy an area of 875 meters in South North direction and 850 meters in the East West (Fig. 2). The width of the streets is 10.5 meters. The layout was oriented parallel to the Chili river and diagonally to the contours, rotated 20º to the north. This way water evacuation was facilitated, since there was a slope in the two directions of streets.

SOLAR ACCESS OF THE URBAN LAYOUT
In order to discuss the solar access of the urban layout of Arequipa we have followed a methodology that we presented in the 2008 PLEA Conference [7]. The average time in shade of the four possible facade orientations of the urban grid was calculated using Ecotect and figure 3 shows the results obtained in three different orientations of the urban layout: north-south (0º), rotated 22.5º and 45º.

Figure 1: Monthly diurnal averages: temperature, direct and diffuse solar radiation.

Figure 2: Map of Arequipa.

Figure 3: The effect of changing the orientation on the isolation of the streets.
In the case of the north-south layout, the North facade receives sunlight during most of the year, particularly from March to October. Only from November to January this orientation remains frequently in shade. The East-West facades are exposed to the sun an average of 50% all year.

In contrast, when the urban layout is rotated in relation to the sun's axis the isolation of the four facades is more equilibrated. With a 45º rotation, the North facade receives less sun in June, but in December receives an average of more than 50% of the day. On the other hand, the SE facade now has more than the E facade, having a maximum value of 80%. In the same way the incidence of the sun in the NW diminishes as compared to the W.

As a consequence, the isolation increases in the morning and is reduced in the evening compared to the north-south orientation. This can be positive because it contributes to warm the spaces quicker during the morning from the cold night temperatures. Furthermore, the probability that all the facades receive isolation any day of the year is increased. This way, it is possible to reduce the effect known as "cold wall", by which the walls that do not receive solar radiation always remain cold increasing discomfort by asymmetric radiation.

**Dwellings Typology**
The Spanish tradition of regulating the activities through courtyards was quickly adopted in the city because most of the activities could be done outdoors, due to the mildness of the climate. The existence of an Inca precedent in which spaces were organized around a central space called “Cancha” also contributed to this (Fig. 4).

The predominant dwelling typology consists of a courtyard building organized around a central space or succession of spaces connected through hallways. The first open space is the most important. It is communicated with the outside through an entrance hallway. This space serves as a connection with the public space and holds the main functions of the house; hall, writing-desk, dining room and dormitories. The dining room communicates through open verandas with the rear space, occupied by an orchard.

The rooms located around the courtyard have a reduced span, usually below four meters. These spaces have lateral communications around the patio, working as a corridor. As a result, most of the spaces are connected to the courtyard and the houses have a strong indoor-outdoor relationship (Fig. 5).

**Constructive System**
A volcanic stone known as “sillar” is the most commonly used construction material. The walls are formed by two rows of sillar polished to the outside and coarse towards the interior. The space between both is filled up with small stones, lime, pieces of brick, etc. The total width of the wall varies between 0.9 and 1.2 meters (Fig. 6).
ANALYSIS OF THE WINDOWS

The design of windows is a complex process in which decisions are taken during the design stage that critically affect habitability and energy performance of the buildings. Large windows allow more daylight into a space, but they may also allow excessive heat gains or losses. As a result, the combined effect of daylight and temperature must be considered to adequately select the window size [8].

To determine the influence of the design of windows in the energy consumption, we have used the software Parasol. This tool permits to calculate the cooling and heating loads based on the direction, dimension of the glazed surface, thermal mass and ventilation. Figure 7 presents energy loads as a function of the orientation of a well sealed space (0.5 ach) with high thermal mass, and the window-to-wall ratio for a value from 80% to 10%. A double-glazed window with clear glass has been considered.

![Figure 7: Energy loads as a function of the window-to-wall ratio.](image)

Results show that the reduction of glazed surfaces in any orientation reduces the heat loads during both day and night. It is thus recommended to reduce the windows to a value that guarantees an adequate illumination level but also reducing the energy demand. To study this we have used a method based on configuration factors, that extends the radiation properties of diffuse sources to luminous exitance of all kinds of building surfaces irrespective of their shape [9,10]. We have assumed that all the materials involved in the calculations assimilate to a perfect diffuser or Lambertian body. Moreover, the winds predominate all year from the NE during the night and first hours in the morning, and from W-SW in the evening. Therefore, the increase of ventilation during the morning could reduce the energy loads on east wall.

We have selected for daylighting analysis the House of El Moral, one of the most representative and better conserved buildings of the Arequipa baroque period (Fig. 10). The illumination values have been calculated for the winter and summer solstices, for overcast and clear skies. For each one of these cases we have studied the illumination at 9:00, 12:00 and 15:00 solar time.

Results indicate that the illumination decreases quickly as we move away perpendicularly from the window (Fig. 8) and even in these narrow spaces, values descend below 150 lux. These results have been validated with measurements.

![Figure 8: Illumination of the House of El Moral, June 12th, clear sky.](image)

It is necessary to indicate, that although in Arequipa the solar radiation is intense and the sky usually clear, the available daylight in vertical surfaces of the windows is not as high as we would have expected [11]. The overcast sky method indicates that as the distance to the Equator decreases, the altitude of the sun increases and daylight increases in vertical surfaces. Nevertheless for clear skies (predominant in the region), the daylight levels begin to descend when the relation between the greater solar altitude and the increase of the angle of incidence on vertical surfaces is unfavourable (Fig. 9). These values have been calculated using a sky model [12], that defines the vertical illumination (in lux) for clear sky based on the azimuth (Φ) and the height (θ), by the equation below.

\[
Ev = 4000 x θ^{1.3} + 12000 x \sin^{0.3}θ x \cos^{1.3}θ x [(2 + \cosΦ) / (3 - \cosΦ)]
\]

And in the case of overcast sky, similar to the CIE model, using the following equation.

\[
Ev = 8500 x \sinθ
\]
Figure 9: Illumination as a function of the latitude, equinox 12:00 hours. Overcast sky (above) and clear sky (below).

STUDY OF THE COURTYARDS

The energy captured by the surfaces of the courtyards has a great influence on the thermal behaviour of the indoor spaces [13]. To analyze this question we used a methodology that defines the courtyard forms using two parameters, R1 and R2 [14]. R1 is the relationship between the perimeter P and the height H (P/H) and R2 is the relation between the width W and the length L, (W/L). R1 ranges from 1 to 10 in whole number increments. The value 1 is generated in the deepest courtyards and 10 in those with the lowest walls around them. R2 ranges from 0.1 to 1. The value of 1 is produced when they are square and 0.1 with the maximum difference between width and length. It is assumed that the longest sides of the courtyards are oriented to the north and south.

In order to compare the incidence of the solar radiation in all the combinations of R1 and R2, altogether 100 cases, the total area of the courtyard walls has been considered constant and equal to 484 m². For a maximum depth (R1=1) and difference between W and L (R2=0.1), it is 1x10 m and 22 m high. Figure 10 shows the total annual value obtained for each case using Ecotect.

The heavy and thick silla r walls of the courtyards act like a thermal regulator of the high daily swing. During the day, the walls store the solar energy which is re-emitted after sunset, helping to warm the spaces when the night temperatures are below the comfort level. This means that it is advisable that the courtyard surfaces be exposed to the maximum possible amount of isolation.

For larger values of R1 (less depth) the absorption of solar energy is obviously greater. This absorption is more significant for values of R1 between 1 and 8. After this value the reduction of the height of the courtyard has less influence on the absorption of energy. Regarding the relation between width and length (R2), there are not large variations in proportions near the courtyard. Only for values of R2 between 0.1 and 0.2 is a significant absorption of energy observed.

ON-SITE MEASUREMENTS AND COMFORT LEVEL

Data loggers have been placed in the main office of the Architectural Association of Arequipa to take real measurements of environmental parameters (Fig. 11).

Results indicate (Fig. 12), that the indoor spaces have almost constant temperatures during the day and night, around 22 °C. At night, the measured temperature in the open spaces (loggers 1, 4 and 5) decreases several degrees with respect to the interior space. This decrease becomes more than five degrees when no cover exists (logger 4). During the day, a remarkable increase of temperature only takes place in the courtyards when no shading is provided. The inner surface temperature of the
walls have been measured with an infrared thermometer (PCE-888), also registering very stable values, with a maximum around 24 °C. Measurements indicate that the RH remains around 50% during the daily cycle.

Fanger’s method has been used to analyze the human response under these parameters and determine the satisfaction level of the users. We used the software Comfort, which process the equation of thermal balance automatically. The predicted percentage of unsatisfied in the indoor spaces is far below 10% (5.5 %), indicating thermal satisfaction with the space.

CONCLUSION
For this latitude and for these proportions of space, the most appropriate orientation for the urban layout to ensure that the walls in all directions have the most solar absorption is 45°. The SW wall, which is the most unfavourable wall in this orientation, receives solar radiation an average of 20% of the day from May to July.

It is recommendable that the courtyard walls absorb solar energy because they can regulate the low night temperatures, due to their great thickness and thermal inertia. It is deduced that values of R1 (P/H) above 8 and R2 (W/L) values above 0.2 have little influence in the absorption of energy.

The illumination level decreases very quickly as we distance ourselves perpendicularly to the facades, frequently registering values below 150 lux towards the back of the spaces. As a consequence, vertical windows, designed in the traditional manner, are more indicated than horizontal windows, since they favour a greater penetration of illumination. On the other hand, it is advisable to use the daylight that the direct solar radiation provides, which is specially intense in the city. The use of horizontal reflection elements such as light-shelves or blinds are therefore advisable. They do not significantly reduce sky light [15].

The measurements taken on site indicate that the houses of Arequipa provide spaces in which a very satisfactory level of well-being can be achieved. In the analysed house, the predicted percentage of dissatisfaction using Fanger’s method is only 5.5%.

Results can be useful in the development of contemporary architecture respectful of local values.

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REFERENCES