International Scientific Journal
Journal of Environmental Science
http://environment.scientific-journal.com/

Courtyard Building a thermal and daylight regulator in hot and arid regions. A case study

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***Abstract*—This paper investigates in indoor thermal and luminous environments of the existing courtyard buildings in an arid area, in order to identify daylighting strategies and thermal comfort conditions in this type of building. As Biskra town is situated in the hot and dry region of Algeria and facing a hot and intense radiation, drives us to seek a balance between thermal and luminous environments. During summer and winter seasons, monitoring campaigns have been conducted to collect air temperature and illuminance levels data using a digital monitoring instrument; these on-site measurements intend to assess courtyard impact on it adjacent spaces under clear sky conditions. A Special attention based on courtyard building's architecture of different morphologies and periods such as: traditional, colonial, post-colonial and contemporary samples. The selection of relevant samples morphologies can reveal many strategies on climate adaptation under local conditions. The important findings are related to the high potential for natural lighting and thermal control that courtyard building offer, and later, discovered the relationship between the morphological indicators and the qualities of thermal and luminous environments of adjacent spaces, in addition, courtyard remains more effective in controlling, regulating and homogenizing the daylight. The trilogies (Indoor spaces/outdoor/courtyard) are interacting in systemic ways for enhanced building's thermal and luminous performances and solve the dilemma between daylighting and protecting the building from hot sunlight in arid regions.**

Keywords*— Courtyard building; Daylighting; Thermal environment; On-site measurement; Arid climate.

I. Introduction

Buildings are responsible for an increasing energy use and greenhouse gas emissions. An alternative approach to the way the buildings are designed is needed to improve the environmental performance of buildings and minimize their electricity consumption [8]. Courtyard building is one of the oldest architectural forms, dates back at least 5,000 years and take divers shapes in many regions of the world [2]. The earliest civilizations all had courtyards inside buildings [3]. Courtyards are special spaces that are outside yet almost inside [9]. Few architectural elements are more closely associated with comfort, protection, and security than the courtyard [3]; for all those considerations, we will investigate in courtyard buildings potential as an environmental sustainable morphology and an alternative solution to a new building design; a serene architecture, combined with the environment, taking into account landscape, climate, and local specificities [4].

Thermal and luminous environments influence user's comfort and building energy consumption [11]. However, the natural lighting system might not work independently facing a hot and intense solar radiation [8], which consequently causes overheating that disrupts thermal comfort. The assessment of existing introverted architecture will be useful in finding effective and valuable strategies adequate to thermal and luminous environments. Under a hot and dry climate conditions, most research subjects treat thermal and luminous comfort independently. This present research evaluates the overall effects of both daylight and thermal conditions in courtyard buildings and the role of the courtyard as a regulator of the indoor comfort conditions.

II. Presentation of the case study

The city of Biskra is located in the South-East of Algeria. Typical of Sahara town, it is characterized by a hot and dry climate most of the year with a short winter extending from December to February. See Table 1 [12].

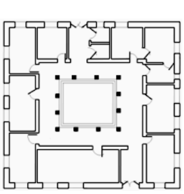
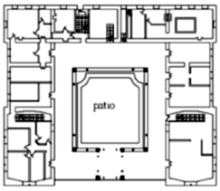
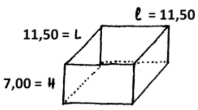
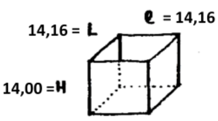
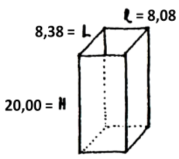
TABLE I. BISKRA'S DEMOGRAPHIC, GEOGRAPHIC AND CLIMATIC DATA.

Geographic data	Demographic data	Climatic data
Area: 21,671 km²	Population: 633,234 persons	Max. Temp: 42 °C in July
Latitude: 34 ° 51'01 "N	Density: 29 (per./km2)	Min. Temp:7 °C in January
Longitude: 5 ° 43'40"E Altitude: 120 m above sea level		Average annual Temp: 21.5 °C

III. Courtyard building samples

Cases study office buildings have been selected from a variety of typologies covering the entire architecture scenery (panorama) of Biskra: traditional, colonial, post-colonial and contemporary (Tab.2).

TABLE II. CONDITION OF COURTYARD BUILDING SAMPLES

Building samples		
Traditional (One-storey building)	***Colonial (Two-storey building)***	***Contemporary (Five-storey building)***
		
Building 1st floor	***Building 1st floor***	***Building 1st floor***
		
Courtyard type 1	***Courtyard type 2***	***Courtyard type 3***
		
Courtyard dimensions	***Courtyard dimensions***	***Courtyard dimensions***
		

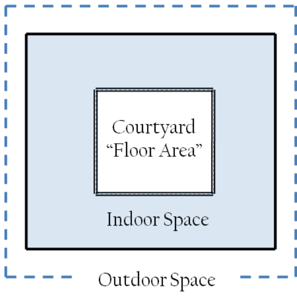
In order to analyze the influence of arid climate on daylight performance of the models, we have selected the city of Biskra as one of the hottest arid regions in the Algerian desert. Under clear sky condition, simulations were running for the same types of glazing: single glazed for both summer and winter seasons.

IV. Morphological analysis of Samples

A. *Global link analysis*

One of the most important features of a courtyard building is to possess not one but two vertical envelopes. The external one, separating the building from its external environment, the other internal, separates the interior spaces of the courtyard itself. If we stick to a purely topological approach to the plan, we find, in any courtyard building, the three successive zones included in each other [1].

Fig. 1. courtyard building surrounded areas



We are studying the connections between the courtyard and the interior spaces. Either a direct connection: it is made through the piercing internal envelope of the building, or an indirect link: it takes place through a space that comes to interfere between the two preceding ones, an intermediate space. We shall see that these may be galleries or small open spaces which, In any case, have a situation and intermediate qualities between the courtyard and the interior spaces [1].

B. *Hierarchy and Dimensional report*

Here we articulate the hierarchy of the center/periphery to assess the degree over, at least large, removal of interior spaces in relation to the courtyard. This makes it possible to extract, and this is the essential point, the position of the interior spaces in relation to the courtyard. This spatial hierarchy used to evaluate the thermal and luminous qualities of the areas with a direct impact of the courtyard, and those farthest often devoid of openings on the outside, which have a high thermal inertia compared to areas directly overlooking the courtyard [1].

TABLE III. CROSS-SECTION RELEVANT TO THE DEPTH OF THE THREE ZONES

P > E.I > I

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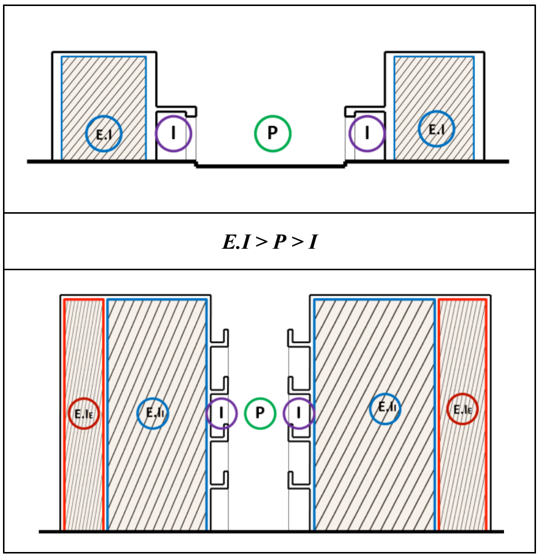


There are several ways of approaching these relationships; the first is to compare the courtyard surface with that of the interior spaces by possibly presenting this ratio as a percentage. A second way seems best to compare either of the surfaces; lengths are taken along a cross-section taken on the building, by comparing the respective depths of the three zones: the courtyard, intermediate or transitional shelter space and the indoor spaces (Table. 3).

V. Morphological indicators

The morphological indicators used in this research make it possible to evaluate the thermal and light environments from the characteristics of this building typology and its courtyard. According to the literature review, important ratios and morphological indices are exclusively chosen in relation to solar penetration and natural lighting.

A. Courtyard opening Ratio

The ratio of the courtyard opening is calculated from the relative amount of the courtyard area to the total surface area of the building. This report allows the understanding of: the courtyard size, its exposure to the solar ray and the daylighting penetration amount.

Opening Ratio = Courtyard area/Building floor area (1)

B. Opening/Wall Percentage

Opening/wall ratio affects both thermal and luminous environment. In the arid area, this ratio must be regulated in a way to allow daylighting without causing an overheat gains.

C. Aspect ratio

One of the important considerations of the effectiveness of a courtyard is the opening to the sky and it is of a paramount importance [9].

Aspect Ratio = (Courtyard floor area)^2/(average height of surrounding walls)^2 (m^2) (2)

The greater the Aspect Ratio, the larger is the exposure of the courtyard to the sky. This exposure allows warming by sunlight, cooling by radiation in the cool night, and some wind penetrations. (Aspect Ratio has been used in the design of natural lighting found in: Baker, Fanchiotti and steemers, 1993) [9].

Finally, the table 4 below summarizes the different ratios and indicators already mentioned above of our courtyard buildings samples.

TABLE IV. THE DIVERSE RATIOS OF THE SELECTED SAMPLES

	Sample 1	Sample 2	Sample 3
Opening Ratio	22%	15%	7%
Opening/Wall proportion	30%	25%	41%
Aspect Ratio	2,69	4,09	0,16

VI. Monitoring campaigns

A. Seasonal onsite measurements Protocol

The data collected during the summer and winter of 2016 under season's extreme conditions. These monitoring campaigns aim to explore and to assess the thermal and the luminous environment of the selected courtyard buildings. The work's step progress was:

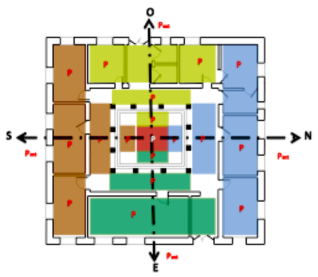
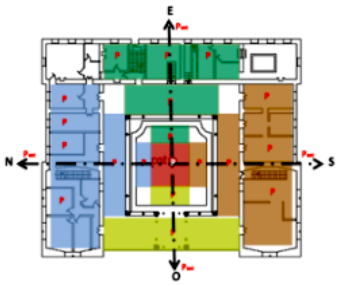
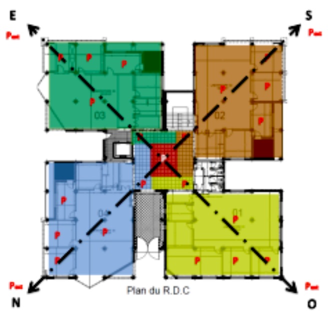
- Representative courtyard buildings samples selection from the case study area, old and new courtyard buildings with specific morphological characteristics.
- Record climate data *in situ* of air temperature and illuminance levels
- For all the survey, mobile measurements Records were conducted under clear sky conditions
- Monitoring days are chosen relatively to season's behavior, summer hottest days and winter coldest days
- Monitoring temporalities every two hours from 8 Am to 5 Pm to cover thermal and daylight variations

The monitoring period took 5 days from the 25 to 29 July 2016, it represents a part of the hot season. In winter, the period selected of the same duration went from February 1 to 5 of 2016. Noteworthy, courtyard buildings were occupied during the monitoring and all air conditioner, heating units, and artificial lighting turned off.

B. measurement stations

Courtyard buildings were divided into zones, where the center of each zone is a measurement point. The axes oriented North-South and East-West are significant to evaluate the courtyard impact on the thermal and the luminous environment of adjacent spaces (Tab.5). The choice of these measurement points will reveal some of the building's morphology factors that influence illumination and temperature variations and identify Physio-Morpho-Climatic interactions around courtyard building areas.

TABLE V. MEASUREMENT STATIONS LOCALISATION

Sample 1 (stations localization)	*Sample 2 (stations localization)*
	
Sample 3 (stations localization)	***Legend***
	Courtyard central zone Northern zone Eastern zone Southern zone Western zone - · - · · Variation Axis P Measurement point

The monitoring instrument used is an "LM/FI 20" a digital multifunction measurement instrument combined 4 in 1: anemometer, hygrometer, thermometer and light meter. It records values with high accuracy.

The on-site monitoring data obtained will be compared to several levels to provide more detail about thermal and the luminous environment and highlight courtyards impact on adjacent spaces micro-climate.

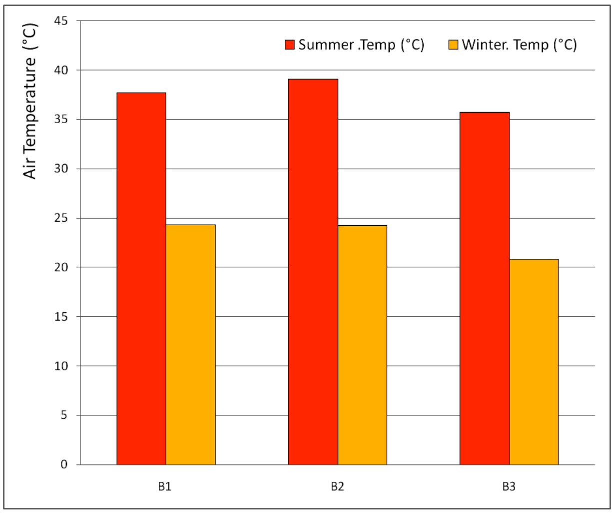
VII. Results analysis

A. Courtyard samples variations

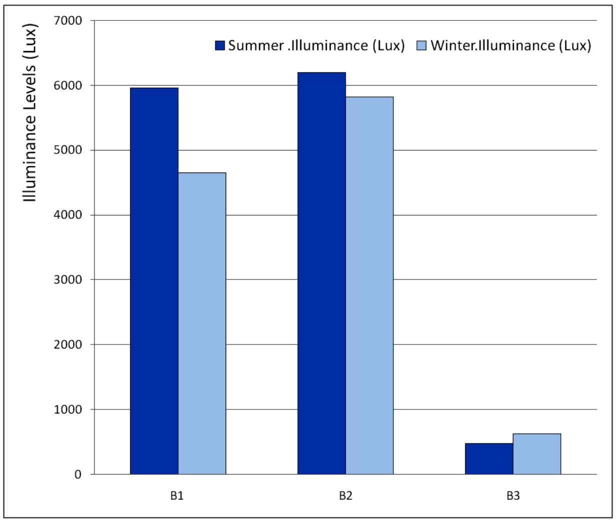
Firstly, compare the thermal and the luminous environments between the different courtyards samples. Results show a broad variation between courtyards behavior in buildings of single, double, and multi-storey (Fig. 2).

Fig. 2. Temperature/Illuminance levels variations

Courtyards seasonal air temperature variations (°C)



Courtyards seasonal Illuminance levels variations (Lux)

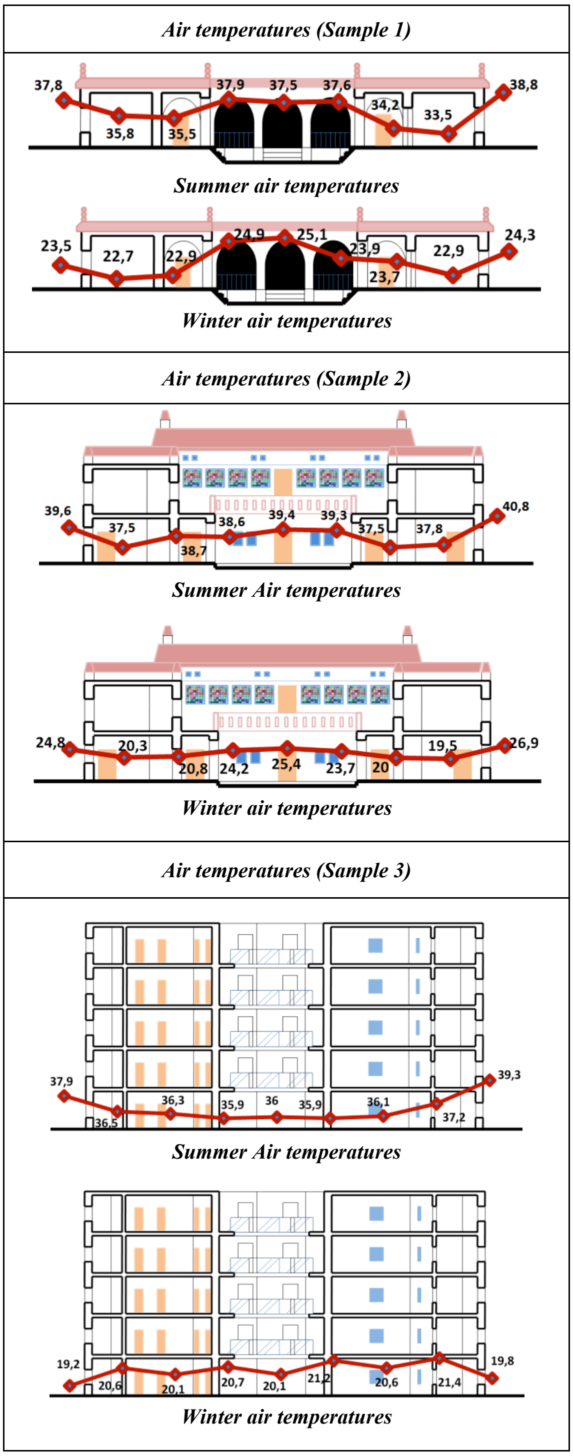


In relation to the air temperatures, the deeper is the courtyard the less exposed to summer sun and in consequence, it is less heated. Courtyard's depth performing well and cover most of the summer bioclimatic objectives. In a hand, depth decreases significantly temperatures but seems inadequate to warm the building in winter. Other, depth has negative impact on the luminous environment. Relative to our case, some exceptions revealed climate and morphological indicators which have a negative impact on daylighting such as: narrow courtyard opening, unilateral illuminated side.

B. Courtyard building samples variations

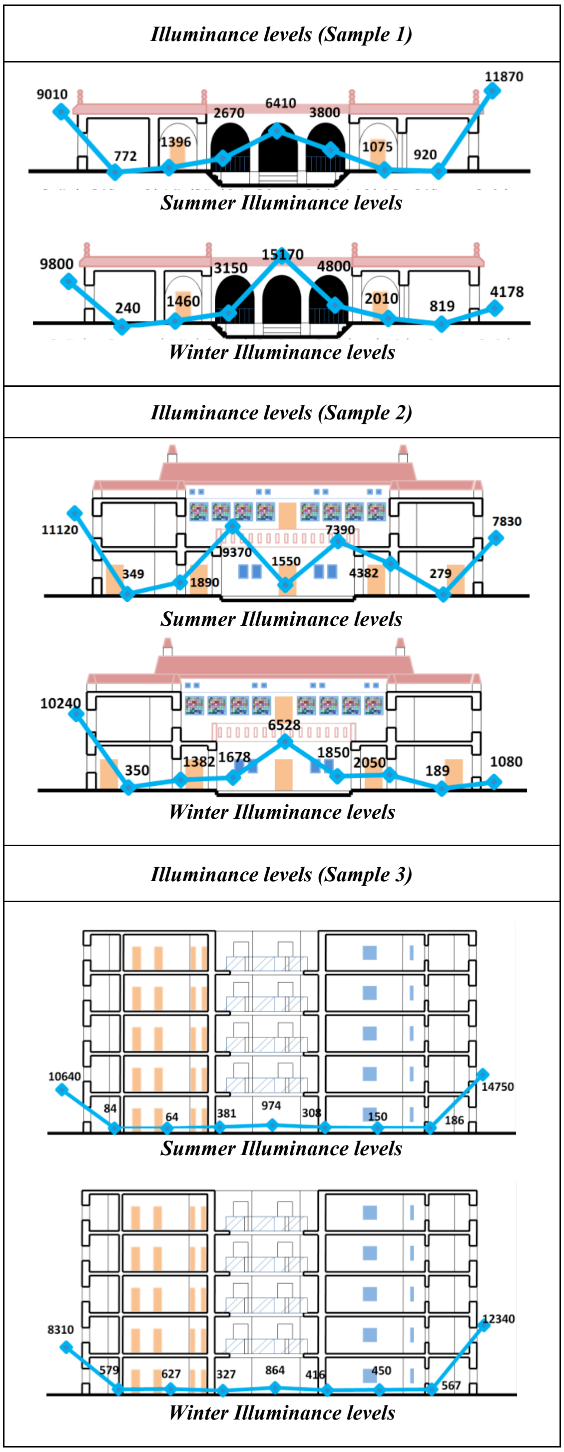
The obtained data measured after summer and winter monitoring campaign have been translated into graphs, then superposed on transversal sections along the axis. Later, discuss the temperature degree and illuminance level changes between the trilogies (courtyard/indoor spaces/outdoor) (Table. 6 and 7).

TABLE VI. TEMPERATURE VARIATIONS IN THE SELECTED SAMPLES (SUMMER/WINTER SEASONS)



The temperature degrees decrease, in a hierarchical way, from the outdoor to the indoor areas, especially from the courtyard side with intermediate spaces. Samples (1 and 3) respond almost to both summer and winter objectives because of the courtyard domination (P > E.I > I), while building 2 with elongate and interior space domination and a lowest south wall height seems not adapted to such arid area temperatures. Courtyard domination in building controls readily the thermal and luminous environments; it cools in summer and warms in winter buildings indoor spaces with different rungs.

TABLE VII. TEMPERATURE VARIATIONS IN THE SELECTED SAMPLES (SUMMER/WINTER SEASONS)



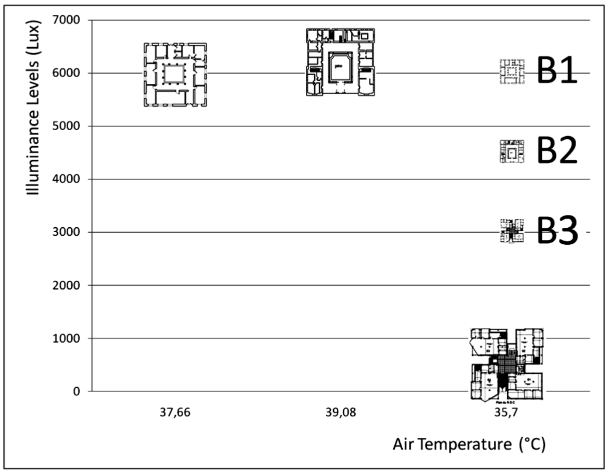
Depth and storey numbers decrease significantly the illuminance levels, daylighting looks more effective from the exterior than from the courtyard, but the advantages of illuminating by a courtyard is to provide more daylighting possibilities and protection by galleries, arches, awning, and corridors, opening positions and various sizes, orientation, vegetation and multi-courtyard shapes diversities. During the winter season, lighting naturally northern and eastern interior spaces couldn't be possible and enough without the presence of a courtyard, this last is a daylighting strategy of the first degree; it homogenized and increased illuminance levels even in an early and late daytime.

VIII. Thermal and daylight potential

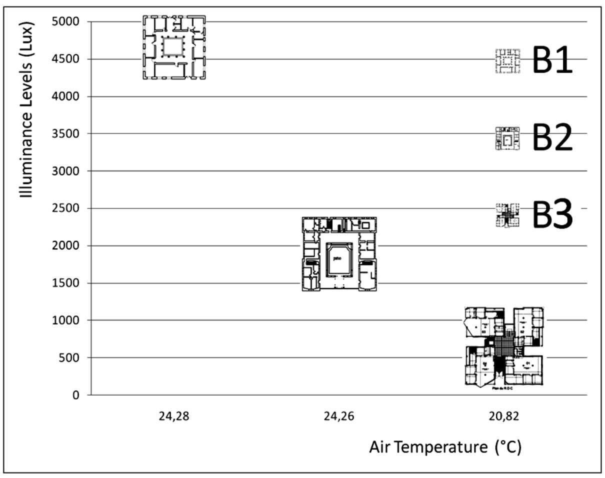
The cumulated courtyard buildings daily and seasonal means thermal and luminous annual potential has been established. Each sample performs differently; the morphological characteristics of buildings generate specific thermal and luminous environments for both summer and winter seasons (Fig. 3).

Fig. 3. Air temperature/Illuminance annual potential

Air *temperatures/Illuminance levels Summer potential*



Air temperatures/Illuminance levels Winter potential



During the winter season, buildings 1 and 2 with one and two-storey are the most enlightened and the more warmed as they are: the shallowest courtyard, the average opening ratio, and solar shadow index, with a high aspect ratio. Furthermore, building 3 negatively behave in winter and lost the ability to warm the building mostly characterized by: a deep courtyard and a narrow courtyard opening. During the summer season, building 3 is protected from overheated; their morphologic characteristic is the presence of intermediate spaces all around courtyard's walls. Building 2 exposition to outdoor area cause thermal cumulating in the indoor areas.

At this stage of development, we cannot prescribe a list of morphological parameters with quantitative precision, but proportional intervals within the limits of our research would be useful, two cases can be discussed:

1. Case one: the building of 1 to 2-storeys:

A square courtyard type with an average of opening ratio between 15% to 25%, an aspect ratio of 2 to 4, and a Solar Shadow index of 0,40 to 0,60, intermediate spaces especially in non-protected courtyard walls. Non-dense vegetation; climbing plants would be more useful. Roof protection and wall insulation to minimize heat transfers and strengthens the presence of the courtyard.

2. Case two: building with deep courtyards (5-storey and more): building with deep courtyard seems the ideal model for thermal comfort in summer. In order to increase its luminous quality, we recommended: an extroverted form and a greater opening ratio.

IX. Conclusion

The monitoring campaign was so rewarding, offer a number of information about daily and seasonal thermal and luminous environment in a courtyard building of hot and arid region. A relevant conclusion admits the use of courtyards in buildings as a bioclimatic strategy to solve the dilemma of illuminating and protecting passively buildings from sunlight. Also noted that courtyard offers more opportunities for both thermal and daylight environments through the interior and the exterior of the building's vertical surfaces.

Lighting the courtyard building from the outside can offer more quantitative and qualitative possibilities of illumination. But the advantage offered by the courtyard remains more effective in protecting, regulating and homogenizing the lighting environment in accordance with the thermal environment. The outdoor space or the exterior of the building is less protected and more exposed to climatic factors, especially the sun (source of natural light and heat).

Courtyard building's morphology parameters should be closely linked proportionate to the courtyard's geometric composition, which can be designed in a relative combination with important indicators such as: depth, diverse ratios, and courtyard type. The Global link proportions, which have a primordial control on the building's thermal and luminous environment using courtyards, Can be recommended in proportionately approach; like a deep rectangular courtyard, indoor space domination, and relatively reduced ratios.

In order to provide the most satisfied thermal and luminous environments according to morphological indicators needs a reversed analysis based on the prediction of building morphology from the optimum values of temperature, relative humidity, illuminance levels and wind speed. This can be possible only by rethinking morphology as a geometric proportions and ratios, which can be linked in the conception process with the extreme climate data parameters of a particular region.

Courtyard as a singular space can't behave without the other part of the building area; we found that the three important areas (Outdoor, indoor and courtyard areas) are interacting in a systemic ways. The three areas can offer a sufficient and homogeneous illuminance levels with sun protection with a component method based on many morphological ratios and climate factors to control daylighting in a building, the most important are: depth limitation, windows/wall ratio, orientation and of course a crucial building typology choice.

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