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Courtyards as a passive strategy in semi dry areas. Assessment of summer energy and thermal conditions in a refurbished school building

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A B S T R A C T

This paper presents the results of applying an experimental and theoretical model for the assessment of courtyards as a passive strategy for interior space conditioning. Two representative case studies, in a refurbished pre-elementary school building in Mendoza, Argentina, were selected for the analysis. The summer thermal behaviour was analysed through HOBO H08-003-02 data loggers installed in two courtyards and in the adjacent classrooms. The record included weather data every 15 min for 40 summer days. Finally, a dynamic simulation of the two case studies and theoretical cases was carried out. The objective was to assess the impact of different open space design variables on the energy consumption necessary for obtaining comfort conditions in the interior space (base temperature: 25 °C). Overall results indicate that, in semi dry areas with a large number of clear sky days, the shade condition of the courtyard is the strategy that most highly impacts the thermal and energy conditions in classrooms.

1. Introduction

Cities are environments where human activities converge. Nowadays, half of humanity lives in them. According to United Nations' projections, by the year 2025 there will be a 70% increase in urban population due to a rising birth rate and to changing economic structures that will result in abandonment of rural areas. Even if cities occupy only 2% of the planet surface, the urbanisation trend highly impacts ecosystems due to their high energy demand. In Argentina, the growth of cities over the last 40 years has increased energy demand from 4000 TOE (tonne of oil equivalent) to 10,000 TOE [1]. With the lowest share of renewable energy in Latin America, more than 90% of the energy in Argentina comes from fossil fuels.

Buildings constitute the biggest single contributors to anthropogenic climate change [2], accounting for 45% of world energy consumption and a similar share of greenhouse gas emissions. Buildings' energy consumption varies according to their morphology and technology, urban morphology and climate. In any case, 70% of total energy consumed in buildings is explained by the thermal conditioning of spaces.

Over the last century, building construction was characterised by an increasing dependence on conventional energy to reach appropriate thermal and lighting levels. From the architectural point of view, minimizing energy consumption in buildings implies combining habitat production with climatic and environmental particularities in order to achieve better interior comfort conditions. Traditionally, construction typologies associated to human needs — shelter, work and rest — were structured around an open space as an organisation centre, usually called courtyard. This courtyard regulates the architectural idea from which interior spaces are then distributed.

In traditional architecture, the courtyard has contributed, even if in a passive way, to improve local climate conditions and to create comfortable interior spaces. Several authors have demonstrated that temperatures in those interior spaces located next to courtyards can be lower than in exterior spaces [3–7]. These conclusions need to be qualified depending on climate, microclimate, building construction characteristics such as form, dimensions, courtyard orientation and amount of greenery to shade them.

It is important to take into account that incorrect design decisions can make courtyards less comfortable than open surroundings and can jeopardise comfort conditions in adjoining

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spaces. Therefore, many researchers have focused their attention on the influence of the courtyard's geometric and physical parameters on incoming solar radiation [8–10]. Bioclimatic conditioning of buildings relies on the design strategies associated with the form and material definition of the project and its immediate surroundings. The geometry of open spaces plays a decisive role in their thermal behaviour [11]. Specifically for dry climates, Ratti et al. [12] proposes a combination of:

(i) larger surface area and high thermal mass,
(ii) daylight via the courtyard and a shallow plan form,
(iii) narrow spaces for shade,

to create a context where low energy strategies are possible, limiting air conditioning loads. The outcome is that the surrounding microclimate can interact positively with interior spaces.

Improving microclimate conditions in courtyards in summer also depends on controlled dynamic shading. Olgyay and Olgyay [13] focus on the fact that the effectiveness of a shading device depends on the proportional success with which the shading device covers a given surface area during the overheated period without intercepting the sun's energy at unheated times.

In Mendoza, Argentina, a semi dry climate area, courtyards have been for centuries shaded with green 'roofs', particularly with bowers of grape-vines or creepers. This type of climbing plant has been used to prevent or reduce heat gain on massive surfaces that define the open space. Without any doubt, a green coat fulfils its sun protection function. However, the difference from any other protection is that it gives off short-wave radiation and absorbs radiant energy, especially in the red wave length, which will no longer be transferred to the surrounding open space or to the interior of the building [14].

Galleries have been employed for the same purpose, as intermediate spaces between interior and exterior environments. This type of transitional spaces, can act as connectors to some phenomenon and as a barrier to others. Thus, galleries act as climate 'filters' under feasible control by occupants [15].

Nowadays, open spaces are experiencing transformations in their form and material qualities due to a group of factors. The most important factor constitutes the higher space use index that reduces the courtyard area and turns intermediate spaces into permanent spaces, losing their buffering qualities as intermittent spaces.

In the case of school buildings, these transformations derive from regulations that have progressively reduced the open space required per student – from 5 m^2 per student in 1938 to 1.50 m^2 per student in 1998. These legal changes have gone hand in hand with practical reasons: construction of newly required classroom spaces that grow into courtyards of existing buildings; constraints derived from the limitation on the size of the land plot and the greater need of classroom areas to be constructed in new buildings [16,17].

In general, pre-schools in Mendoza are refurbished 'half courtyard' houses. Their architectural concept is characterised by a longitudinal axis that results in a line of tall rooms communicated with each other by an outside gallery that constitutes a transition space between the interior spaces and the courtyard (Fig. 1a). The house is adapted to perform school functions while preserving its original structure: the building grows to make room for a higher number of classrooms by adding spaces along the longitudinal axis until reaching the back of the land plot. Furthermore, classrooms grow towards the lateral courtyard turning the gallery into an internal corridor that divides the courtyard into two (Fig. 1b).

Regarding shading devices, the green 'roofs' composed by bowers of grapevines or creepers (usually used in housing typologies) have been replaced in school buildings with horizontal "shading fabric" canopies. These solar protections do not offer the same benefits as green ones, since they do not prevent air heating and sometimes heated air is retained beneath the canopy.

For all of the aforementioned reasons, the effect of two main courtyard design variables – geometry and shade – was studied in order to assess summer energy and thermal conditions in a refurbished school building.

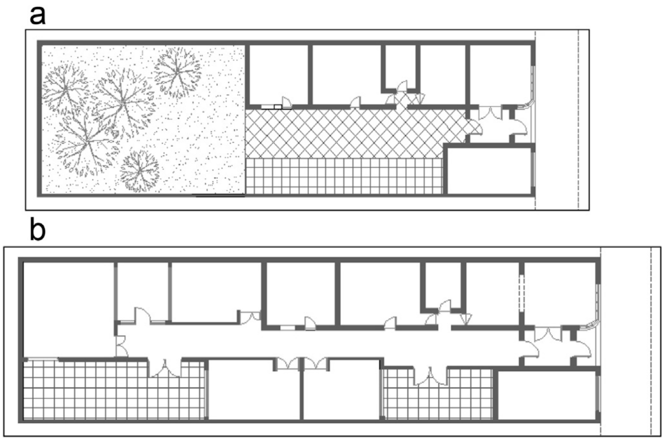

Fig. 1. a: Half courtyard house. b: Half courtyard house fitted for school functions.

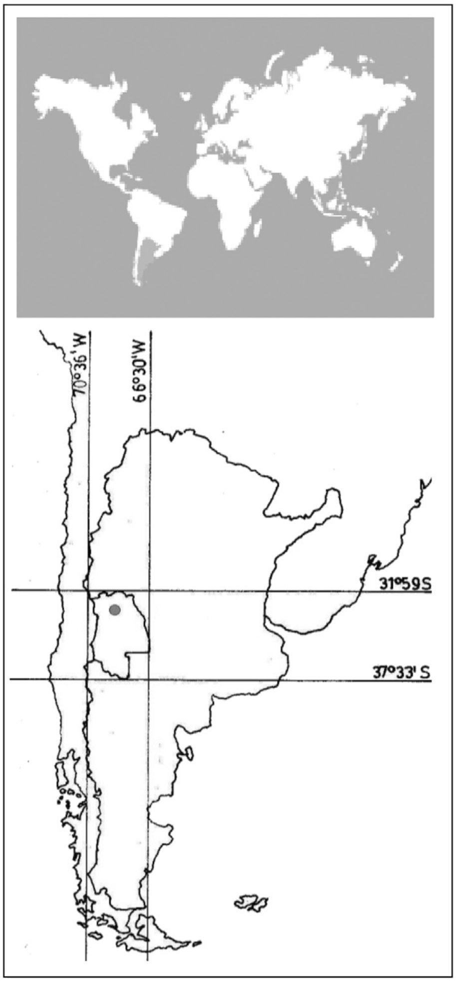

Fig. 2. Location of Mendoza, Argentina.

Table 1
Climate data for Mendoza, Argentina.

Annual values	
Maximum mean temperature	24.5 °C
Minimum mean temperature	9.6 °C
Mean temperature	16.5 °C
Global horizontal irradiance	18.4 MJ/m^2
Relative humidity	56%
Relative heliophany	63%
July	
Maximum mean temperature	15.7 °C
Minimum mean temperature	0.8 °C
Mean temperature	7.3 °C
Global horizontal irradiance	10.2 MJ/m^2
Relative humidity	63%
Relative heliophany	58%
January	
Maximum mean temperature	32.3 °C
Minimum mean temperature	17.4 °C
Mean temperature	24.9 °C
Global horizontal irradiance	26.1 MJ/m^2
Relative humidity	49%
Relative heliophany	66%
Heating degree-days ($T_b = 18$ °C)	1384 °C
Cooling degree-days ($T_b = 23$ °C)	215 °C

Source: Servicio Meteorológico Nacional — Fuerza Aérea Argentina.

Table 2
R_1 and R_2 ratios for courtyards.

	Geometrical data		Resulting ratios
Courtyard 1	Perimeter, *P*	19.20 m	$R_1 = 3.84$ equals 4
	Height, *H*	5.00 m	
	Width, *W*	3.10 m	$R_2 = 0.47$ equals 0.5
	Length, *L*	6.50 m	
Courtyard 2	Perimeter, *P*	30.40 m	$R_1 = 9.07$ equals 9
	Height, *H*	3.35 m	
	Width, *W*	4.20 m	$R_2 = 0.38$ equals 0.4
	Length, *L*	11.00 m	

2. Case study

2.1. Environmental data

Mendoza is located in central western Argentina (32°40′ South latitude, 68°51′ West longitude, 750 m above sea level) in a semi dry continental climate with low percentages of atmospheric relative humidity and long sunlight hours. It corresponds to a BWk climate, according to the climate classification by Köppen–Geiger–Pohl [18], see Fig. 2. Some weather records are shown in Table 1.

2.2. School building characterisation

A pre-elementary school located in the metropolitan area of Mendoza was selected for this work. The dwelling house is situated in a low-density residential area. It was built approximately in 1950 and refurbished in the year 2000. The land plot has a narrow shape (10.25 m × 35.30 m) with an interior surface area of 304.3 m^2 and 77.15 m^2 of open space. The school plan is structured around two main courtyards, with similar construction technology and solar protection but with geometric differences, defining their interest as study cases.

The school building complies with the Building Code of Mendoza and the School Building Legislation in Argentina [19,20], but has no special passive conditioning strategies and users are not involved in any kind of environmental management. It is a building subjected to minimum control.

Fig. 3 shows the plan and sections on the pre-elementary school. Monitored courtyards and interior spaces are identified.

2.3. School courtyard characterisation

The methodology designed by Muhaisen and Gadi [10] was used to geometrically characterise courtyards. School courtyards present simple cubic shapes with different values of R_1 and R_2. The former ratio is taken as the ratio between the courtyard's floor perimeters *P* and the form's height *H* (*P*/*H*). This ratio indicates the depth of the form and it ranges between 1 and 10 in one degree steps. The latter ratio, which indicates the elongation of the form, is the ratio of the rectangular courtyard width *W* to its length *L* (*W*/*L*). It varies between 0.1 and 1 in tenth of degree intervals.

Table 2 presents geometric data and ratio results for the two courtyards analysed.

Both courtyards have a similar elongation of the form as their R_2 ratios are only one-tenth of a degree apart (0.4 and 0.5). The main

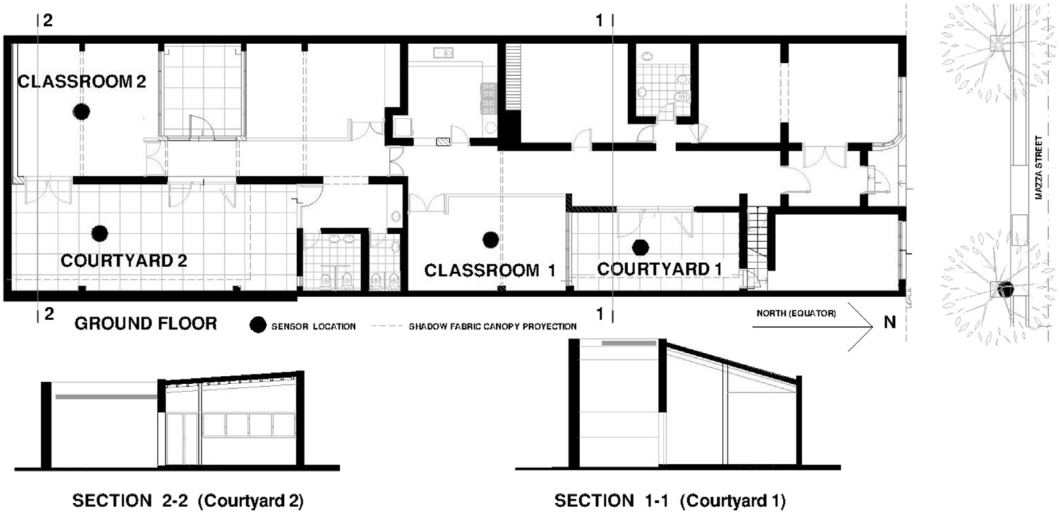

Fig. 3. Case study plan and sections.


Courtyard 1 Courtyard 2

Fig. 4. Materials and shading strategies for open spaces.

difference between the courtyards is in the depth of the form rated by R_1: courtyard 1 has a value of 4 and courtyard 2 rates 9. Therefore, courtyard 1 has a compact form and, for the purpose of this study, was called “boxed-type”. The second courtyard presents an open form and was therefore named “open-type”.

Both courtyards present similar materials: vertical parapets of massive brick walls, most of them 0.20 m thick, painted in a light colour (Thermal conductivity $\lambda = 0.72$ W/m °C, absorption coefficient $\alpha = 0.26$ and emissivity $\varepsilon = 0.90$) [21] and concrete floors which are 53% surrounded by strips of red mosaic. Thermo-physical properties of concrete are: Thermal conductivity $\lambda = 1.4$ W/m °C, absorption coefficient $\alpha = 0.60$ and emissivity $\varepsilon = 0.88$, and those of red mosaic are: Thermal conductivity $\lambda = 1.4$ W/m °C, absorption coefficient $\alpha = 0.63$ and emissivity $\varepsilon = 0.93$ [21]. For images of the studied courtyards see Fig. 4.

Courtyards are protected by “shading fabric canopies” that are marketed under the technical specification that states a 90% blockage of solar radiation. These canopies cover a similar percentage in both courtyards: 65% of the exposed floor area in courtyard 1 and 72% of the floor area of courtyard 2.

Courtyards present shade conditions associated to their shape and solar protection device. Shadows projected by form – named SAF – and shadows projected by fabric canopies – called SAC – were graphically obtained for each courtyard and calculated by area and by percentage of vertical and horizontal envelopes, on an hourly basis, for a summer representative day between 8:00 a.m. and 4:00 p.m. Solar position was defined using a programme called Geosol 2.0 that allows obtaining solar coordinates – altitude and azimuth – in a given location throughout a day [22].

Results indicate that the courtyard geometry has its highest influence on shade conditions during the first morning hours and late afternoon hours, reaching values of 85% in the “boxed-type” courtyard and 70% in the “open-type” courtyard. At solar noon the courtyard geometry has a reduced impact in both cases. Fig. 5 represents the area shaded by form (SAF).

A reverse phenomenon is observed in the shade projected from the canopies, where a larger area is shaded at solar noon, 40% in the “boxed-type” courtyard and 32% in the “open-type” courtyard. Fig. 5 shows the area shaded by canopies (SAC).

This behaviour is consistent with the solar angle with respect to the vertical parapets during the first morning hours and last afternoon hours and to horizontal protections at solar noon.

2.4. Classroom characterisation

Classrooms next to both courtyards have similar size and type of windows – Classroom 1 is 22.86 m^2 in size, with 24% being windows, and classroom 2 is 28.60 m^2 with 27% being windows. They present minor differences in shape, window orientation and envelope materialisation.

Morphology of classrooms and their relation with exterior space are defined from two factors: Form Factor and Effective Form Factor [23,24].

Form Factor (FF) defines the formal structure of the space from the capacity to exchange heat with the exterior and is expressed as the ratio between total envelope surface area and floor area. Classroom 1 has a Form Factor of 4.53 and Classroom 2 one of 3.48. This indicator defines an “open” geometric structure in the first case and a “compact” one in the second case. It should be taken into account that an FF of 2 indicates the highest compactness (corresponding to a semi-sphere).

The location of the classrooms in the building shows different levels of heat exchange with the exterior space. Therefore, heat exchange capacity is associated to an Effective Form Factor (EFF),-which is expressed as the ratio between the exposed envelope surface area and the floor area. Classroom 1 has an EFF of 2.75 and Classroom 2 one of 3.33. The smaller is the factor, the less exposed is the envelope (see Table 3).

A combined analysis of the two factors (FF and EFF) enables the description of Classroom 1 as an open form from a geometric view point and with less exterior exposure. Whereas, Classroom 2 shows a compact form and more exterior exposure.

Table 3
Form factor (FF) and effective form factor (EFF) in classrooms.

	Surface (m^2)	Envelope total (m^2)	Exposed envelope (m^2)	FF	EFF
Classroom 1	22.86	103.64	62.76	**4.53**	**2.75**
Classroom 2	28.60	99.64	95.18	**3.48**	**3.33**

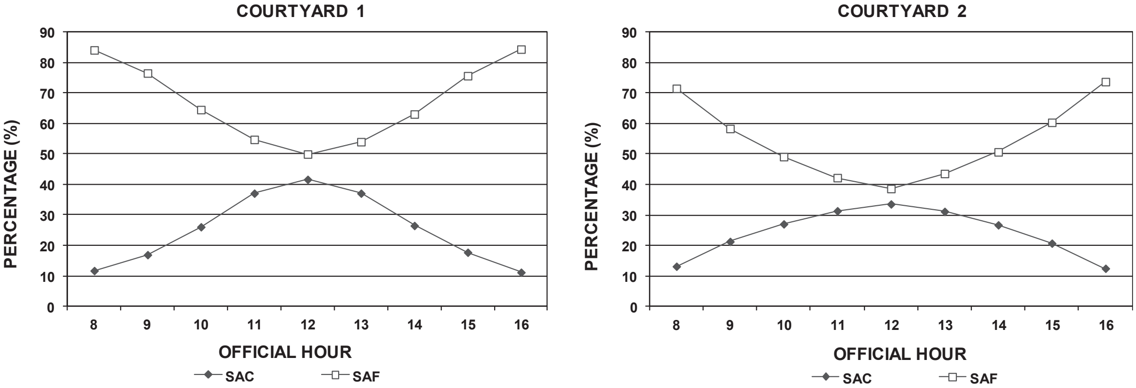

Fig. 5. Hourly distribution of areas shaded by form (SAF) and by canopies (SAC).

Table 4
Total loss coefficient (Q_t) by floor classroom area unit.

	Constructive component	$\frac{A_i}{A_t}\left[\frac{m^2}{m^2_{class}}\right]$	K_i [W/m^2 °C]	$Q_i = [K_i * A_i / A_t]$ [W/m$^2_{class}$ °C]	$Q_t = \Sigma Q_i$ [W / m$^2_{class}$ °C]
Classroom 1	Roof	1.02	1.09	1.12	**6.81**
	Wall	1.49	2.70	4.00	
	Window	0.24	6.98	1.70	
Classroom 2	Roof	1.01	0.64	0.65	**6.51**
	Wall	1.24	2.70	3.34	
	Wall 1[a]	0.80	0.74	0.59	
	Window	0.28	6.98	1.92	

A_i: constructive component.
A_t: total floor classroom area.
Q_i: net loss coefficient by constructive component and by total floor classroom area.
Q_t: total loss coefficient by total floor classroom area unit.
[a] Insulated wall.

Regarding orientation, Classroom 1 has two horizontal windows facing the Equator (North in the Southern Hemisphere) while Classroom 2 presents one horizontal window facing North and one glass door facing East. Solar exposure to the North is similar in both classrooms and the difference is given by the East glass door in Classroom 2.

Construction technology in both classrooms involves plastered brick walls (0.20 m thick), simple contact and single glass windows and light wooden roofs. Classroom 2 presents some differences in wall and roof insulation. These are: 20% of the envelope has a double-brick wall with insulation (0.05 m of expanded polystyrene) and also 5% of walls are buried because of the difference in elevation between the school lot and the contiguous one. The roof of Classroom 1 is better insulated than that of Classroom 2 (0.10 m to 0.05 m of expanded polystyrene).

Ventilation, as a passive strategy, is not applied because exterior temperatures are higher than interior ones during the daytime, and when exterior temperatures are lower and could benefit classroom performance, the school is closed. Nevertheless, the technology of the windows causes infiltrations of more than one air renewal per hour.

According to the objective of this paper, and for an appropriate comparison between the behaviour of classrooms with differences in their constructed surfaces, in their morphology and technology, a total loss coefficient (Q_t) was calculated by area unit of total floor classroom area. Q_t was estimated by calculating exposed surfaces of different building components and their thermal conductance (see Table 4).

Resulting values show a total loss coefficient by area unit of 6.81 for Classroom 1 and of 6.51 for Classroom 2. That is, a slightly lower total loss coefficient for Classroom 2. The difference is around 5% and defines this interior space as more conservative.

3. Thermal conditions

3.1. Measurement method/data collection

The method used consists in measuring air temperature with ONSET HOBO RH data loggers. H08-003-02 data loggers have two inner channels, one for temperature (range between - 20 °C and 70 °C and accuracy from ±0.7 °C to 21 °C), and the other one for relative humidity (range between 25 and 95% RH and accuracy ±5%). These sensors were located in the selected courtyards and classrooms, and also in the immediate urban canyon – used as a reference parameter for open spaces. In courtyards, sensors were placed below the centre of the shading fabric canopies. Sensors in classrooms were placed in the centre of the space. Every data logger was hung at a mean height of 2 m [25]. Location of data loggers is shown in Fig. 3.

Data loggers were placed in plastic boxes, drilled with holes on four of their six sides in order to protect them from children. The effect of the plastic box was compensated for by the removal of the sensor from its original plastic case [26]. In the case of exterior measurements, in addition to the described plastic box, an aluminium protection was placed over it to prevent impinging solar radiation from reaching the sensor.

Measurements were done between December 2007 and December 2008 in four periods, one in each season. In each period, data was recorded every 15 min, for 40 days.

3.2. Thermal results and analyses

3.2.1. Thermal behaviour

The data obtained from measurements every 15 min were averaged on an hourly basis to better understand trends. The

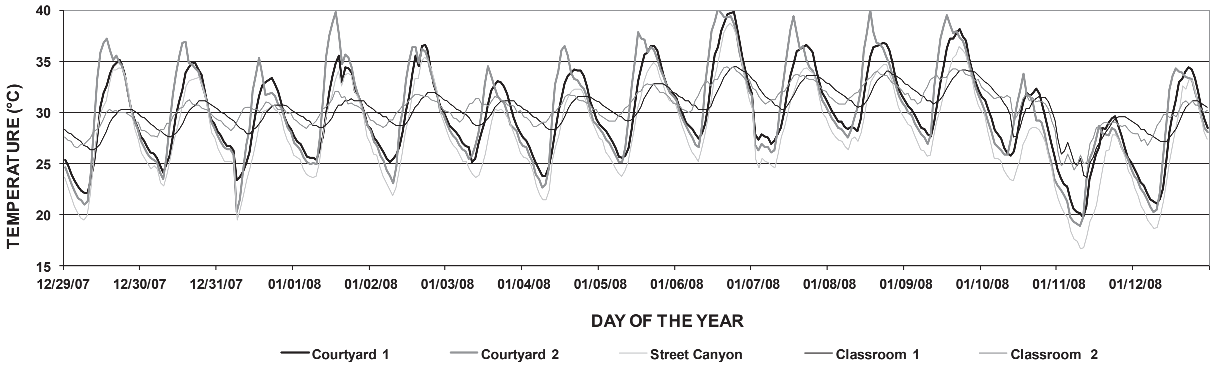

Fig. 6. Thermal measures in summer.

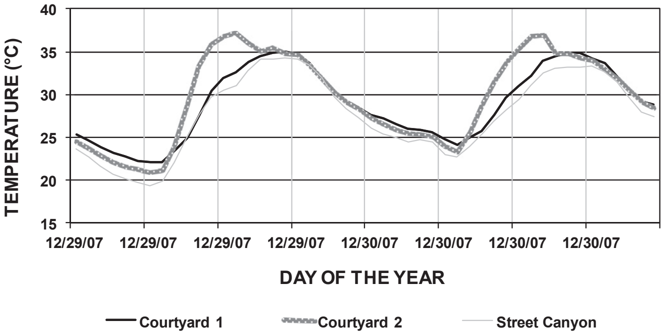

Fig. 7. Thermal behaviour of courtyards in stable conditions.

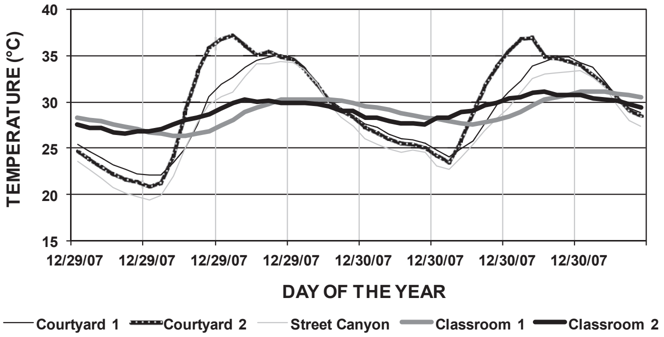

Fig. 9. Thermal behaviour of classrooms.

graphic analysis allows identifying for the summer period – December 14th 2007 to January 24th 2008 – stable performances in classrooms with respect to exterior temperature variations. Maximum exterior temperatures varied around 30 °C and 35 °C and minimum ones between 19 °C and 25 °C. This behaviour is explained by the significant inertia of interior spaces that can be observed in Fig. 6. The graphic shows a 15 day sequence selected from the whole summer period.

3.2.2. *Courtyard performance*

To minimise the influence of inertia during unstable periods on classroom–temperature curves, two days showing repetitive behaviour associated to previous stable conditions were analysed (Fig. 7).

Graphics of temperature in canopy-protected courtyards show the following:

There is an hourly displacement of maximum temperatures: the "open-type" courtyard (Courtyard 2) starts its heating period first and reaches maximum temperatures at 1 p.m. (official time), because of the higher solar exposure of its surfaces. Such exposure is the result of the shape of the courtyard and its orientation, which generates heating conditions from the beginning of the day, with relative efficiency of the canopy as shading element. Even though the "shading fabric" controls direct radiation – depending on its density–, it does not prevent air from heating up. Whereas, in the "boxed-type" courtyard (Courtyard 1), with less solar exposure (see Fig. 8), the start of the heating period is delayed and thus maximum temperatures are reached at 5 p.m. (official time), 4 h later than in Courtyard 2.

Concerning horizontal protection and to prevent temperature increases, previous research has reported that the "shading fabric canopy" has an efficiency of 7% in Courtyard 1 and 5% in Courtyard 2 [17].

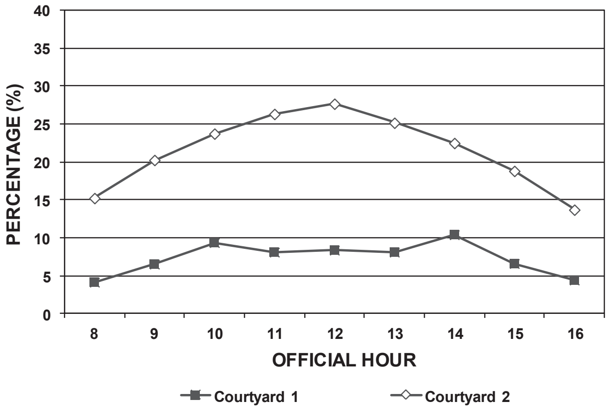

Fig. 8. Areas with solar radiation (vertical and horizontal surfaces).

The comparison of the highest temperatures shows that the "open-type" courtyard is 2 °C warmer than the "boxed-type" courtyard. This is explained by the combined effect of the open morphology and the relative efficiency of the canopy in the "open-type" courtyard. In the "boxed-type" the relative efficiency of the canopy is compensated by the shape that is more effective for solar control. Therefore, shape plays a decisive role in the thermal behaviour of courtyards. In Fig. 8 it can be observed that the "boxed-type" courtyard has a lower percentage of areas with solar radiation throughout the day.

At minimum temperatures, differences of about 0.5 °C are observed. This variation results from the better cooling capacity of the open courtyard (Courtyard 2). Potential cooling of the "boxed-type" courtyard (Courtyard 1) is conditioned by the larger amount of accumulated mass and the smaller sky view.

These on-site measurement results are consistent with the ones found by Muhaisen and Gadi [10] in analytical analyses. In their research, which addresses solar heat gain and energy requirements in summer, they concluded that when the courtyard buildings are deeper and more elongated (when R_1 is closer to 1 and R_2 is nearer 0.1), the more adequate strategy is to reduce the required cooling load.

The studied courtyards show higher maximum and minimum temperatures than those measured in the street. This is derived from the shape and the construction technology of the courtyards in comparison to the surrounding streets as well as from the use of sun protections – canopies – that are less efficient than the shade cast by the trees along the tree-lined streets typical of Mendoza.

In relation to measures obtained in similar conditions [27], it can be inferred that showing higher temperatures than the surrounding area is a characteristic of courtyards with a massive envelope in hot dry regions.

3.2.3. *Classroom performance (Fig. 9)*

Temperature graphics for the two classrooms evaluated show that they have similarities in highest and lowest temperatures and differ in the time in which maximum temperatures are reached.

Maximum and minimum temperatures result from the combined effect of classroom shape and construction technology, internal gains – a common factor for both spaces and usage.

As indicated by shape and materiality analyses, Classroom 1 is more compact than Classroom 2 in terms of the effective form factor (EFF = 2.75), and also less conservative due to its construction technology ($Q_t = 6.81$). Classroom 2 combines the same factors in the reverse way: a higher effective form factor and lower heat loss (EFF = 3.33, $Q_t = 6.51$).

As the school is used from 7 a.m. to 3 p.m., the possibility of using night ventilation as a cooling strategy is limited. This condition defines an average difference between higher and lower

Table 5
Maximum, mean and minimum temperatures in classrooms and courtyards.

		Temp. max (°C)	Temp. min (°C)	ΔT	Temp. mean (°C)	Courtyard-classroom difference
Classroom 1	Day 1	30.31	26.34	3.97	28.32	
	Day 2	31.12	27.52	3.60	29.32	
	Average	*30.715*	*26.93*	*3.78*	***28.82***	
Courtyard 1	Day 1	35.06	22.09	12.97	28.57	
	Day 2	34.85	24.10	10.75	29.47	
	Average	*34.95*	*23.09*	*11.86*	***29.02***	**0.2 °C**
Classroom 2	Day 1	30.26	26.55	3.71	28.40	
	Day 2	31.17	27.54	3.63	29.35	
	Average	*30.715*	*27.04*	*3.675*	***28.87***	
Courtyard 2	Day 1	37.22	20.95	16.27	29.08	
	Day 2	36.89	23.43	13.43	30.16	
	Average	*37.05*	*22.19*	*14.85*	***29.62***	**0.8 °C**

temperatures of 3.78 °C in Classroom 1 and 3.67 °C in Classroom 2 (Table 5).

Regarding average temperatures, interior ones are slightly lower than exterior ones (0.20–0.80 °C). The interior is close to thermal equilibrium with the exterior. Studies carried out at the School of Architecture at Universidad de Gran Canaria, Spain [28] show that, in a building with “minimum control”,[1] interior average temperature should be 3 °C above exterior average temperature depending on internal gains (metabolism), energy consumption (lighting, electrical appliances) and solar gain (solar radiation, exterior temperature). In the studied cases of this research, the first two variables are constant. The third variable is different because solar radiation gain is not equal for both courtyards. These conditions generate reduced differences in average temperatures. The combined effect of shape and canopy in Courtyard 1 generates proximities between average interior and exterior temperatures that only differ by 0.2 °C (Classroom 1). That value is higher (0.8 °C) in the Courtyard 2–Classroom 2 relationship because of less favourable exterior conditions (see Table 5).

Compared to Classroom 2, Classroom 1 presents a 2-h delay in temperature peaks. Courtyard 1 reaches maximum temperatures at 5 p.m. and Classroom 1 at 6 p.m., while Courtyard 2 gets to maximum temperatures at 1 p.m. – because of its morning solar exposure – and Classroom 2 at 4 p.m. These time differences define better morning conditions in Classroom 1 and better afternoon conditions in Classroom 2.

4. Energy consumption

4.1. Dynamic simulation/data estimation

The thermal analysis is complemented with energy consumption data. As the thermal behaviour of the classroom is free-floating, and therefore there is no reference variable (cooling consumption), a direct comparison of energy consumption between classrooms is only possible by performing a dynamic simulation. In this case, the software used was Energy Plus, version 6.0 [29]. This programme allows the estimation of energy consumption and interior temperatures. These temperatures are, in this case, the control variables used to validate energy consumption. Moreover, this methodology allows expanding the case study scenarios by comparatively determining energy consumption associated to different courtyard designs (geometry and solar protection).

Energy Plus is a dynamic energy analysis and thermal load simulation program. Based on a user’s description of a building from the perspective of the building’s physical make-up and associated mechanical and other systems, Energy Plus calculates heating and cooling loads necessary to maintain thermal control set points, conditions throughout a secondary HVAC system and coil loads, and the energy consumption of primary plant equipment. Simultaneous integration of these details – and many other – define that Energy Plus is able to simulate a real building performance [29].

Among the key capabilities of Energy Plus are: Heat balance based solution technique for building thermal loads that allows for simultaneous calculation of radiant and convective effects at both the interior and exterior surfaces during each time step; transient heat conduction through building elements such as walls, roofs, floors, etc. using conduction transfer functions; improved ground heat transfer modelling through links to three-dimensional finite difference ground models and simplified analytical techniques; combined heat and mass transfer model that accounts for moisture adsorption/desorption either as a layer-by-layer integration into the conduction transfer functions or as an effective moisture penetration depth model (EMPD); ASCII text based, user definable weather input files that include hourly or sub-hourly environmental conditions.

Geometric data input was performed using the Open Studio software, plug-in for Sketch Up. After that, physical properties were incorporated with the IDF Editor programme. A weather file was created *ad hoc* with data from *in situ* measurements that allowed a high level of correspondence between the physical model and interior measures taken on site.

The weather file was created with the following measured-on-site conditions: Global radiation on horizontal surface (measured with Kipp and Zonen Solarimeter), Dry bulb air temperature and relative humidity (measured with ONSET HOBO data loggers) and wind direction and speed (measured with a Davis weather link station). Diffuse Radiation on horizontal surface was calculated with the Isotropic Diffuse Model [30].

Figs. 10 and 12 show measured and simulated temperatures in all the studied cases. In Classroom 1, the 15, 16 and 18th of December achieve an adjustment with an average daily variation of 0.28 °C. On the 17, 19 and 20th of December, the average daily variation is 0.55. Average measured temperatures rise by 0.26 °C above simulated temperatures in sunny hours due to user action. At night, thermal behaviour is similar (Fig. 10). The correlation between measured and simulated data has an R^2 equal to 0.92 (Fig. 11).

In Classroom 2, measured temperatures vary on a greater level than simulated ones, due to the building’s use. It can be observed

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[1] Conventional building fulfilling environmental regulations, but without special features of passive conditioning (insulation, for example), and in which occupants are not involved in any environmental management (ventilation, among other strategies).

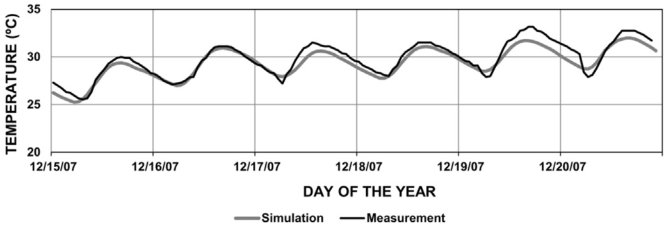

Fig. 10. Classroom 1: temperature measurements and simulations. 15–20th December, 2007.

that the 15, 16 and 18th of December, maximum and minimum temperatures are similar, with an average daily variation of 0.08 °C. On the 17, 19 and 20th of December, the average daily variation is 0.16. In sunny hours, average measured temperatures rise by 0.90 °C above simulated temperatures also due to user action. As in Classroom 1, at night, the thermal behaviour of both curves is similar (Fig. 12). The correlation between measured and simulated data has an R^2 equal to 0.82 (Fig. 13).

From the adjustment of simulation model and measured temperatures, energy consumption estimated with Energy Plus turns out valid.

4.2. Energy results and analysis

From the energetic point of view, consumption to reach comfort temperatures (base temperature 25 °C) is 0.42 kWh/m^2 in Classroom 1 and 0.60 kWh/m^2 in Classroom 2.

Aiming to compare measured cases with theoretical cases – that present variations in courtyard geometry and shade conditions – the validated model was run for different scenarios.

For the shape variable different values of R_1 were considered, indicating the depth of the form (Muhasein's methodology [10]). As regards the solar protection, energy consumption in classrooms was calculated with and without full solar exposure. The following four scenarios were defined:

Scenario A1. Relative comparison of Courtyard 1, "boxed-type" (a) $R_1 = 4$ and $R_2 = 0.5$, with full solar exposure, and (b) a courtyard with same orientation, materiality and solar exposure; and a geometric variation $R_1 = 9$ and $R_2 = 0.5$. This variation defines a courtyard with more open conditions. This comparison aims to determine the influence of exterior space morphology on the energy requirements of the interior to reach comfort in Classroom 1.

Scenario B1. Relative comparison of Courtyard 1, "boxed-type"(a) $R_1 = 4$ and $R_2 = 0.5$, with full solar exposure, and (b) a courtyard with partial solar exposure due to the use of "shading fabric canopies". This comparison is useful for quantifying the effects of solar protection on energy consumption in Classroom 1.

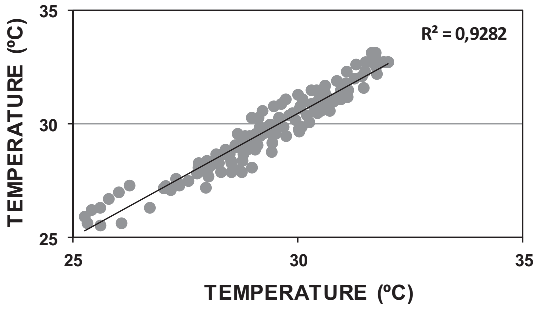

Fig. 11. Classroom 1: correlation between measured and simulated temperatures. 15–20th December, 2007.

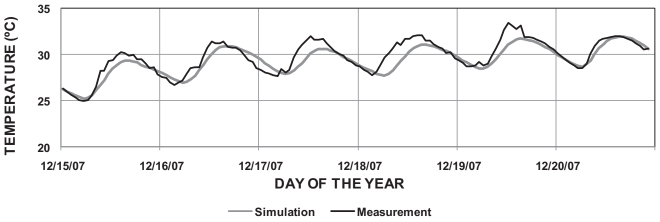

Fig. 12. Classroom 2: temperature measurements and simulations. 15–20th December, 2007.

Scenario A2. Relative comparison of Courtyard 2, "open-type" (a) $R_1 = 9$ and $R_2 = 0.4$, with full solar exposure, and (b) a courtyard with the same orientation, materiality and solar exposure; and a geometric variation $R_1 = 4$ and $R_2 = 0.4$. This variation defines a courtyard with closer conditions. This comparison, as in Scenario A1, aims to determine the influence of exterior space morphology on the energy requirements of the interior to reach comfort in Classroom 2.

Scenario B2. Relative comparison of courtyard 2, "open-type" (a) $R_1 = 9$ and $R_2 = 0.4$, with full solar exposure, and (b) a courtyard with partial solar exposure due to the use of "shading fabric canopies". The effect of solar protection on energy consumption in Classroom 2 is quantified by this comparison.

Analytical results show that Classroom 1 consumes 0.42 kWh/m^2 with full solar exposure. In Scenario A1, the more open geometry of Courtyard 1 (a variation in R_1 from 4 to 9) increases energy consumption in Classroom 1 by around 14%. In Scenario B1, the use of a "shading fabric canopy" reduces energy consumption by approximately 21%.

The same analyses performed for Classroom 2 yielded a consumption of 0.60 kWh/m^2 with full solar exposure. In Scenario A2, the enclosed geometry of Courtyard 2 (a variation in R_1 from 9 to 4) reduces energy consumption in Classroom 2 by approximately 23%. The lower exposure of Courtyard 2 defines lower exterior temperatures and therefore lower interior temperatures in Classroom 2, which consequently leads to less energy necessary to reach the desired temperature of 25 °C. In Scenario B2, the use of a "shading fabric canopy" diminishes energy consumption by around 18%.

For a synthesis of the results obtained for the four scenarios see Fig. 14.

As regards exterior space geometry, when the courtyard morphology is more open (higher values of R_1) energy consumption of the interior space increases due to a higher solar exposure of the open space. Solar protections collaborate with courtyard's shape in its shading, reducing auxiliary energy requirements in the interior space. In the studied cases, the technology of the vertical

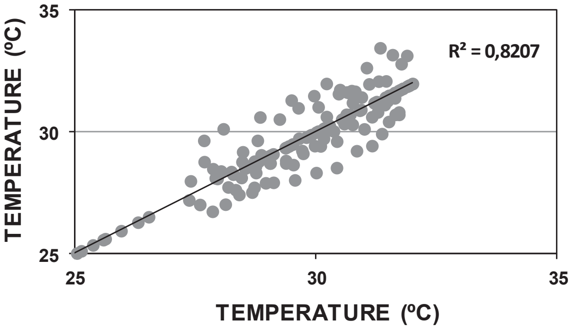

Fig. 13. Classroom 2: correlation between measured and simulated temperatures. 15–20th December, 2007.

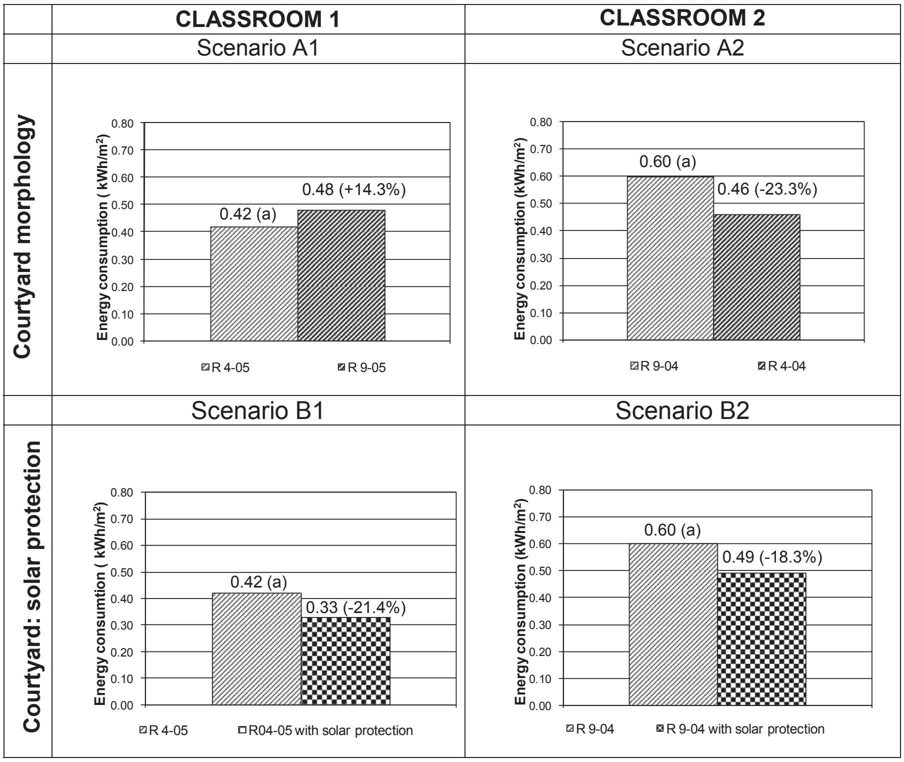

Fig. 14. Energy consumption to reach comfort temperatures (base temperature 25 °C) in classrooms associated to different courtyard conditions.

envelope of the classroom (with mass, but without insulation) allows an energy exchange. For this reason courtyard conditions have a strong impact on interior spaces.

5. Conclusions

According to the monitored real cases and dynamic simulations, bioclimatic conditioning of interior spaces relies not only on design strategies associated to the project but also on the design of surrounding space.

This work has focused on determining the influence of the surrounding space on thermal and energy conditions of the interior in summer. Nevertheless, optimal results for daytime hours jeopardise passive nocturnal cooling and reduce solar heat gain in winter.

Some guidelines for exterior space design can be derived from the evaluation of inner courtyards in summer, with a North–South main axis:

In the hot time of the day, the shade condition of the exterior is one of the variables with the biggest impact on the behaviour of the interior of classrooms. Therefore, a courtyard with higher percentage of directly impinging radiation jeopardises the thermal response of the interior space. This condition depends on construction technology, on courtyard morphology and materiality, and on the type of solar protection used.

As the construction technology is permeable to exterior microclimate conditions, courtyards have a strong influence on the resulting interior temperature.

Regarding shape, the geometry and materials used in open spaces play a primary role in their thermal behaviour. In the case of North–South oriented courtyards, and for equal materiality of the courtyard, low geometric ratios of R_1 and R_2 limit solar access to a greater extent in the morning and in the afternoon.

For solar protection, the “shading fabric canopy” shows relative efficiency because it controls direct radiation but fails to prevent the rise in exterior air temperature, since it also diminishes air movement because the heated air remains under the canopy.

However, simulated data shows that, from the energetic point of view, small interior air temperature reductions imply significant energy savings to reach comfort temperatures.

At night, courtyard performance is perceptibly different due to the higher convective and radiative cooling capacity of open spaces with high R_1 and R_2 ratios. This benefit only impacts interior space behaviour if ventilation is used as a passive cooling strategy.

All in all, results suggest that in semi dry areas, characterised by cold winters, hot summers and a large number of clear sky days, it is necessary to adopt compromise solutions that combine blockage of the solar resource in summer with guarantee of full access in winter. To suit both strategies, exterior spaces should be design as an open typology with efficient shading devices for summer. In this way an adequate solar access in the cold period is achieved as well as a minimisation of the radiation heating effect in the hot season. When appropriate solar protection is not guaranteed, the use of a self-shading form to ensure less radiation in summer is recommended, even if this reduces access to the resource in winter.

Further research could assess the construction technology of courtyards aiming at reducing solar heat accumulation on the massive surfaces. The use of “green” walls could constitute an appropriate alternative.

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References

[1] National Energy Secretariat. Residential energy consumption in Argentina [Consumo energético residencial de la República Argentina] http://energia3.mecon.gov.ar/; 2010.

[2] Declan Butler. Architects of low-energy future. Nature 2008;452:520–3.

[3] Filippín C. Thermal response of solar and conventional school buildings to design and human-driven factors. Renew Energy 2005;30:353–76.

[4] Cantón MA, Cortegoso JL, Fernández JC, de Rosa C, et al. Environmental and energy impact of the urban forest in arid zone cities. Archit Sci Rev 2001;44:3–16.

[5] McPherson EG. Accounting for benefits and costs of urban greenspace. Landsc Urban Plan 1992;22:41–51.

[6] Arauzo I, Morató M, Rueda S. Climate, urbanism, comfort and energy: the influence of temperature on infiltration-conditioned demand [Clima, urbanismo, confort y energía: influencia de la temperatura en la demanda de climatización por infiltración]. Barcelona: Urban Ecology Agency (Agencia Ecología Urbana); 2002.

[7] Aldawoud A. Thermal performance of courtyard buildings. Energy Build 2008;40:906–10.

[8] Muhsen MA. Solar radiation and courtyard house forms II: application of the model. Build Environ 1978;14:185–201.

[9] Etzion Y. The thermal behaviour of non-shaded closed courtyards in hot-arid zones. Archit Sci Rev 1995;33:79–83.

[10] Muhaisen AS, Gadi MB. Effect of courtyard proportions on solar heat gain and energy requirement in the temperate climate of Rome. Build Environ 2006;41:245–53.

[11] Cantón MA, Fernandez J, Mesa A, et al. Energy assessment of the patio-house evolution in the urban architecture of arid zones. In: Living in deserts: is a sustainable urban design still possible in arid and hot regions? Argelia: Algerie and ENSAT Ghardaïa; 2006. pp. 55–68. EPAU – France.

[12] Ratti C, Raydan D, Steemers K. Building form and environmental performance: archetypes, analysis and an arid climate. Energy Build 2003;35:49–59.

[13] Olgyay A, Olgyay V. Solar control and shading devices. Princeton University Press; 1957.

[14] Bellomo A. Green walls. Project guidelines [Pareti Verdi. Linee guida alla progettazione]. Napoli: Sistemi Editoriali; 2003.

[15] Ganem C. Environmental rehabilitation of the envelope of houses. The case of Mendoza [Rehabilitación ambiental de la envolvente de viviendas. El caso de Mendoza]. Catalunya Tech. (UPC); 2006 [PhD thesis].

[16] Toranzo V. Pedagogy and architecture in Argentinean elementary schools [Pedagogía y Arquitectura en las Escuelas Primarias Argentinas]. J Stud Exp Educ 2008;7(13):11–40 (Rev Estud Exp Educ).

[17] Cantón MA, Ganem C, Fernández Llano J. The courtyard in school architecture. Impact of solar protections in summer thermal conditions [El patio en la arquitectura escolar. Impacto de las protecciones solares en las condiciones térmicas de verano]. Area J 2009;15 (Rev Área).

[18] Geiger R, Pohl W. Revision of Köppen–Geiger climate maps of the earth. Germany: Justus Perthes; 1953.

[19] Office of Private Works in Mendoza's Town Council (Dirección de obras privadas de la Municipalidad de Capital Mendoza). Urban and building code of the city of Mendoza. Second review and updating [Código urbano y de edificación de la ciudad de Mendoza. Segunda Recopilación y Actualización] www.ciudaddemendoza.gov.ar/gestion-urbana/gu-planificacion-urbana/codigo-edificacion-urbana; 2000.

[20] Ministry of Education, Science and Technology (Ministerio de Educación, Ciencia y Tecnología). Criteria and basic standards of school architecture [Criterios y Normativas básicas de arquitectura escolar] www.me.gov.ar/infra/normativa/normativa/index_normativa.htm; 1993.

[21] Incropera FP, De Witt DP. Fundamentals of heat and mass transfer. John Wiley & Sons; 1996.

[22] Hernández A. GEOSOL: a computational tool for calculating solar coordinates and estimating hourly solar irradiation [GEOSOL: Una herramienta computacional para el cálculo de coordenadas solares y la estimación de irradiación solar horaria]. J Prog Renew Energy Environ 2003;7:11.19–24 (Avances Energ Renov Medio Ambiente).

[23] Olgyay V. Architecture and climate [Arquitectura y Clima]. Barcelona: Ed. Gustavo Gili; 1998.

[24] Esteves A, Gelardi D. Teaching in sustainable architecture: architectural project optimisation programme based on thermal balance [Docencia en Arquitectura Sustentable: Programa de Optimización de Proyectos de Arquitectura basado en el balance térmico]. J Prog Renew Energy Environ 2003;7:10.31–4 (Avances Energ Renov Medio Ambiente).

[25] Oke TR. Initial guidance to obtain representative meteorological observations at urban sites [Iom report]. Geneva: World Meteorological Organisation; 2004.

[26] Cantón MA, Fernández Llano J. Summer thermal behaviour of different shadow configurations in urban courtyards in arid climates. Methodology validation and case studies [Comportamiento térmico de verano de diferentes configuraciones de sombra en patios urbanos emplazados en climas áridos. Validación del método y estudio de casos]. J Progr Renew Energy Environ 2007;11:01.89–95 (Avances Energ Renov Medio Ambiente).

[27] Meir IA, Pearlmutter D, Etzion Yair. On the microclimatic behaviour of two semi-enclosed attached courtyards in a hot dry region. Build Environ 1995;30:563–72.

[28] Architectural Construction Department. Superior Technical School of Architecture (Departamento de Construcciones Arquitectónicas. Escuela Técnica Superior de Arquitectura). Universidad de Las Palmas de Gran Canaria, España. editorial.dca.ulpgc.es/...proyecto/3-1-Proyecto-DiagnosticoBioclimatico.doc.

[29] U.S. Department of Energy. Energy plus simulation software. Energy Efficiency and Renewable Energy. EERE; 2012.

[30] Liu, Jordan. The long-term average performance of flat-plate solar energy collectors. Sol Energy 1963;7:53.