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Thermo – lighting optimization proposal for school buildings in subtropical hot – humid climates: Monitoring and computer simulation on autumn period

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ABSTRACT

The rate of glazed area to floor area and to sun-exposed wall area of a room is one of the main relationships in energetically optimized architecture. This paper shows the results of the hygrothermal and lighting behaviour on autumn period, of a Primary School which was monitored for a year. It was selected from a universe of 60 school prototypes located in Resistencia, a hot-humid mid-latitude city in the Northeast of Argentina. The measurements were compared with simulations through Simedif, Ecotect and its Radiance interface, in real occupation conditions. A root mean square error of 0.6 °C was obtained. Then the thermal behaviour of the building with an optimized envelope by regulating its glazed areas was simulated for the same period of autumn. Better hygrothermal comfort conditions were verified with the optimization proposal, as well as higher levels of illuminance and uniformity in the spatial distribution of natural light, which would be reflected in an electrical consumption saving for lighting. Consequently, this study will contribute to determining criteria for sizing suitably glazed areas to achieve wellness conditions, which are not covered in full in the current Planning and Building Codes, for school buildings in Resistencia.

1. Introduction

In school buildings of subtropical hot-humid climate cities, light and hot become antagonistic factors, because the maximization of glass surfaces for better views and more natural lighting [1–3], often contrast with the need to avoid overheating of indoor air in summer as well as visual discomfort caused by glare [4]. At the same time, solar energy is a renewable and abundant regional resource, which if well used through passive design, can help to reduce electricity consumption in the education sector.

One of the main relationships in passive solar energy building design [5] is the glass area per orientation to the floor area and to the facade area of a room [6,7]. A conscientious design in building windows is becoming increasingly important to health, behaviour, productivity and energy savings. This requires careful modelling and design optimization. Predictive capabilities of building simulation have been reflected in many areas of architectural design and energy assessment of buildings and urban environments [8–10]. In relation to this, Planning and Building Codes play a decisive role in regulating the development of urban environments [11].

In the city of Resistencia (27.45° South Latitude; 59.05° West Longitude; 52 m Altitude), Province of Chaco, which belongs to the bio-environmental zone I-b 'Too Hot', according to the Argentine Institute of Standardization and Certification regulations—IRAM [12], windows collect solar radiation at any season of the year. This is because its urban grid is half orientation (45° relative to true North). Therefore, the application of recommended values according to Criteria and Basic Standards of School Architecture of the Ministry of Education, Culture, Science and Technology of Chaco, based on the IRAM norms [13], would not be valid. They state that the maximum ratio between glass area (considered from 1 m height) and floor area, not be excessive, recommending a maximum of 18% in locals facing East or West and 25% in locals facing North or South.

Moreover, this norm limits windows sizes defining the ratio of glazed area by floor area. However, geometry shows that, for the same floor area, a rectangular base classroom has more sun-

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exposed wall area than a square base one of the same height [6]. This can result in increased flows of heat through the sunny walls in the first case, and therefore, lead to overheating during autumn and spring in a very hot and humid climate, as Argentinian Northeast Region.

Different fields of research that investigate how indoor temperature interacts with lighting, showed that discomfort glare due to daylighting anticipates overheating related to solar radiation. These take into account the influence of the window's transparency on thermal parameters [14]. For example, the work of [4] tested the effects of thermal comfort on glare sensation and showed different glare responses in similar lighting scenarios with different perceived temperatures.

The use of automated shading and daylighting systems to improve the energy performance of buildings has increased considerably in recent times. Konstantoglou and Tsangrassoulis [15] concluded through a review of previous works that the complexity of automatic control systems significantly affects their efficiencies although the energy performance of buildings and the level of thermal comfort of the occupants considerably improve with the use these systems.

The present research is focused on determining criteria for sizing suitably glazed areas by floor area and sun-exposed wall area, for school buildings of the urban zone of Resistencia, which lead to achieving the necessary wellness conditions. For this purpose, a number of 63 hygrothermal and lighting behaviour monitoring of seven school buildings in Resistencia was carried out during a year, with last generation instruments provided by the Ministry of Education of Chaco. Monitoring also included interviews and surveys with teachers and students, as well as informative talks.

This paper shows the results of the measurements carried out during the period of autumn 2012 in a Primary School, and its comparison with simulations made by the computational tools SIMEDIF, ECOTECT and its Radiance interface, in real conditions of occupation. Furthermore, the thermal and lighting behaviour of the building with an optimized envelope simulated for the same period of autumn is analysed, in order to define criteria of regulating glazed areas suitable for regional reality.

As previously mentioned, these criteria are not covered in full in the current regulations for a mid orientation urban centre, so this work will contribute to the formulation of a comprehensive database for school buildings of the urban zone of Resistencia, which could be taken as a reference for school buildings of subtropical hot-humid climates. In addition, there are no systematic studies, that consider thermal and lighting issues simultaneously in buildings with intermittent occupancy such this developing, from a wide universe of analysis in the city of Resistencia, as representative examples of the regional situation. This work is also relevant because the measures, as well as the simulations, were carried out in real conditions of occupant behaviour, a problem that has not been sufficiently accounted for, according recent literature reviews [10,16].

2. Methodology

2.1. Measurement equipment

For the measurement of meteorological variables an *ONSET* (*USA*) *H21-002 Micro Station* was used. The school that is presented in this work is at a distance of 2.6 Km from the micro station. Internal variables were measured with *20 HOBO* (*USA*) *MOD.U12-012 data loggers*. In Table 1, the variables and equipment used are detailed.

The data loggers were fixed on one of the walls of each local selected (generally the opposite to the blackboard) 2.10 m high and in the centre of it, equidistant to the side windows, protected from direct solar radiation and from air conditioning equipment and separated from the wall by a medium density fibreboard plate, so do not take the surface temperature of it. Lighting measurements are representative of natural and artificial lighting average, not being the objective to record illuminances on the work plane (0,80 m) as recommended, but get a local average to guide humidity and temperature data analysis. Then, overheating could be attributed to direct solar incidence when there are excessive illuminance increases, or wasting energy when lights are left on at night.

2.2. Selected prototypes

Seven establishments were selected from a universe of sixty school prototypes of Resistencia city, of initial, primary, secondary and tertiary level, which have been referents in different governance periods, significantly repeated in the Northeast Argentinean Region. This analytical units were systematised in a technical data bank verifying different situations of implantation (centric, periurban and suburban), orientation, typological conformation (open linear floor plan with galleries and double or simple bay compact floor plan, from one to three levels) and techno-constructive solutions (heavy and medium heavy traditional technology). The selection criterion to monitor prototypes based on that they have a high exposure to direct sunlight as a common factor.

2.3. Monitoring schedule

An uninterrupted schedule of measures was carried out from April 2012 to March 2013 inclusive, monitoring the seven buildings grouped by their proximity, into three groups (one each ten days of each month). That programming responds to the need of getting a good database for statistical analysis, as well as the optimization of the number of sensors available, alternating the measured locals. The prototype that is presented in this work was monitored during the second ten days of each month, with a sampling frequency of 10 min. To display the measurement results, the period of autumn 2012 was selected, as it is the worst season for school activities because the atmosphere is still warm and windows already collect solar radiation. Specifically, we detail eight days of the June monitoring that presented the most critical cases of overheating and cooling.

2.4. Statistic analysis

In order to determine parameters that allow to analyse the collected data and assess appropriate glass areas by floor area and by sun-exposed facade area, correlations were made from the definition of hygrothermal and dimensional indices, for each local monitored, taking as a reference proper comfort ranges according to the climatic reality of the Northeast Argentinean Region, given by Jacobo and Vedoya [17], researchers of the Technological Research Institute for Human Habitat Design of Faculty of Architecture and Urbanism, Northeastern University:

- Maximum Temperature with RH between 20% and 50% = 29.5 °C;
- Minimum Temperature with RH between 20% and 50% = 25.0 °C;
- Minimum Temperature with RH 80% = 20.0 °C.

A winter comfort zone from 20 to 25° C and a summer comfort zone from 25 to 29 °C based on these reference values were differentiated. The most useful indicator was a *Combined Discomfort Index by Temperature and Relative Humidity*, *Id* (*T* + *RH*) [Eq. (1)], considering a temperature comfort range between 20 and 27 °C and a relative humidity comfort range between 35% and 65%. This is a relative index between the inner and outer discomfort situation, as

Table 1
Variables measured and equipment used.

Meteorological Variables measured	Measurement equipment	
Solar Global Irradiation (W/m^2)	Solar Radiation Sensor, HOBO S-LIB- M003 Silicon Pyranometer	*ONSET (USA) H21-002 Micro Station*
Dry Bulb Temperature (°C) Relative Humidity (%)	ONSET S-THB-M002 Temperature and Relative Humidity Sensor, with HOBO MOD. M-RS3 weather shelter.	
Wind speed (m/s) and wind direction	Wind Speed and Direction Sensor. ONSET MOD. S-WCA-M003 Weather vane and anemometer.	
Internal Variables measured	**Measurement equipment**	
Dry Bulb Temperature (°C) Relative Humidity (%) Illuminance (Lux)	20 HOBO (USA) for Temperature/Relative Humidity/Light MOD.U12-012 data loggers	

the ratio between two observable frequencies and its complement is the *Temporary Comfort Index* (*It*) [Eq. (2)]

$$I_d(T+HR) = \frac{N_i}{N_e} = \frac{N_i/N}{N_e/N} = \frac{f_i}{f_e} \quad (1)$$

$$I_t = \frac{N_c}{N} = 1 - \frac{N_i}{N} = 1 - f_i \quad (2)$$

where: $\boldsymbol{N_i}$ is the number of measures inside a room and $\boldsymbol{N_e}$, the number of measures of exterior ambient, that are out of the comfort range (20–27 °C); ***N*** is the total number of measures in the considered period; $\boldsymbol{f_i}$ is the observable frequencies in an interior ambient and $\boldsymbol{f_e}$ is the observable frequencies in an exterior ambient, that are out of the comfort range; ***Nc*** is the number of observables that are inside the comfort range.

On the lighting aspect, *Index by Excess or Low Illuminance* were defined, *Id* (*Illum+*) [Eq. (3)] and *Id* (*Illum−*) [Eq. (4)], and its complementary, *Temporary Comfort Index* (*It Illum Range*) [Eq. (5)], considering a comfort visual range between 300 and 500 lx, in relation to the average Solar Irradiation value of sunny days, 500 W/m^2. The *Illum+* index allowed inferring overheating by direct solar gains when illuminance values exceed the limit of comfort. The *Illum*−index allowed inferring natural lighting lack of use and direct solar incidence obstruction, when the Solar Irradiation was greater than 500 W/m^2, which contribute to unnecessary energy consumption for artificial lighting.

$$I^{+}_{dIllum} = \frac{N_{c+}}{N} \quad (3)$$

$$I^{-}_{dIllum} = \frac{N_{c-}}{N} \quad (4)$$

$$I_{Il} = \frac{N_c}{N_t} \quad (5)$$

where: ***N*** is the number of measures in which Solar Irradiation was greater than 500 W/m^2; ***Nc+*** is the number of measures in which interior illuminance was greater than or equal to 500 lx, and ***Nc-*** the ones in which Illuminance was less than or equal to 300 lx, when Solar Irradiation was higher than 500 W/m^2; ***Nc*** is the number of measures in which Illuminance (***Ill,i***) was inside the comfort range (300 lx ≤ Ill, i ≤ 500 lx) and ***Nt*** is the total number of measures in the considered period.

In order to obtain a comprehensive diagnosis of the hygrothermal situation, the overall behaviour between the seven monitored buildings was compared, determining the best performance case that is presented in this paper.

3. Case study

The prototype under study is the School of Primary Education No 1058, located in the educational complex of San Miguel neighbourhood of Resistencia city. It is inserted in a residential zone of low building density (Fig. 1) and also includes a secondary school and a kindergarten, which were monitored simultaneously.

These prototypes are representative of the official production of school architecture current run in the Province of Chaco, characterized by the application of traditional technology of brick load-bearing masonry, flush joint in the outside seen and all indoors revoked; reinforced concrete structure; interior plasterboard ceilings with 38 mm glass wool thermal insulation, accompanying the 30% slope under AU-L1 metal cover; bent sheet No 16 openings and 3 + 3 mm laminated glass. The Primary School No 1058 is an open-plan prototype with linear development in 'E', around courtyards and multipurpose room. It includes 10 common classrooms arranged in 3 transverse wings along with 4 common classrooms and 4 special classrooms (library, computer room and 2 workrooms) arranged in a longitudinal wing. It works in two shifts (morning and afternoon) with an average of 20 students per classroom. In the same building works the UEP No 172 Tertiary Institute, in two shifts (afternoon and night) with an enrolment of 1001 students aged 18–60 years, since May 2012.

Each classroom has 4 windows located on opposite sides (cross ventilation), with the following characteristics:

a) SE or NE Exposed Face: Windows made of 2 pennants of 0.45 × 2.00 m and 2 sliding panels of 1.15 × 2.00 m (with sunshades);
b) SW or NW Face with gallery: 2 windows with sliding panels of 1.20 × 2.00 m. On this same side doors are located, which have two top fixed panels of 0.46 × 1.50 m and two opening leaves of 2.05 × 1.50 m.

As protective devices, classrooms have 0.80 × 2.00 m sunshades covering 50% of the windows towards SE and NE, and galleries towards NW and SW. Depending on the case, internal curtains were incorporated. In some classrooms, in the absence of curtains, users placed daily papers or posters in the windows to block direct solar radiation (Fig. 2).

Table 2 shows some dimensional indicators of common classroom case study modules, which references are: (***expA***) sun-exposed facades and roofs area discounting gA; (***gA***) total area of glass in windows and doors through which direct sunlight pass, considering the reduction corresponding to the protection provided by sunshades and galleries; ($\bar{\alpha}$) weighted average solar absorptance of all the sunny surfaces; (***gF***) glaze factor calculated for each room distinguishing them by the cardinal orientation in which glass windows and doors are positioned; (***vsF***) volumetric shape factor of each local, which measures the ratio between the area of heat loss and the volume of air to be heated/cooled; (***psF***) plan shape factor of each local, ratio of the floor width and length.

These common classrooms have 4 luminaires of 2 fluorescent 36 W tubes each and two ceiling fans. Data provided by the provincial biller company indicate that the school presented

Fig. 1. Primary School Location and pictures of its highly exposed to direct solar radiation facades.

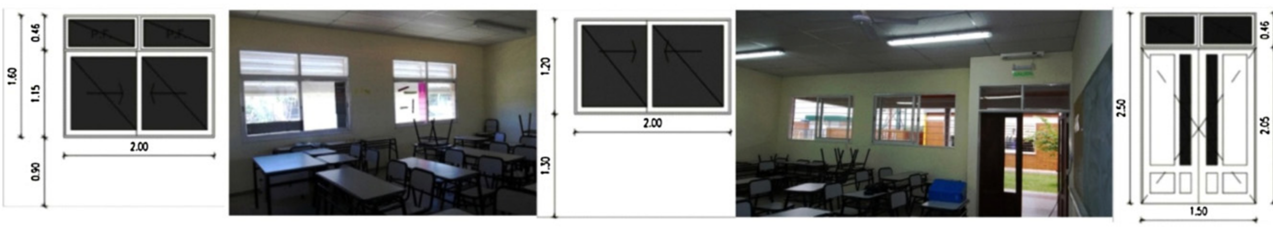


Fig. 2. Details and pictures of a type classroom openings.

Table 2
Dimensional indicators of type classrooms.

Type Classroom	Vol. (m^3)	Height (m)	Floor Area (m^2)	expA (m^2)	gA, a (m^2)	gA, b (m^2)	gF, a	gF, b	$\bar{\alpha}$	vsF (m^{-1})	psF
Classroom 5	139	3	46.4 (6.95 × 7.00)	90.7	2	4.24	0.012	0.025	0.53	0.67	0.99
Classroom 7	139	3	46.4 (6.95 × 7.00)	127.27	2	4.24	0.006	0.013	0.38	0.93	0.99

the maximum power consumption in May 2010 with a value of 3633 kWh as well as in October and November 2011, with values of 3700 kWh and 3500 kWh, respectively, while consumption in June and September 2011 was 3300 kWh.

4. Hygrothermal – lighting monitoring results of june (late autumn)

4.1. Meteorological variables measured

The monitoring period covered eight days from 12/06/12 at 12:00 until 19/06/12 at 12:00 h (Fig. 3). It can be clearly distinguish two phases within that period, the first (warm) from 12 to 15/06, with an average temperature of 29.3 °C and an average relative humidity of 76%, which maximum temperatures are out of the comfort upper limit, away from the statistical values for this month in the city of Resistencia. In this phase, the maximum wind speeds are in the order of 8 m/s and northeast predominant direction, and maximum global solar radiation in the order of 624 W/m^2, with some cloudiness. The second phase (cool) from 16 to 19/06, does record similar values to the statistics, with a sharp decrease in average temperature (17.5 °C) and increase of relative humidity (88%), decrease of wind speed with a maximum in the order of 3.9 m/s and South predominant direction, and global solar radiation with a maximum in the order of 211 W/m^2, corresponding to cloudy days. This phase is completely outside the comfort zone.

4.2. Monitored rooms

The HOBO sensor of each monitored classroom location is indicated in Fig. 4.

This month, classrooms 5, 7, 9, 11, 12 and 14 of the transverse wings were monitored. These have glazed areas orientated to SE and NW faces, and they are occupied in the morning shift (from 8:00 to 12:15 h) by an average of 20 students. Of these, classrooms 5, 9 and 11 are also occupied in the afternoon and night shifts (from 14:00 to 23:00 h) by an average of 35 students of the tertiary institute. Of the longitudinal wing, classrooms 2 and 4 were monitored, which work in the morning, the Library and Workroom A that are occupied from Monday to Thursday afternoons and nights by an average of 45 students of the tertiary institute. Except for classroom 5 and the Workroom, classrooms were protected with internal shading devices at SE and NE. During weekdays classes developed normally. The occupants only made use of fans in the warmer days and permanent artificial lighting during occupancy hours.

4.3. Indices analysis

According to global diagnosis, this prototype had the best hygrothermal behaviour, although the design of its openings should be modified to allow proper distribution and use of natural light. It is most of the year below the rank of visual comfort because the entry of excessive solar radiation from NE and SE is blocked by internal

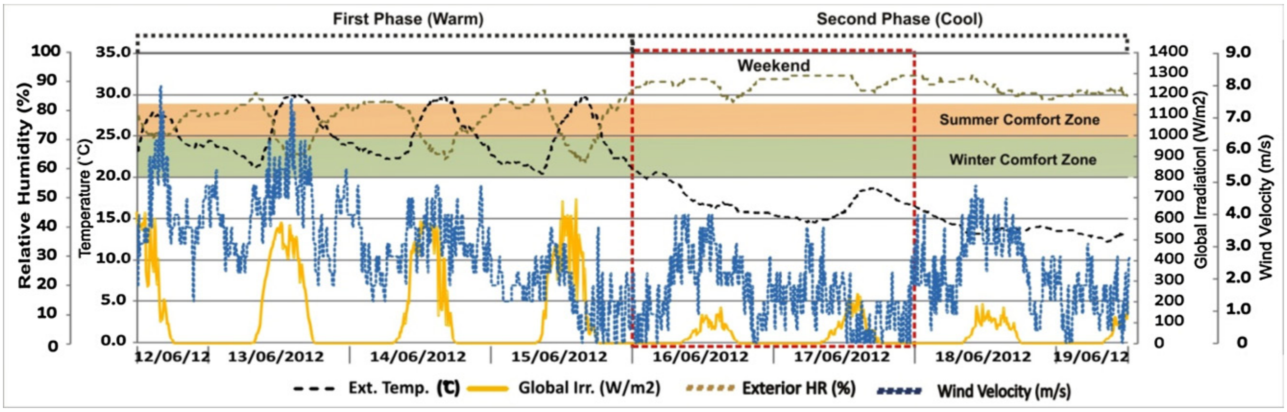


Fig. 3. Evolution of meteorological measured variables, period 12/06/12–19/06/12.

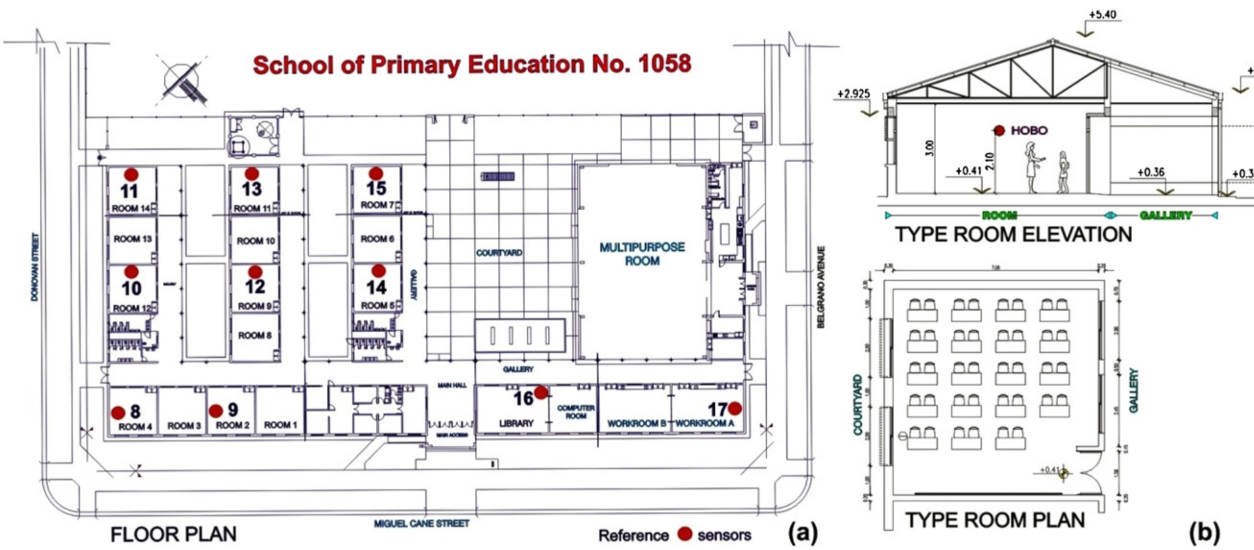


Fig. 4. School plan with the location of sensors (a). A type classroom plan and elevation (b). References: Room 4 (#8), Room 2(#9), Room 12 (#10), Room 14 (#11), Room 9 (#12), Room 11 (#13), Room 5 (#14), Room 7 (#15), Library (#16) and Workroom A (#17).

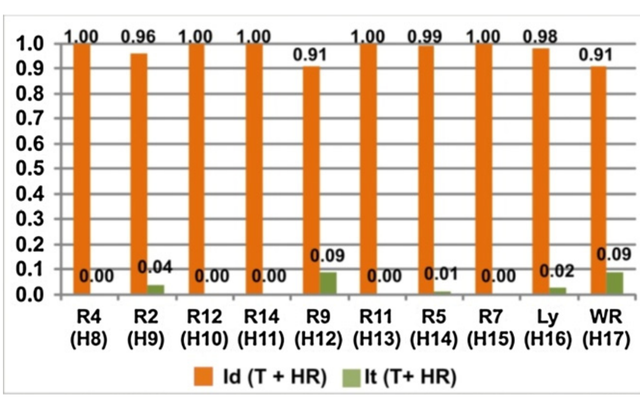


Fig. 5. Hygrothermal comfort indices.

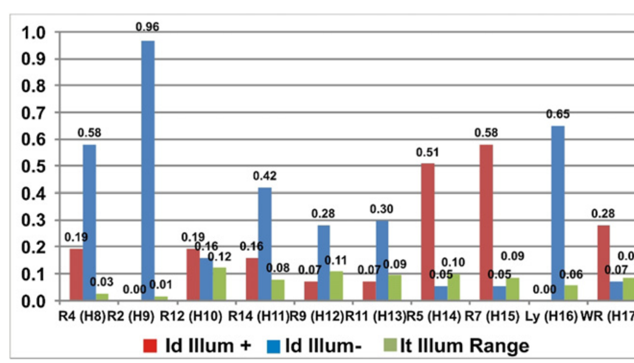


Fig. 6. Illuminance comfort indices.

curtains. On the other hand, hygrothermal discomfort indices are high throughout the period of June monitored (Fig. 5). Such discomfort is mainly due to overheating and high relative humidity. Overheating occurs to a greater extent in classrooms where the tertiary institute works, because of the high degree of occupation. In classrooms 5 and 7 this situation coincides with high rates of visual discomfort due to excessive illuminance (Fig. 6).

4.4. Internal variables measured

Figs. 7–12 illustrate the evolution of temperature, relative humidity and illuminance (natural + artificial) of the most representative monitored rooms, grouped according to their characteristics, in contrast to the meteorological variables. In the temperature graphs, the differentiated hygrothermal comfort zones for winter (20–25 °C) and summer (25–29 °C) are marked in two colours; in the relative humidity graphs, the comfort zone between 35 and

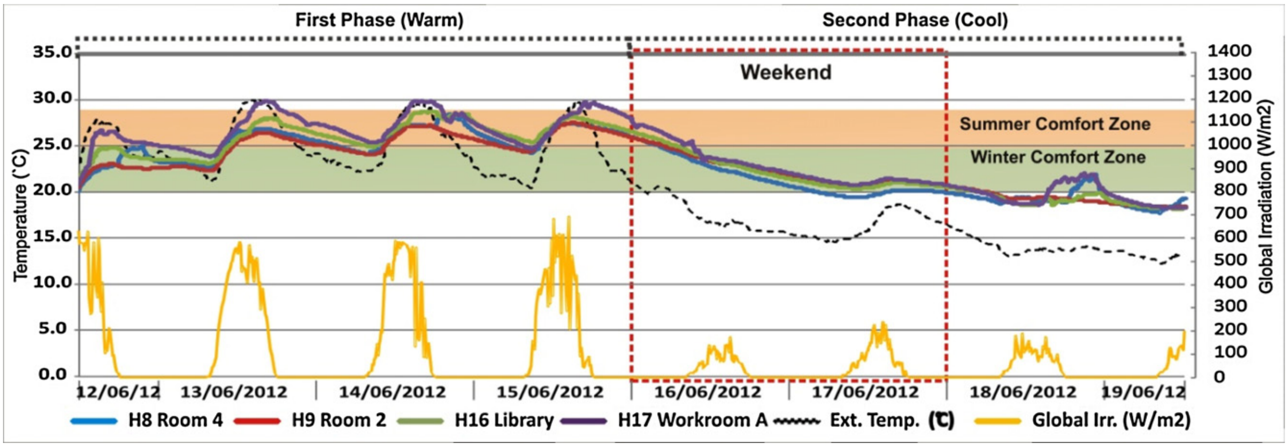


Fig. 7. Temperature evolution of locals with glazed areas facing NE–SW.

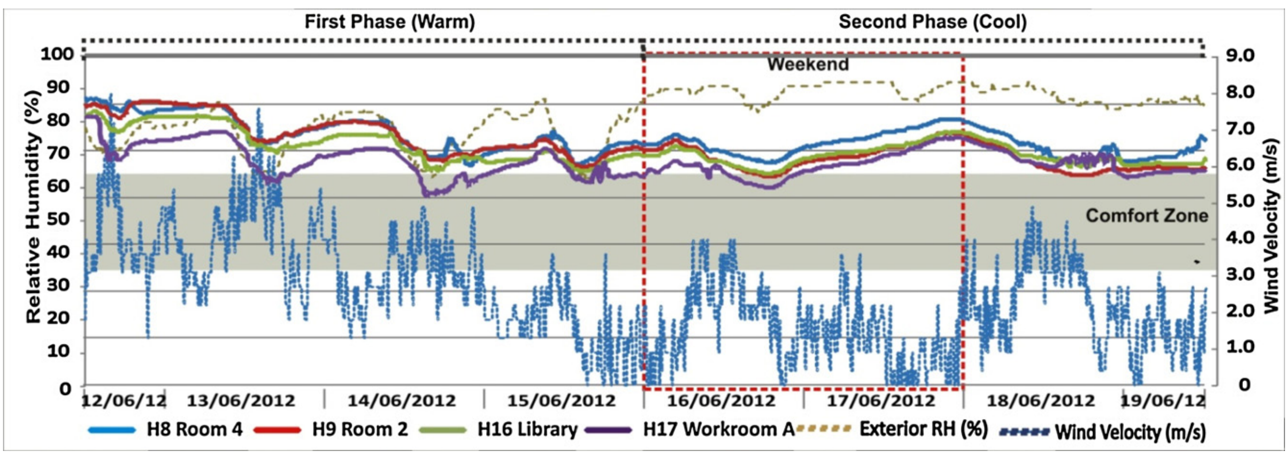


Fig. 8. Relative Humidity evolution of locals with glazed areas facing NE–SW.

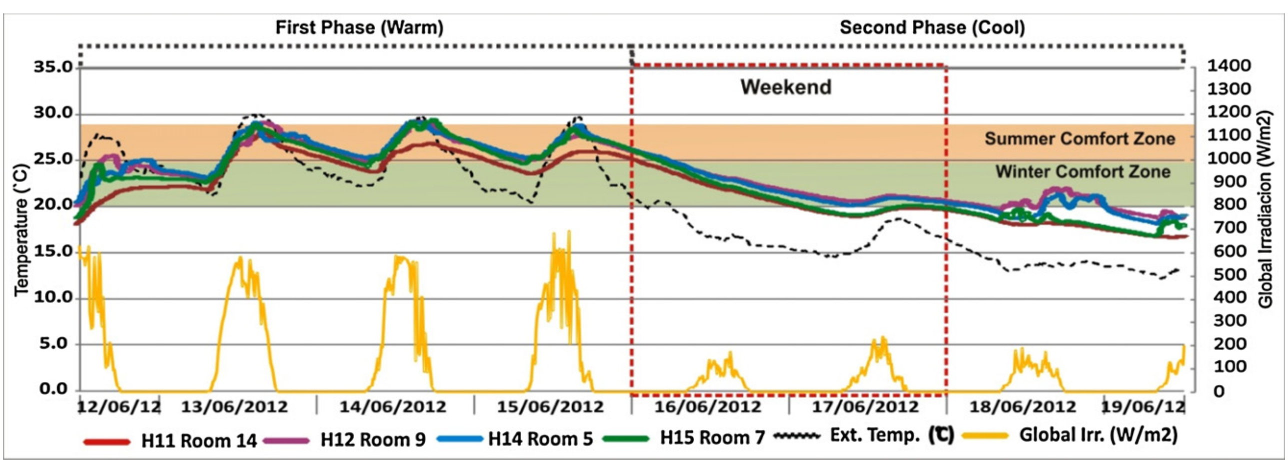


Fig. 9. Temperature evolution of locals with glazed areas facing SE–NW.

65% is indicated and in the illuminance ones, the visual comfort zone between 300 and 500 lx is highligted.

In the ***first phase*** (***warm***), locals are at an average temperature of 26 °C and 73% of relative humidity. The combination temperature—humidity places these classrooms outside the comfort range, because of the high relative humidity. Workroom A and classroom 5 have peak temperatures exceeding the upper comfort limit (29.9 °C and 29.1 °C) with relative humidity of 73 and 77% respectively. It is highlighted here the influence that occupancy loads by adults of the tertiary level have, producing 2–3 °C of temperature increase, compared with the occupation by children which is almost imperceptible. Minimum temperatures remain near the upper limit of winter comfort zone. The average thermal amplitude is 4.4 °C, while the difference between the average indoor—outdoor temperature is 1.7 °C, indicating the existence of ventilation losses through gates and/or open windows or large infiltrations when

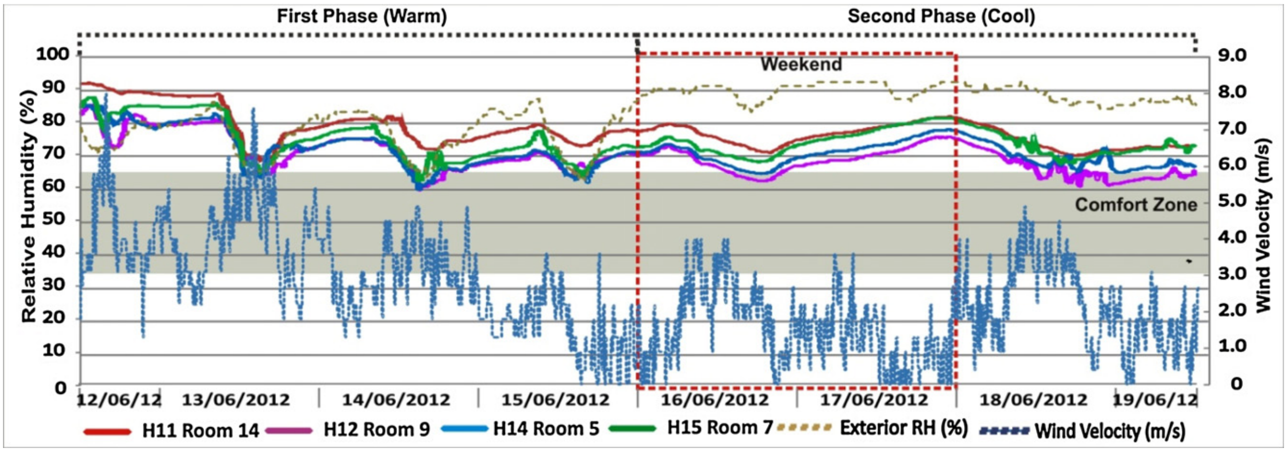


Fig. 10. Relative Humidity evolution of locals with glazed areas facing SE–NW.

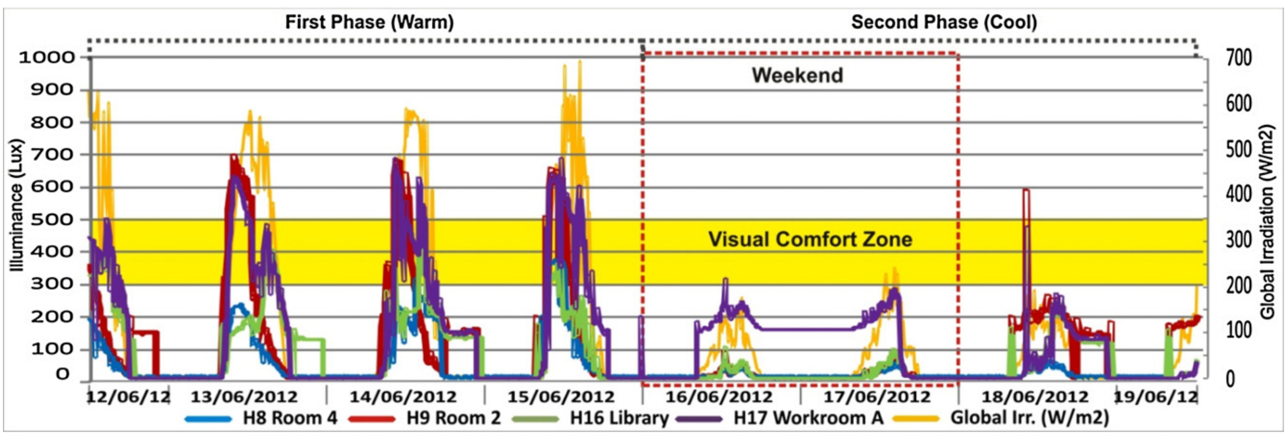


Fig. 11. Illuminances evolution (natural + artificial lighting) of locals with glazed areas facing NE–SW.

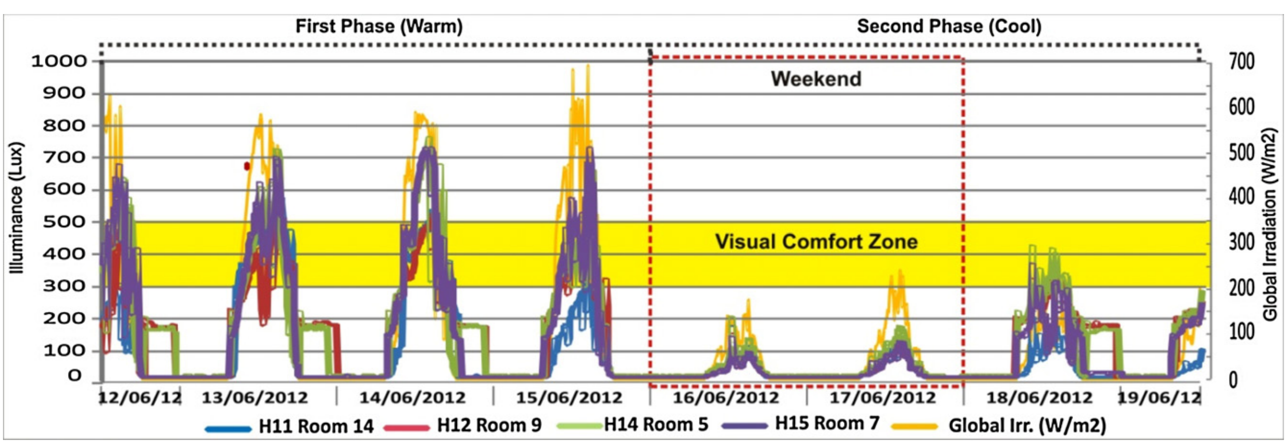


Fig. 12. Illuminances evolution (natural + artificial lighting) of locals with glazed areas facing SE–NW.

they are closed. The average illuminance is 143 lx, well below the recommended limit, although the average maximum is 556 lx.

In the ***second phase*** (***cool***), locals are to an average temperature of 21.1 °C and 72% of relative humidity, therefore outside the relative humidity upper limit. The average thermic amplitude is 2.9 °C, while the average indoor- outdoor temperature difference is 4.8 °C, indicating a slow response of the building envelope to the temperature drops. The average illuminance is 55 lx, well below the recommended limit, with an average maximum of 218 lx. It should be noted that the most influential factor in both phases is the relative humidity that exceeds the upper comfort limit.

Faced with the variability of external conditions in this autumn period, locals respond better to low temperatures than to high ones and thus the high probability of occurring overheating. Classrooms that have three facades exposed (7, 11, 14, 4 and Workroom A) while are in good comfort conditions during the typical days of June to Resistencia climate, also present discomfort conditions due to unexpected increases in temperature and humidity. Classroom 7 for example, fluctuates in the summer comfort zone in the warm phase, exceeding at times the upper limit, while in the cool phase falls below the lower limit. This is to be expected given its high volumetric shape factor that negatively influences the thermal comfort and energy consumption of it. For this reason, a Split air conditioner was incorporated in 2013. Temperatures near 29 °C are excessive when combined with high relative humidity, which remains well above 65%, being the most influential factor in both phases. Instead, in the coolest phase, the unavailability of sufficient solar radiation contributes to the classroom cooling. Only classrooms 9 and 5 are in the comfort zone during occupancy hours, at this phase.

In the month of June increases the time lapse of higher illuminance, given the lower elevation angle of the sun above the horizon that favours greater sunlight on buildings. While this is beneficial in cold days, direct solar incidence must be controlled on the glazed and opaque areas, for susceptible overheating. Room 4 and Workroom A have the same behaviour in terms of illuminance in the morning, passing the 500 lx, given the orientation of their windows to NE without internal protection and with sunshades that protect only 50% of them. The consequence of this is the overheating produced, so it is estimated that the sunshades are not an effective shading device during the first hours of sun for this time of the year. While in Room 4 illuminance values decline towards evening, in the Workroom, past the solar noon, values increase again by the contribution of diffuse illumination on the SW face. In Room 2 illuminance values are lower because internal curtains are closed due to direct solar incidence, so not even with artificial lighting the 500 lx are reached.

In Rooms 5 and 9, the maximum illuminances occur between 12:00 and 14:00 h and the maximum temperatures between 14:00 and 16:00 h. Therefore, a strong contribution of diffuse radiation is seen when the sun does not incident directly through the glazing. The maximum temperature peak coincides with the maximum external temperature at 15:00 h. The combined effect of internal occupation gains, sun-air temperature and natural ventilation gains are added to that. Higher illuminances are seen when the sun strikes the NW face.

5. Validation and simulation in SIMEDIF and ECOTECT

To guide the proposals of optimized design, building theoretical models were made in SIMEDIF for Windows [18] and ECOTECT V5.20 [19], in an interactive modelling methodology, making use of the potentialities offered by each computational tool. SIMEDIF is a code developed at the Non-Conventional Energy Research Institute (INENCO, Argentina) that has been largely validated throughout years of experimental work by numerous research groups [20].

In both programs, the measured meteorological data were entered and uniform parameters were defined in terms of characteristics and physical properties of the various components and operating conditions for each space analysed. Absorption and convective coefficients were also defined in SIMEDIF considering the average wind speed of the period and in relation to the building under study, as well as indexes and radiation areas, whose determination was helped by ECOTECT, from the sun exposure analysis [21].

For space reasons, only two of the most representative locals simulated in 6 full days of the period are showed, two of them without occupation (16/06 and 17/06) for being weekend. Room 7 which has three facades exposed and Room 5 with two facades exposed. Figs. 13 and 14.

Both rooms, located in the transverse wing overlooking the training courtyard with openings to SE–NW, have an important hourly variation in its internal gains, with a high level of activity. Room 7 (7th grade) is occupied only in the morning shift, while Room 5 (6th grade) is occupied in the morning shift and in the tertiary level afternoon and night shifts.

Two indices were used to validate between simulated and measured data: the *Root mean square error* (RMSE) and the *Mean absolute percentage error (MAPE).* The RMSE [Eq. (6)] quantify the deviation magnitude between measured and simulated values in terms of the variables units by the square root of the mean square error. The MAPE [Eq. (7)] is a performance indicator that measures the size of the absolute error in percentage terms.

$$\mathrm{RMSE} = \sqrt{\frac{\Sigma_{i=1}^{N}[(x_{sim})_i - (x_{med})_i]^2}{N}} \tag{6}$$

$$\mathrm{MAPE} = \frac{\Sigma_{i=1}^{n}\frac{|x_{med}-x_{sim}|}{|x_{med}|}}{N} \tag{7}$$

where $\boldsymbol{x_{sim}}$ represents the simulated values, $\boldsymbol{x_{med}}$ the measured ones, and **N**, the number of measurements.

In Table 3 we present the values of RMSE and MAPE calculated for the total period, for the school days and for the weekend. The RMSE values of the rooms' temperature simulated with Ecotect and Simedif show average deviations lower than 0.8 °C for the whole period. In both rooms analysed, the RMSE is in the order of 0.6 °C in shool days. While the maximum RMSE, 0.8 °C, was observed in Room 7 for the weekend simulation through Ecotect. On the other hand, the *Mean absolute percentage error* does not exceed 2.5% for the whole period.

Similar orders of adjustment were verified in other classrooms for the period of June indicated. These demonstrate the validity of the physical models made with both software treated as complementary tools. Also, these settings were achieved with fewer simulations, thanks to the precision of the instruments used for the measurement of internal variables and local weather variables, as well as the training acquired in the simulation methodology in previous works [22]. Especially, as regards the specification of air changes and use of internal shading devices, whose control is difficult when simulating building in real conditions of use [9,23,24].

6. Optimization proposal

Once validated the school physical model by adjusting the simulations with the measured data of the autumn period, it was possible to make changes in the glazed areas and new simulations in ECOTECT under the same climatic conditions, analysing reliably the impact on interior temperature and lighting of different design alternatives. Before performing the redesign alternatives, average illuminance obtained was adjusted by Radiance Ecotect interface, with the average measured during the monitoring period.

Firstly it is considered that, during the hours of classrooms occupancy, the area of windows for natural lighting should be the appropriate in each case to ensure an illuminance level of 300 lx at least and 500 lx as optimal value on the work plane, according to Argentine Institute of Standardization and Certification—IRAM regulations [25], and as numerous lighting codes recommend [8] (e.g. CIE—International Commission on Illumination in Austria, CIBSE—Chartered Institution of Building Services Engineers in UK, IESNA—Illuminating Engineering Society of North America, etc.). Besides, it is considered that the distribution of light is space-dependent, influencing the shape of the classroom (square or rectangular) and the proportions and placement of windows.

Such study was possible from the Ecotect Radiance interface, trying different window sizes and locations to achieve the conditions mentioned. This is an export interface to the software RADIANCE [26], in a synthetic image system that allows taking advantage of the precision and complexity of lighting simulation algorithms, speeding modelling and calculation time for the con-

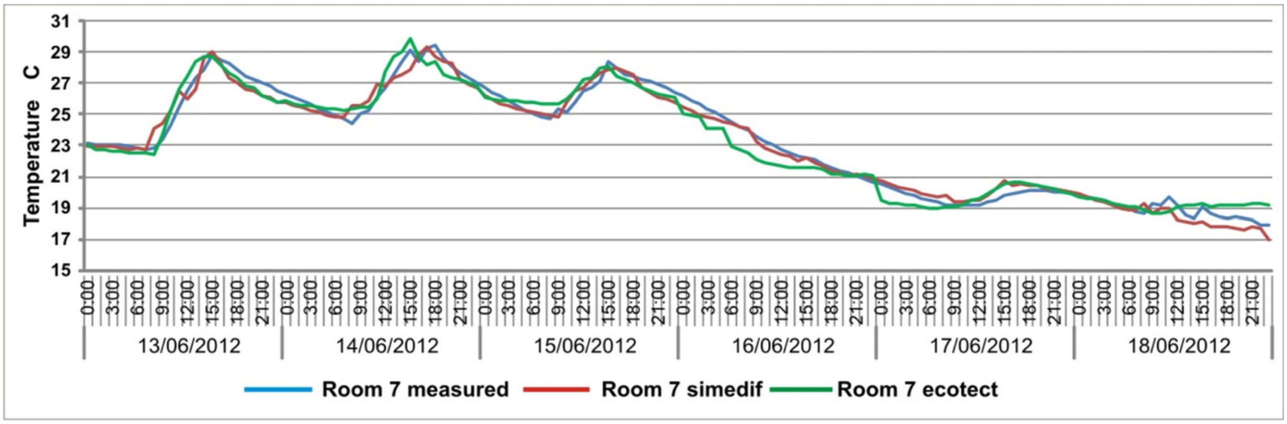


Fig. 13. Contrasting of measured and simulated data in Simedif and Ecotect. Room 7.

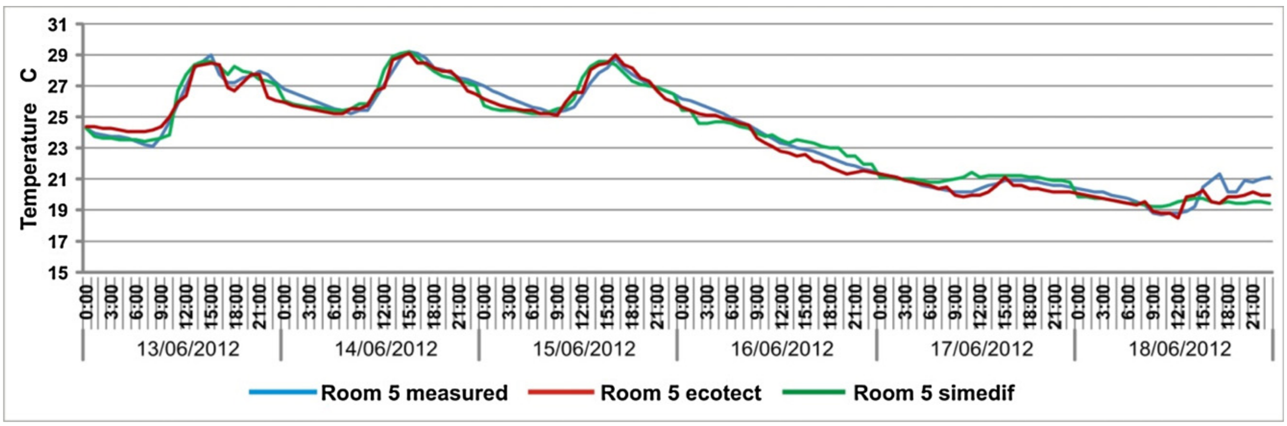


Fig. 14. Contrasting of measured and simulated data in Simedif and Ecotect. Room 5.

Table 3
Root mean square error (RMSE) and Mean absolute percentage error (MAPE) between measured values and simulated values with SIMEDIF and ECOTECT. Rooms 7 and 5.

		ECM (T °C)			MAPE (T %)		
		TOTAL PERIOD	SCHOOL DAYS	WEEKEND	TOTAL PERIOD	SCHOOL DAYS	WEEKEND
Room 7	ECOTECT	0.7	0.6	0.8	2.5	2.3	2.5
	SIMEDIF	0.5	0.6	0.4	1.8	1.9	1.2
Room 5	ECOTECT	0.6	0.6	0.5	2.1	2.1	1.7
	SIMEDIF	0.5	0.6	0.4	1.8	2	1.2

ceptual analysis required. Radiance remains the 'general-purpose' lighting simulation tool [27], validated extensively [e.g. 28,29]. Furthermore, a link between Radiance and a dynamic thermal programme has been demonstrated by others [30,31]. Concerning this, one of the main features of ECOTECT is its capability to interact with other analysis engines, as Radiance [8,32,33]. Ecotect can use data from and to Radiance, which can then use it to produce shading masks and analyse facade cover [21].

Radiance uses the latitude, longitude, and time zone of the site, as well as the date and time set by the user, for the basic calculation of sky properties. So the more representative type of sky was defined in relation to the in situ measurement time: 'Sunny', uses the clear sky CIE model to generate a localized sun and clear sky to represent the best condition (13, 14 and 15/06 monitoring days); 'Intermediate Sky', uses a sky between sunny and cloudy representative of midseason design conditions (16, 17 and 18/06 monitoring days). The testing was done in three hours for each day, 9:00 h, 13:00 h and 16:00 h. The calculation of natural light levels (lux) was deployed by a grid of analysis that was set for each classroom, at the work plane height (0.80 m). Displays representing the amount of light incident on each inner surface, with illuminance values in 'contour isolux lines' and 'false colour scale' were established.

In a first conceptual design stage the proposal based on two common classrooms with windows facing SE and NW, 5 and 7. These were taken as type classrooms to analyse the different situations of the building plan. Starting from the existing situation with a ratio of glass area by total floor area of 22% and a ratio of glass area by total facade area of 40%, redesign alternatives were made, using the same existing 3 + 3 mm laminated glass without adding external shading devices. Taking into account the diagnosis of the monitoring, surveys and in situ observations, the original sliding windows were discarded. They not only reduce the effective area of ventilation to 50% but also have multiple disadvantages, such as less tightness

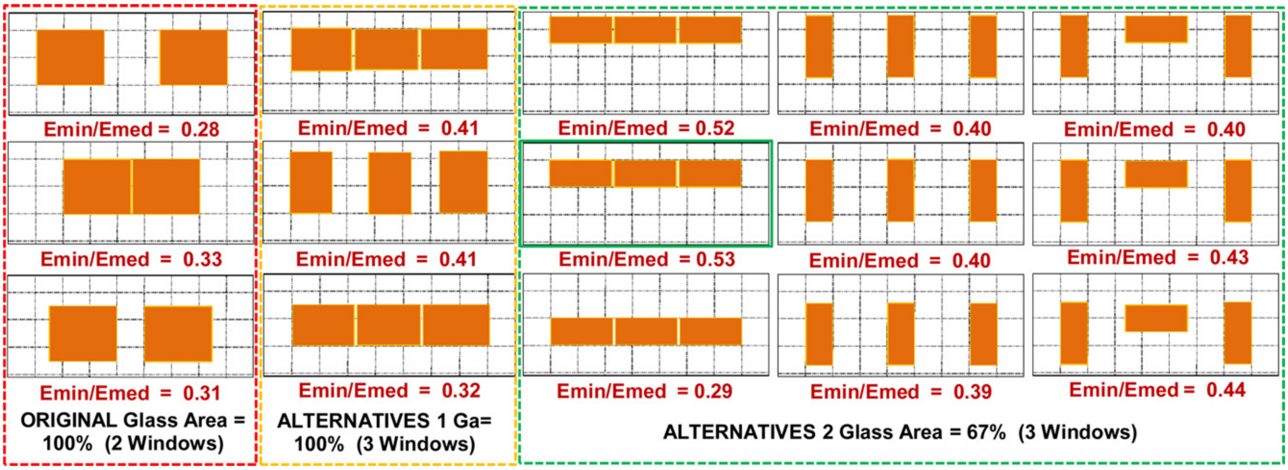
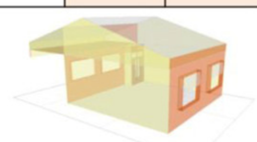
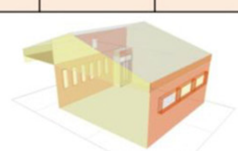


Fig. 15. Position alternatives of windows on the SE wall.

Table 4
Dimensional variables of the original and improved models, simulated by Ecotect.

	ROOM MODEL (m)	ORIENTATION	WINDOW SYSTEM	SHADING DEVICE	VAIN PROPORTION (m)	EFFECTIVE GLASS AREA (m)	FLOOR AREA	SUN-EXPOSED FACADE AREA	GA/FIA (%)	GA/FaA (%)
ORIGINAL	Widht: 6.95; Length: 7.00 Height: 3.00	SE	2 sliding windows with pennants	sunshades 50% of vain	Pennants: Widht: 2.00; Height: 0.45 Sliding: Widht: 2.00; Height: 1.15	6.4	50.8	15.2	12.60	42.11
		NW	2 sliding windows	gallery	Widht: 2.00 Height: 1.20	4.8	50.8	12.8	9.45	37.50
					Totals	11.2	50.8	28	22.05	40.00
IMPROVED	Widht: 6.95 Lenght: 7.00 Height: 3.00	SE	3 high projecting windows	none	Widht: 1.80 Height: 0.80	4.32	50.8	17.3	8.50	24.97
		NW	6 narrow and high vertical pivoting windows	gallery	Widht: 0.40 Height: 1.30	3.12	50.8	13.7	6.14	22.77
					Totals	7.44	50.8	31	14.65	24.00


ORIGINAL MODEL


IMPROVED MODEL

GLASS AREA RATIO REDUCTION (%)		GA/FIA (%)	GA/FaA (%)
	SE	4.1	17.1
	NO	3.3	14.7
	TOTAL	7.4	16.0

Table 5
Temperature and Lighting Averages of Room 7, originally measured situation and improved model.

ROOM 7	ORIGINAL	IMPROVED	ORIGINAL	IMPROVED	ORIGINAL	IMPROVED	ORIGINAL	IMPROVED	ORIGINAL	IMPROVED	ORIGINAL	IMPROVED
Date	Max. T°C	Max. T°C	Min. T°C	Min. T°C	Average T°C	Average T°C	Amplit.	Amplit.	Int.-Ext. Diff.	Int. - Ext. Diff.	Average Illum. (lux)	Average (lux) Illum.
13/06/2012	29.0	27.3	22.7	23.2	25.5	25.1	6.3	4.1	1.2	0.3	178	427
14/06/2012	29.5	28.5	24.3	25.4	26.8	26.6	5.2	3.1	2.1	1.4	190	432
15/06/2012	28.5	27.8	24.7	25.5	26.4	26.3	3.8	2.3	4.0	2.4	144	428
16/06/2012	26.2	26.4	20.5	24.4	23.1	25.4	5.7	2.0	5.2	7.6	25	214
17/06/2012	20.5	23.0	19.1	22.0	19.7	22.6	1.4	1.0	4.9	6.3	29	212
18/06/2012	19.8	21.3	17.8	20.5	18.8	21.0	2.0	0.8	3.4	6.9	88	217

and hard drive by users due to lack of maintenance. A projecting and pivoting window system was considered instead.

We divided the most exposed facade (SE), in modules of 0.80 × 0.80 m, respecting the heights of the existing ledge (0.90 m from the floor) and upper lintel (2.10 m from the floor). We also took into account the measures available in the market for the selected window system type. Based on such modulation, different windows configurations and locations were tested, with the original glass area and reducing the glass area to 67% compared to the first case (Fig. 15). The main project strategy to obtain such percentage was to limit the glazed area to the minimum recommended value for the demands of lighting, according to norms, taking into account an additional area of approximately 30% to be occupied by aluminium frames.

Respecting the window to wall ratio obtained, new possible locations were tested in rectangular proportions studying the variations in the light distribution on the work plane through Radiance—Ecotect. The aim was to prevent direct solar incidence

Table 6
Temperature and Lighting Averages of Room 5, originally measured situation and improved model.

ROOM 5	ORIGINAL	IMPROVED	ORIGINAL	IMPROVED	ORIGINAL	IMPROVED	ORIGINAL	IMPROVED	ORIGINAL	IMPROVED	ORIGINAL	IMPROVED
Date	Max. T°C	Max. T°C	Min. T°C	Min. T°C	Average T°C	Average T°C	Amplit.	Amplit.	Int.-Ext. Diff.	Int. - Ext. Diff.	Average Illum. (lux)	Average (lux) Illum.
13/06/2012	29.2	26.0	23.1	22.2	25.9	23.9	6.1	3.8	0.0	1.4	198	391
14/06/2012	29.3	27.4	25.3	24.5	27.0	25.7	4.0	2.9	2.7	0.5	205	386
15/06/2012	28.8	28.1	25.3	25.4	26.7	26.3	3.5	2.7	4.3	2.4	146	390
16/06/2012	26.2	25.2	21.4	23.4	23.7	24.3	4.8	1.8	5.2	6.6	35	193
17/06/2012	21.4	22.0	20.2	21.0	20.7	21.5	1.2	1.0	5.8	5.2	40	196
18/06/2012	21.3	20.4	18.7	19.7	20.0	20.2	2.6	0.7	4.0	6.1	143	195

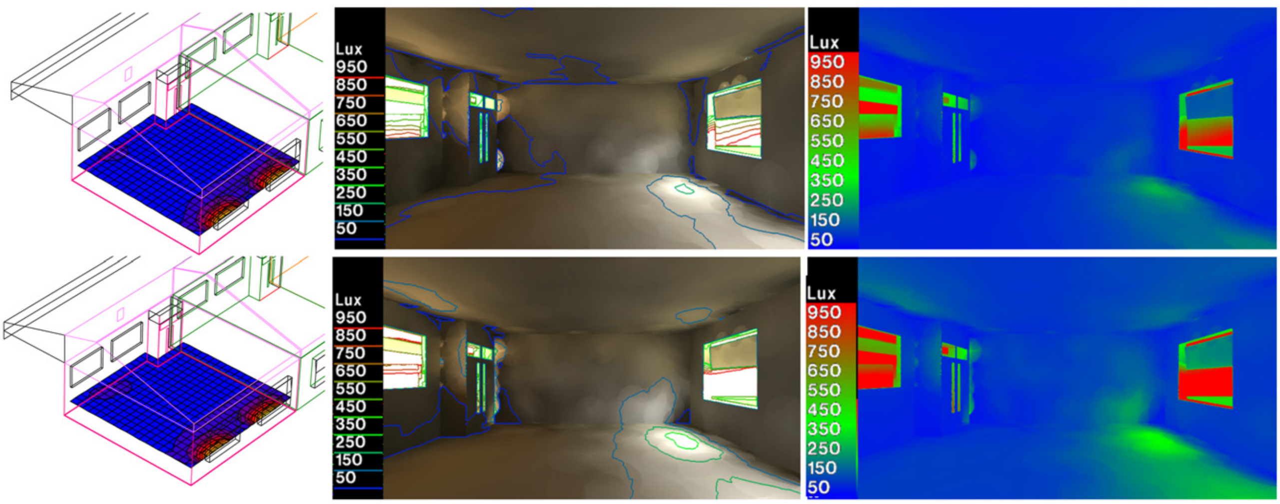


Fig. 16. Images of Room 7 original situation: analysis grid—contour lines and false colour (Radiance Interface). Date 14/06/12. Up 9:00 h. Down 16:00. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

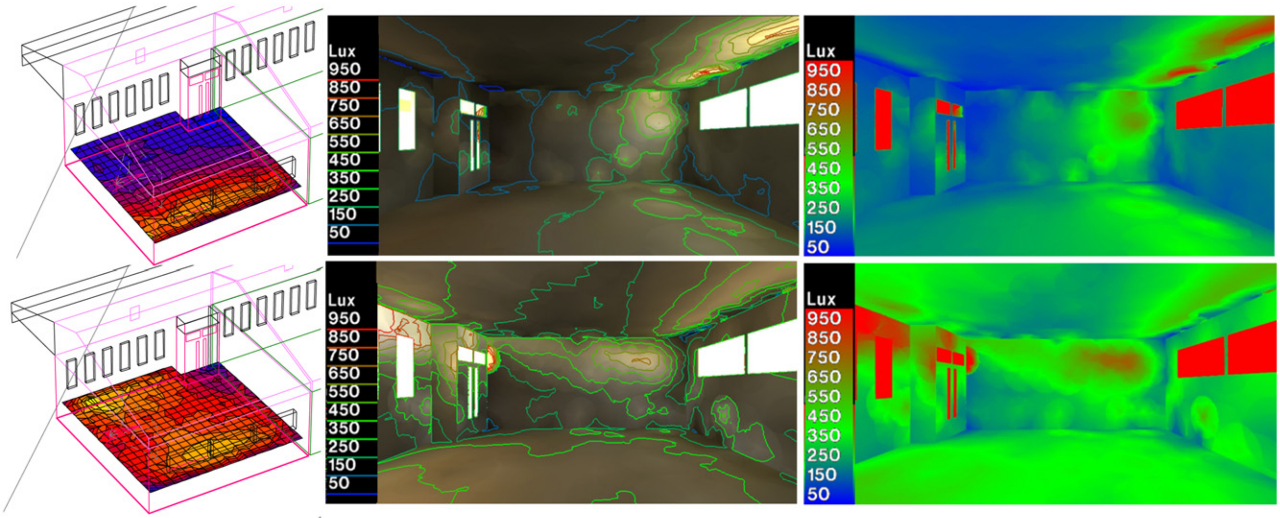


Fig. 17. Images of Room 7 improved: analysis grid—contour lines and false colour (Radiance Interface). Date 14/06/12. Up 9:00 h. Down 16:00. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

during morning hours in the period of June analysed, without adding external shading devices. Uniformity of light was then calculated, by the ratio between the minimum (Emin) and the medium (Emed) illuminance, at 9:00 h. It was verified that horizontal high windows (uniformity = 0.53) were the most efficient alternatives. So the system of projecting windows on the SE facade combined with vertical pivoting windows on the NW facade was selected.

Table 4 shows the dimensional variables of the original model and the improved model by ECOTECT, highlighting the percentages of the glazed area ratio reduction according to its orientation. The glass area by floor area ratio was reduced 7.4%, while the glass area by facade area ratio was reduced 16%, resulting in total relations of 14.65% and 24% respectively.

For all exposed above, the optimization proposal for such classrooms consisted in replacing sliding windows with pennants (always closed) and sunshades of SE facades, for high and long projecting windows. High windows are very interesting passive solar systems to use in educational buildings given the quality of the natural light they provide, allowing light to penetrate deeper into the room with a minimum hollow surface. At the same time, they allow ventilating state hot air that is located in the upper area because of stratification [34]. These windows also prevent direct solar incidence in early morning hours without adding external shading devices and as they open outwardly from the base, the air can flow without creating streams, keeping water out in rainy weather. On NW facades, which are protected by galleries, the 2 high and wide sliding windows were replaced by 6 vertical and narrow pivoting windows, so as to increase the effective area of diffuse illumination and ventilation at user's level. The advantages of this system are a high level of tightness thanks to its pressure lock, an easy operation allowing the users multiple positions, a wide field of view with little invasion of interior space and ventilation flow control. Considering that, the number of 4 air changes per hour which was established in the original model, was reduced to 2 in the improved model, during the occupied hours and to 0.25 during unoccupied hours.

Various studies revealed that ventilation shafts (especially active stacks), window-to-wall ratio and window-to-floor ratio, building position and building orientation are the most important elements in order to produce effective natural ventilation [35]. This air ingress and egress openings design, faced with respective fields of positive and negative pressures, according to the classroom volumetric shape and the prevailing winds attack angle, allow increasing both flow and speed of the internal ventilation by pressure difference. By the correct operation of them in hours of lower temperature, cooling of the building mass accumulation (structural ventilation) is optimized. In addition, it facilitates selective ventilation for users, enhancing evaporative cooling of the skin when the humidity is low (comfort ventilation).

In Tables 5 and 6 the temperature and illuminance averages of the real measured situation (original) and of the simulated improved situation, for classrooms 5 and 7 for each day of the assessed period are compared.

In the improved situation, it was verified the optimization of the hygrothermal and lighting behaviour, regulating sudden overheating in daytime periods with adequate ventilation, and cooling at night periods, thus entering the temperature curves to comfort band. Notable improvements were obtained in Room 7, which showed large fluctuations by having three facades exposed and higher volumetric shape factor to the same plan shape factor than Room 5. We succeeded in raising the minimum temperatures up almost 4 °C in cool days (Room 7) and reducing the maximum more than 3 °C on warm days (Room 5). In this way, the internal daily thermal amplitude decreased, without exceeding 5 °C as recommended value. At the same time, the indoor–outdoor temperature difference increased to almost 8 °C in the coolest day, which indicates the better behaviour of the constructive envelope from regulating glazed areas.

In terms of natural lighting, it was possible to increase the illuminance levels in the order of 212 lx in Room 7 and 164 lx in Room 5. Despite the values fluctuate around 400 lx in sunny days and not yet the recommended value of 500 lx is obtained only with natural lighting, classrooms are already within the visual comfort range, with greater spatial light distribution uniformity that results in lower illuminance contrast. Figs. 16 and 17 show the displays obtained through Radiance Ecotect interface for the original and improved model of Room 7, on the sunniest day, 14/06/12, at 9:00 and 16:00 h.

Applying the same model for NE–SW window orientations, illuminance values substantially improved by the contribution of North-east direct radiation. However, it was noted that the sunspot affects approximately 30% of the floor area and the opposite interior facade, with an excess of illuminance (more than 2000 lx), which can affect visual comfort while thermal improvements are not significant. It follows that window systems must be designed according to the orientation and should not apply the same criteria to all classrooms.

According to this analysis and for this particular case, the appropriate ratio of GA/FlA and GA/FaA would be 8.5% and 25% to SE and 6% and 23% to NW respectively, for an adequate use of natural light and hygrothermal comfort.

7. Conclusions

We analysed the results of the hygrothermal and lighting monitoring performed for 8 late autumn days of the month of June 2012, in a Primary school building of Resistencia, Chaco and its comparison with simulations ran by SIMEDIF, ECOTECT and its Radiance interface, in real occupation conditions. From the validation of thermal simulations with a root mean square error of 0.6 °C, we simulated for the same autumn period, the thermal and lighting behaviour of two type classrooms with different volumetric shape factor to the same plan shape factor, with an improved envelope by regulating its glazed areas.

The optimization of the direct gain surfaces, by a ratio of GA/FlA and GA/FaA of 8.5% and 25% to SE and 6% and 23% to NW respectively, allowed raising the minimum temperatures up almost 4 °C in cool days, and reducing the maximum more than 3 °C on warm days, entering the classrooms analysed in the hygrothermal comfort band. At the same time, best levels of illuminance (400 lx average) and more uniformity of natural light spatial distribution were obtained, which would be reflected in an electrical consumption saving for lighting.

The proposal described above, made for the worst autumn school term, can be extrapolated to the classrooms of other buildings under study that meet similar conditions than the classrooms analysed. New investigations are already being conducted for the other seasons, to determine the relevance of its implementation and the scope of its benefits. Subsequently, we will be able to define criteria of regulating glazed areas suitable with regional reality, that are not covered in full in the current regulations for a mid orientation urban centre. As a contribution, this research will lead to the formulation of a comprehensive database to be transferred to the Ministry of Education of the Province of Chaco.

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