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# Experimental monitoring and post-occupancy evaluation of a non-domestic solar building in the central region of Argentina

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ABSTRACT

Previous experience in designing and monitoring bioclimatic buildings in central Argentina suggests that their thermal behavior is a matter of concern and that further research is needed. Thus, the objectives of this work are: to describe the design and the post-occupancy evaluation of a new non-domestic solar building in a continental semiarid region of central Argentina (37°38′ latitude S, 63°34′ longitude, 175 m above sea level), to analyze the building's hygrothermal and energy performance, and to estimate the PMV and PPD. The design guidelines were: to minimize the consumption of conventional energy in thermal-lighting conditioning, to use traditional technology, to maximize the thermal comfort, and to reach an extra-cost lower than 10%. The post-occupancy monitoring of the building was performed along one complete year (August 9th 2011–August 18th 2012). Data-loggers were installed in each functional area to sense the indoor temperature and relative humidity at time steps of 10 min. A meteorological station was installed near the building. The experimental results showed that during winter the average temperature in the areas of permanent use was 20.3 °C (average outdoor temperature: 10.1 °C) and the heating energy consumption was around 73.5 kW h/m$^2$. During summer the average indoor temperature in the building was 26.9 °C, 1.7 °C below the outdoor temperature average (28.6 °C); cooling systems were turned on when the indoor temperature reached 28 °C, at approximately 11:30 AM, when the outdoor air temperature exceeded 30 °C. Mechanical cooling consumed around 59% of the daily electricity consumption. The PDD results obtained for winter and summer representative days meet the requirements of ISO Norm 7730. Heating and cooling energy saving was around 63% and 76.5% respectively. The monitoring showed that the thermal behavior and energy performance met the expectations of both designers and users, and it is considered satisfactory and promising for low-energy consumption buildings.

## 1. Introduction

In most countries, buildings account for 40% of primary energy consumption and are also a significant source of CO$_2$ emissions [1]. The International Energy Agency (IEA) identified the building sector as one of the most cost-effective sectors to reduce the energy consumption. Moreover, reducing the overall energy demand can significantly reduce CO$_2$ emissions from the building sector. In this context, energy efficient buildings are the main protagonists. The IEA produced policy recommendations based on best practices: governments requiring the implementation of building energy codes – for both new and existing buildings – and setting overall minimum energy performance standards and mandatory renovation rates to capture the savings' potential of the building sector [2]. The definition of low energy-building is not unique. Sartori and Hestness [3] affirm that low-energy buildings are those built with special design criteria aimed at minimizing the buildings' operating energy. According to Feist [4], a low-energy building (LEH standard) can be defined as one having an annual heating requirement below 70 kW h/m$^2$ year. In Switzerland, the Minergie Standard for buildings establishes a limit value of 42 kW h/m$^2$, while the German Passive-house Standard establishes an annual heating requirement below 15 kW h/m$^2$ [5].

Many non-domestic buildings are major energy-wasters. New buildings are not necessarily better, with energy use often proving to be much higher than their designers anticipated [6]. Norford et al. [7] found that the most important sources of discrepancy between

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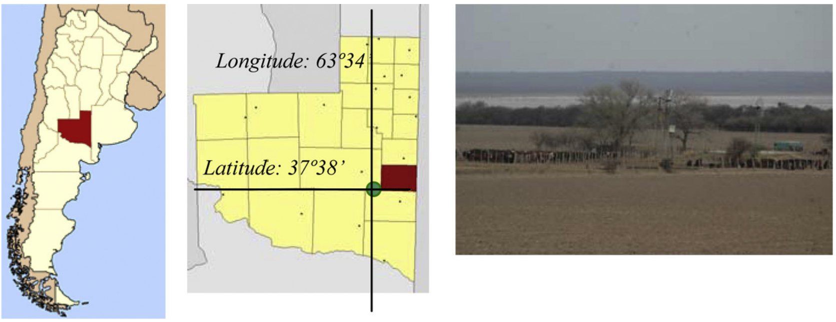


**Fig. 1.** Location of the province of La Pampa and city of Guatraché in Argentina. Right: typical landscape of the study area.

the actual energy consumption and the one predicted by simulation are those related to users' behavior. As shown, careful decisions made in relation to the building design and operation may improve significantly its thermal performance, and, as a result, reduce its energy consumption. The impact of those decisions on the building's thermal behavior will decrease along the different stages of that building's life. Effective and well-thought decisions made at the project's early stage would mean a future decrease in energy consumption in terms of operation and maintenance.

Saving an average 50% in space heating energy use has already been demonstrated by projects built and operated in the UK: the best of these examples achieved impressive savings in the order of 60–75% [8]. In the case of Argentina, in spite of the fact that energy is highly subsidized and it is dependent on importation from other countries, mandatory regulations tending to improve energy efficiency of buildings do not exist. In particular, thermal insulation is not used at all. There are just some non-mandatory recommendations regarding the habitability of buildings. Unlike other developed countries, there is a very important lack of national laws regarding efficiency. Notwithstanding this, researchers made a major effort to promote the challenge of designing efficient buildings, a practice which is not only uncommon but not even recognized in its entire importance.

In this context, the National Institute of Agricultural Technology of Argentina (INTA La Pampa-San Luis Regional Centre) endorsed and supported the construction of a bioclimatic building in the central region of Argentina. The design of this building was committed to the authors in 2006, who applied their previous 10-year experience (1995–2005) in designing and monitoring solar bioclimatic buildings in Argentina to the design of this new building. The analysis of thermal performance and gas consumption suggested that, while their design and construction achievements are already well-suited to face the winter period, the summer time still represents a challenge to be overcome. Thus, further research is needed to improve the energy performance of buildings under summer conditions (Filippín and Beascochea [9] Filippín and Beascochea [10]; Filippín et al., [11]; Filippín [12]).

On the basis of the previous experience, the new bioclimatic INTA building was designed in order to obtain comfort conditions both in winter and summer periods, with energy consumption rates lower than those of a conventional building. Bioclimatic strategies and solar passive heating were included in the building design. The design guidelines were: to minimize the consumption of conventional energy in thermal-lighting conditioning, to use traditional technology, to maximize thermal comfort, and to reach an extra-cost lower than 10%. In 2011, the construction of the building was completed and a one-year post-occupancy monitoring was performed between August 2011 and August 2012. Therefore, the objectives of these work are: (I) to describe the design and the post-occupancy evaluation of a new non-domestic solar building in a continental semiarid region of central Argentina, (II) to analyze the building's higrothermal and energy performance, (III) to estimate both the PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied).

## 2. Building design and location

The city of Guatraché is located in the SE of the province of La Pampa, Argentina (37°38′S, 63°34′W, 175 m above sea level). The building site is located in an area of low houses and low density of construction. This dry region is characterized by plateaus, valleys, hills and crop plains, low grazing lands and open forests (Fig. 1). The climate (Table 1) is classified as a *transition temperate-cold* climate (bio-environmental zone IV) by the Argentinean IRAM Norm [15], which recommends for such a region to use thermal insulation in the whole envelope, to avoid thermal bridges, and to minimize the risk of condensation in walls and roofs. Also, a NW-N-NE-E orientation of the building and cross-ventilation are recommended.

The design of this building prioritized natural conditioning of spaces, low-cost operation and maintenance, and clear zoning of the different functional areas. The strategies were:

- Orientation of the spaces according to their use (offices and administration facing north, services facing south).
- Minimization of the air temperature difference (thermal zoning) between areas with and without direct solar gains.
- Passive solar heating and energy conservation in winter: direct solar gain through North glazing and an insulated envelope to minimize heat losses.
- Passive cooling in summer: use of natural cross ventilation, thermal mass storage, shading and devices for solar control.
- Reduction of the electricity consumption for lighting (through day lighting and energy efficient luminaries).
- Design of the outdoor spaces: use of trees and plants according to the orientation.

The building layout is shown in Fig. 2. To the east, there is a green space with native species from the pampas forest near the building entrance and the pedestrian circulation path, which is a continuation of the sidewalk area. The entrance to the building is defined as an independent area with a double door from which the functional areas are distributed along an E–W axis. The offices face north and they have clear glazing for direct solar gain in winter, with protection eaves and pergolas for summer. The multipurpose room is destined to training-entertainment and socializing activities and it is located on the N–W side and facing north. This area is connected with the rest of the building's areas (management – extension – research) through an east-west circulation. It is also used as garage. The director's office is located in the southern side, with small windows that help visual expansion and assure indirect natural lighting coming from the circulation area and the plenum. The service sector is located to the west of this office.

**Table 1**
Climatic variables.

| | | | |
|---|---|---|---|
| Annual values | Mean temperature (°C) | Maximum | 22.1 |
| | | Mean | 7.6 |
| | | Minimum | 14.6 |
| | Annual mean solar irradiance over horizontal surface (MJ/m$^2$) | | 18.8 |
| | Relative humidity (%) | | 64 |
| July mean temperature (°C) | | Minimum | 1.1 |
| | | Mean | 6.9 |
| | | Maximum | 13.1 |
| Winter thermal amplitude (°C) | | | 12.0 |
| July absolute minimum temperature (°C) | | | −11.0 |
| Winter wind's mean velocity (km/h) | | | 11 |
| July mean solar irradiance over horizontal surface (MJ/m$^2$) [13] | | | 8.1 |
| January mean temperature (°C) | | Maximum | 31.5 |
| | | Mean | 23.2 |
| | | Minimum | 14.6 |
| Summer thermal amplitude (°C) | | | 16.9 |
| January absolute minimum temperature (°C) | | | 39.5 |
| Summer wind's mean velocity (km/h) | | | 11 |
| January mean solar irradiance over horizontal surface (MJ/m$^2$) [13] | | | 23.4 |
| Heating degree-days base 18 °C | | | 1505 |
| Cooling degree-days base 23 °C | | | 379 |

*Sources*: Servicio Meteorológico Nacional–Fuerza Aérea Argentina, 2000 [13].
R. Righini, H. Grossi Gallegos, C. Raichijk, 2005 [14].

The solar collection area (area of effective glass) is around 12% of the building's useful area. A key element in this design is the technical-thermal plenum, which has windows facing the Equator. This plenum is located between the northern and southern areas, at a height of 2.40 m over the circulation (see Fig. 3). This area works as a solar energy gain-storage-compensation sector. The plenum, conceived as a *'thermal steering wheel'*, heats the building's southern area when the windows located between both areas are open. Besides, it optimizes the natural cross-ventilation during summer. Thus, the plenum allows for the building's operation in accordance with the different seasons. This strategy is replicated in the exhibition area where high windows can be opened from a footbridge (plenum's continuation) (Fig. 3).

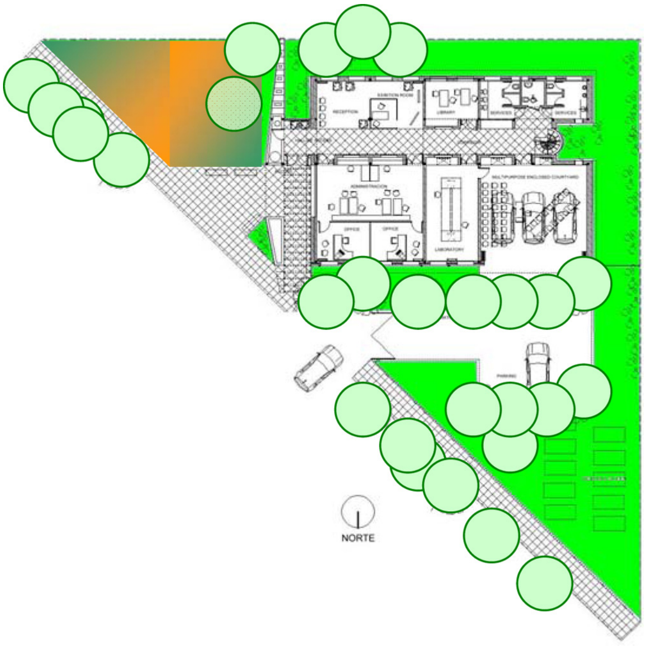


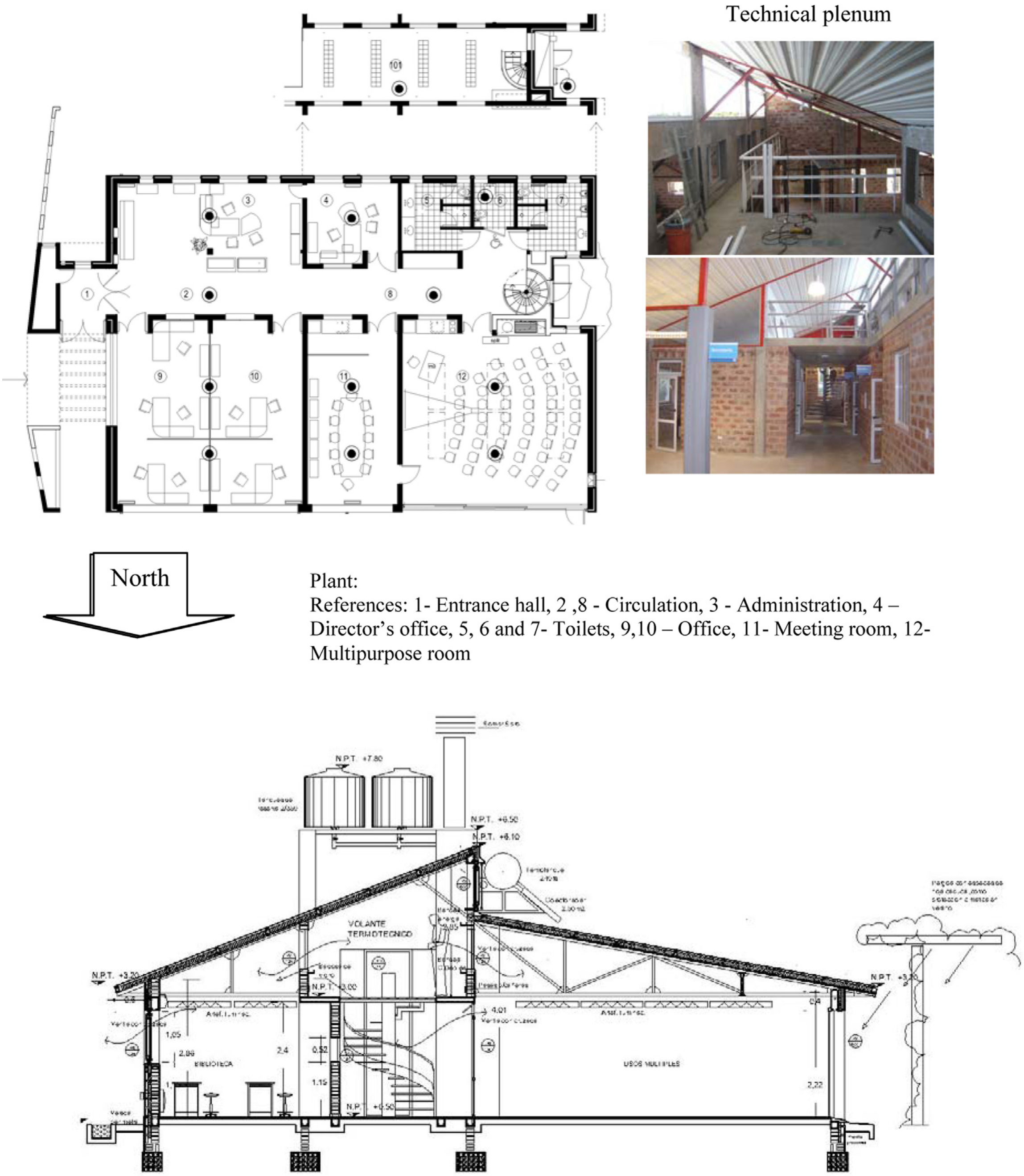
**Fig. 2.** Building layout.

Energy conservation and storage is achieved through the envelope's technology. The walls are three-layered: solid brick as thermal mass in the inner part (0.17 m thick), expanded polystyrene thermal insulation (0.05 m thick) and outer mechanical protection (½ concrete block) ($R = 1.923\ \text{m}^2$ K/W). The sloping roofs are made of pre-painted white tin and 5 mm polythene foam blanket with aluminum film and 0.1 m fiberglass insulation and metal sheet ceiling ($R = 2.94\ \text{m}^2$ K/W). The doors and windows are made of pre-painted aluminum; thermal bridge breaker and hardwood pre-frame (see construction details in Fig. 4). The windows are single-glazed and have mechanical roller shutters with adjustable slats. According to Table 2, the building has a compact layout and a suitable FAEP [16]. The *G*-value (Volumetric Loss Coefficient) meets the requirements of IRAM Norm 11604, 2001 [17]. As a result of the vertical envelope indoor massive brick walls and of the use of massive indoor walls, the building has high inertia (400 kg/m$^2$) [18]. Fig. 5 shows pictures of the North view of the building.

## 3. Experimental monitoring

The post-occupancy monitoring of the building was performed for one complete year (August 9th, 2011–August 18th, 2012). HOBO data-loggers were installed in each functional area to sense the indoor temperature and relative humidity at time steps of 10 min. The plant view shows the sensors' location. The data-loggers were protected by thermal containers of expanded polystyrene with holes, in accordance with the methodology described by Molas et al. [19]. The outdoor meteorological variables (solar radiation, wind velocity, relative humidity and outdoor ambient temperature) were recorded by a meteorological station installed near the building. Simultaneously, two daily readings of the natural gas and electricity meters were performed, both at the beginning and end of the activity period (8:00AM–15:00PM). Also a qualitative survey was answered by the building users.

In this paper, four periods were selected in order to analyze the building thermal-energy behavior and comfort conditions: August 10–25 2011 (winter); October 13–November 4 2011 (spring); December 25–January 9 2012 (summer) and March 26–April 22 2012 (fall). These periods were selected because they are representative of the four seasons.



Plant:
References: 1- Entrance hall, 2 ,8 - Circulation, 3 - Administration, 4 – Director's office, 5, 6 and 7- Toilets, 9,10 – Office, 11- Meeting room, 12- Multipurpose room

**Fig. 3.** Building form and internal planning, cross-section and indoor view of the technical plenum.

### 3.1. Hygro-thermal behavior

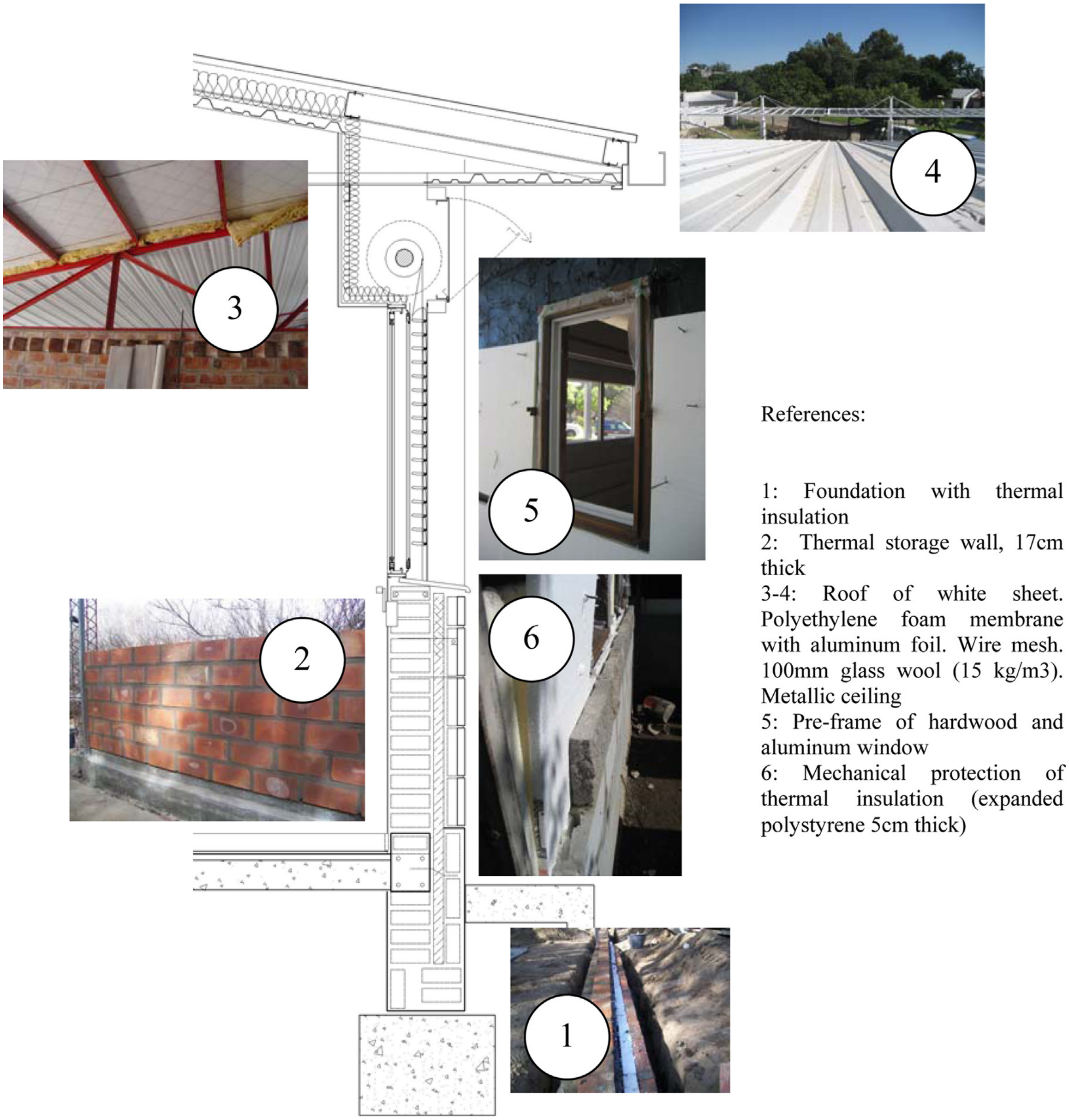
#### 3.1.1. Winter and spring

Figs. 6 and 7 show the measured solar irradiance on the horizontal surface (W/m$^2$), the wind velocity (m/s), the outdoor air temperature and the indoor air temperatures of the functional areas, for the period between August 10 and 25 2011. This period was cold and very windy: outdoor temperature varied from 0 °C to 18 °C, with predominant south-west wind during the whole day, its velocity reaching 4.5 m/s (16.2 km/h). These values are quite usual during the winter periods of the region. Fig. 7 shows the temperature evolution in the different functional areas. A coupling

**Table 2**
Dimensional and thermal–energy indicators.

| Perimeter (m) | Useful area (m$^2$) -1- | $I_c$ (%) | Volume (m$^3$) | Envelope (m$^2$) -2- | | | FAEP (2/1) | Thermal resistance (m$^2$K/W) | | | $G$ (W/m$^3$ °C) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Vertical | Roof | Total | | Wall | Roof | Window | |
| 73 | 269 | 83 | 899 | 209 | 272 | 481 | 1.79 | 1.587 | 2.439 | 0.312 | 1.095 |

$I_c$ = Compactness index; FAEP = relationship between envelope and useful area; $G$ = Volumetric loss coefficient.



References:

1: Foundation with thermal insulation
2: Thermal storage wall, 17cm thick
3-4: Roof of white sheet. Polyethylene foam membrane with aluminum foil. Wire mesh. 100mm glass wool (15 kg/m3). Metallic ceiling
5: Pre-frame of hardwood and aluminum window
6: Mechanical protection of thermal insulation (expanded polystyrene 5cm thick)

**Fig. 4.** Details of the envelope.

of curves at the office and meeting room in the north, and management and director's office in the south, is observed. It should be noted that even though the management area has a vertical envelope facing south, it receives direct sunlight from the north through a high window (Fig. 3). The temperature evolution of the multipurpose room lies below the previous ones and above that in the technical-thermal plenum. As it may be expected, the multipurpose room's behavior is strongly associated with the area's technology and functional characteristics, and also with the outdoor temperature evolution. The large metal sheet door functions as a buffer between outside and inside: the poor air tightness of the door frame, the high conductivity of the non-insulated metal sheet, and the glazed area on the upper portion of the door, increase the heat transfer between the outside and the inside environments. Among the ordinary use areas, no thermal zoning was observed.

Table 3 shows mean temperature values and the maximum and minimum temperature average for the period of use. The indoor temperature average in the building was 19.0 °C, 8.9 °C above the outdoor one (10.1 °C). The thermal amplitudes – both indoors and outdoors – were 3.7 °C and 8.8 °C, respectively. The average temperature in the areas of permanent use was 20.3 °C, whereas in the circulation area, without passive solar use it was 18.9 °C. The toilet, with its vertical envelope, showed an average temperature of 15.8 °C. The multipurpose room showed the lowest average temperature (14.5 °C), only 4.4 °C above the outdoor mean temperature. This is the functional area which shows the greatest thermal amplitude. It reached a maximum temperature average of about 18.4 °C, in the sector parallel to the entrance door, and the minimum temperature average in the area near the door and corridor, 12.4 and 11.4 °C respectively. On sunny days, the maximum temperature reached 21 °C. It is evident, then, that the behavior of this sector must be associated with air leakage through windows and doors.

The second period went from October 13 until November 4 and it was characterized by permanent winds of up to 5 m/s (18 km/h) and mostly by cloudless days with solar irradiance at midday of around 800 W/m$^2$ (Fig. 8). The outdoor thermal behavior varied from colder days with minimum temperatures close to 5 °C to warmer

**Fig. 5.** North view of the building; inside the building: interior view from plenum to offices; vegetable garden activities; multipurpose room view; view from plenum to administration; active participation of cleaning staff.

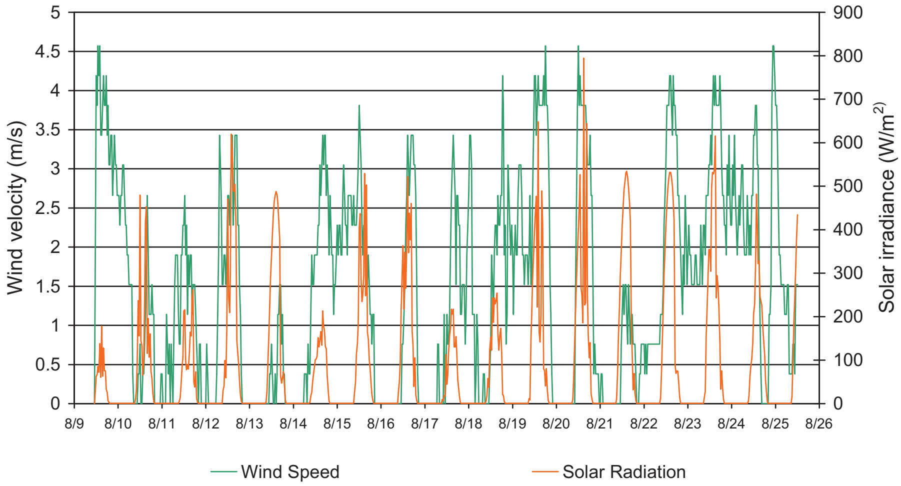


**Fig. 6.** Solar irradiance on horizontal surface (W/m$^2$) and wind velocity (m/s) for the period between August 10 and 25 2011.

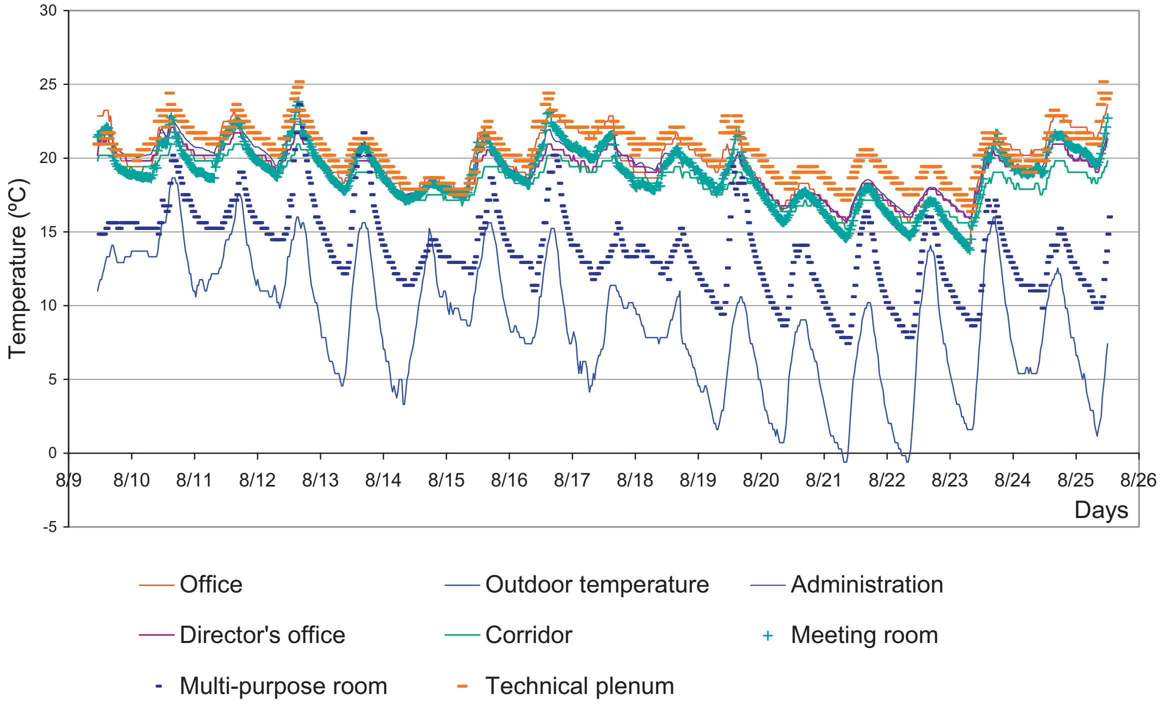


**Fig. 7.** Outdoor air temperature and indoor air temperatures of the functional areas, for the period between August 10 and 25 2011.

periods with maximum temperatures that went above 25 °C. Fig. 9 shows the building's thermal behavior and the temperature of the outdoor air. Table 4 shows the mean temperature and the maximum and minimum temperatures averages for the period of use. As it occurred in the winter period, the temperatures in the offices (meeting room – management – director's office) are coupled. This coupling reinforces the fact that there was no thermal zoning in the building under real conditions of use. The average temperature of the north and south areas were 20.2 and 20.1 °C, respectively. Among them, the corridor, without passive solar heating, showed a value of 19.8 °C., in contrast with the previous period. The multi-purpose room thermal behavior appeared closer to that of other areas. The minimum temperature was 2.3 °C below the recorded in other parts of the building (before: 6.7 °C). The building's mean temperature was 20.0 °C, 1.6 °C above the mean outdoor temperature (18.4 °C). The behavior was satisfactory despite the fact that the period was somewhat critical: even though solar irradiance increased, there were low outdoor temperatures and lack of solar protection since plant cover had not developed yet. In spite of the fact that the outdoor temperature varied from cold to warm alternatively, the indoor temperature remained between 17.5 and 24 °C.

### 3.1.2. Summer and autumn

Fig. 10 shows one of the most critical summer periods: from December 25 2011 until January 9 2012. It was characterized by a sequence of clear sky days and north wind velocities above 12 m/s (43.2 km/h). The outdoor air temperature was above 35 °C and on January 6 even above 40 °C (Fig. 11). The thermal behavior curves of the different areas show coupling. Unlike winter, in summer the temperature of the multi-purpose room is coupled with the temperature of the other areas of the building. Whereas the minimum temperature average of the multi-purpose room is

**Table 3**
Mean, absolute minimum and maximum temperature daily average and relative humidity values for the period of the building's daily use from 10 to 25 August 2011.

| *Functional areas* | | *Temperature (°C)* | | | *Relative humidity (%)* |
|---|---|---|---|---|---|
| | | Mean | Minimum | Maximum | |
| *Office near the* | Corridor | 21.0 | 19.0 | 22.4 | 29.8 |
| | North window | 20.9 | 17.9 | 22.6 | 35.5 |
| *Administration near the* | Corridor | 20.0 | 18.1 | 21.2 | 23.4 |
| | South window | 20.4 | 18.3 | 21.8 | 42.7 |
| Director's office | | 19.8 | 18.1 | 21.0 | 34.9 |
| *Meeting room near the* | North window | 20.2 | 17.4 | 22.0 | 43.9 |
| | Corridor | 19.6 | 18.8 | 20.2 | 33.9 |
| *Corridor* | | 19.9 | 18.1 | 21.0 | 32.5 |
| *Mean temperature and relative humidity in functional areas of permanent use* | | 20.2 | | | 34.2 |
| *Bathroom* | | 15.8 | 14.7 | 16.8 | 44.1 |
| *Multipurpose room near the* | External access | 15.1 | 12.4 | 18.4 | 56.0 |
| | Corridor | 14.5 | 11.4 | 18.1 | 56.1 |
| *Technical plenum* | | 21.5 | 19.0 | 23.2 | 31.2 |
| *Mean temperature and relative humidity* | *Inside the building* | 19.0 | | | 39.4 |
| | *Outdoor* | 10.1 | 5.5 | 14.3 | No data |

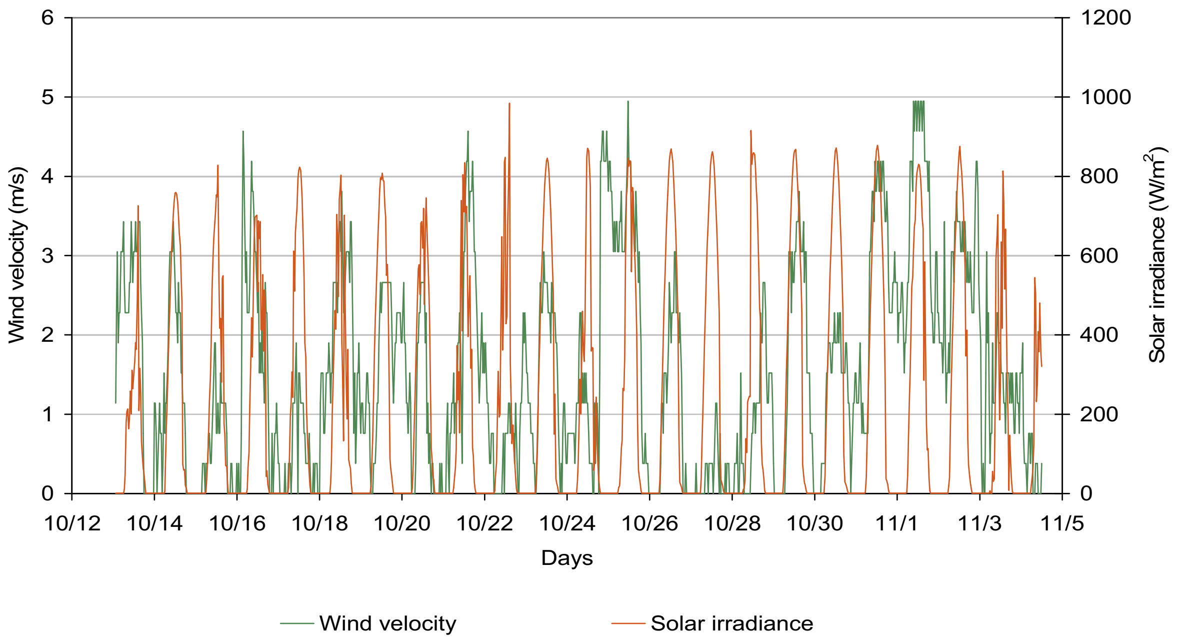


**Fig. 8.** Solar irradiance over horizontal surface (W/m$^2$) and wind velocity (m/s) for the period between October 13 and November 4, 2011.

**Table 4**
Mean, absolute minimum and maximum temperature daily average and relative humidity values for the period of the building's daily use between October 13 and November 4 2011.

| *Functional areas* | | *Temperature (°C)* | | | Relative humidity (%) |
|---|---|---|---|---|---|
| | | Mean | Minimum | Maximum | |
| *Office near the* | Corridor | 20.1 | 18.3 | 21.4 | 34.7 |
| | North window | 20.5 | 18.3 | 21.9 | 40.9 |
| *Administration near the* | Corridor | 19.8 | 18.2 | 21.0 | 39.6 |
| | window | 20.1 | 18.3 | 21.6 | |
| *Director's office* | | 20.5 | 18.5 | 22.1 | 64.6 |
| *Meeting room near the* | North window | 19.9 | 18.2 | 21.4 | 60.0 |
| | Corridor | 20.3 | 18.3 | 21.9 | 65.2 |
| *Corridor* | | 19.6 | 18.4 | 20.7 | 64.3 |
| *Mean temperature and relative humidity in functional areas of permanent use* | | 20.1 | | | 53.8 |
| *Bathroom* | | 17.3 | 16.2 | 18.5 | 45.4 |
| *Multipurpose room near the* | External access | 22.1 | 18.6 | 24.5 | 50.3 |
| | Corridor | 19.7 | 16.1 | 23.3 | 46.5 |
| *Technical plenum* | | 20.7 | 15.9 | 24.6 | 47.0 |
| *Mean temperature and relative humidity* | Inside the building | 20.0 | | | 50.8 |
| | Outdoor | 18.4 | 10.7 | 23.3 | |

**Table 5**
Mean, absolute minimum and maximum temperature daily average and relative humidity values for the period of the building's daily use between December 25 2011 and January 9 2012.

| *Functional areas* | | *Temperature (°C)* | | | Relative humidity (%) |
|---|---|---|---|---|---|
| | | Mean | Minimum | Maximum | |
| *Office near the* | Corridor | 25.9 | 24.3 | 27.7 | no data |
| | North window | 27.9 | 25.9 | 29.7 | 31.2 |
| *Administration near the corridor* | | 26.4 | 22.9 | 28.5 | no data |
| *Director's office* | | 26.3 | 24.6 | 27.8 | 33.3 |
| *Meeting room near the* | North window | 26.8 | 24.5 | 28.9 | 41.1 |
| | Corridor | 26.5 | 24.4 | 28.5 | 34.3 |
| *Corridor* | | 26.0 | 24.8 | 27.4 | 37.7 |
| *Mean temperature and relative humidity in functional areas of permanent use* | | 26.4 | | | 35.0 |
| *Bathroom* | | 26.0 | 23.7 | 26.9 | 33.8 |
| *Multipurpose room near the* | External access | 29.0 | 24.5 | 33.0 | 29.7 |
| | Corridor | 27.2 | 22.9 | 30.5 | 37.1 |
| *Technical plenum* | | 28.5 | 24.0 | 32.4 | 38.3 |
| *Mean temperature and relative humidity* | Inside the building | 26.9 | | | 34.8 |
| | Outdoor | 28.6 | 20.2 | 35.7 | 38.7 |

**Table 6**
Average values of temperature and relative humidity for the period of use of the building from March 26 to April 22 2012 (period without auxiliary heating).

| *Functional areas* | | *Temperature (°C)* | | | Relative humidity (%) |
|---|---|---|---|---|---|
| | | Mean | Minimum | Maximum | |
| *Office near the* | corridor | 20.1 | 14.5 | 23.6 | |
| | North window | 19.8 | 18.7 | 21.0 | 39.2 |
| *Administration near the* | South window | 20.3 | 14.6 | 24.1 | 49.1 |
| *Director's office* | | 19.8 | 14.1 | 23.2 | 40.8 |
| *Meeting room near the* | North window | 20.5 | 13.4 | 25.4 | 48.5 |
| | corridor | 20.3 | 16.4 | 24.0 | 40.2 |
| *Corridor* | | 20.2 | 15.2 | 22.9 | 36.0 |
| *Mean temperature and relative humidity in functional areas of permanent use* | | 20.1 | | | 41.9 |
| *Bathroom* | | 18.8 | 13.7 | 22.5 | 44.3 |
| *Multi-purpose room near the external access* | | 20.5 | 11.7 | 28.5 | 47.0 |
| *Mean temperature and relative humidity* | Inside the building | 20.0 | | | 43.1 |
| | Outdoor | 17.2 | 3.4 | 30.8 | 59.4 |

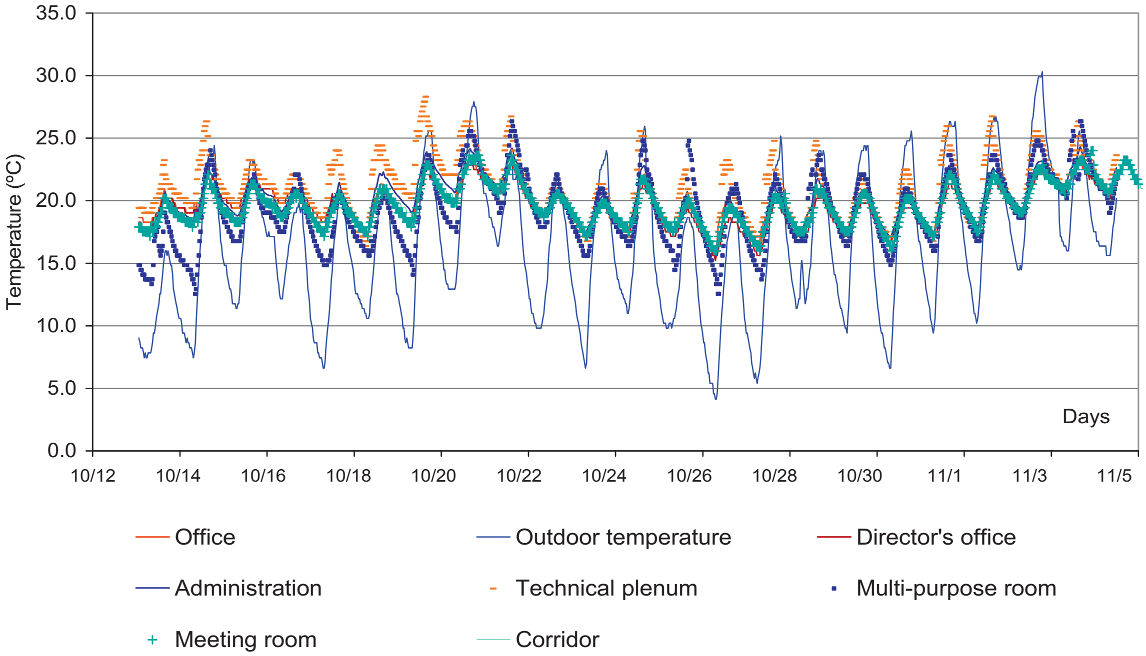


**Fig. 9.** Indoor temperatures of the functional areas and outdoor air temperature, for the period between October 13 and November 4 2011.

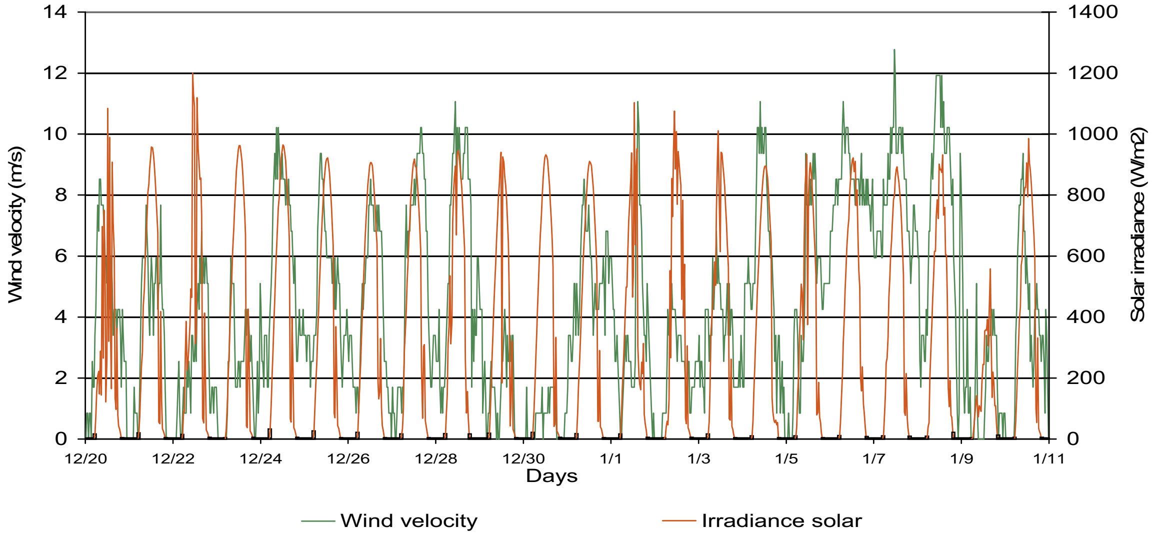


**Fig. 10.** Solar irradiance over horizontal surface (W/m$^2$) and wind velocity (m/s) for the period between December 25 2011 and January 9 2011.

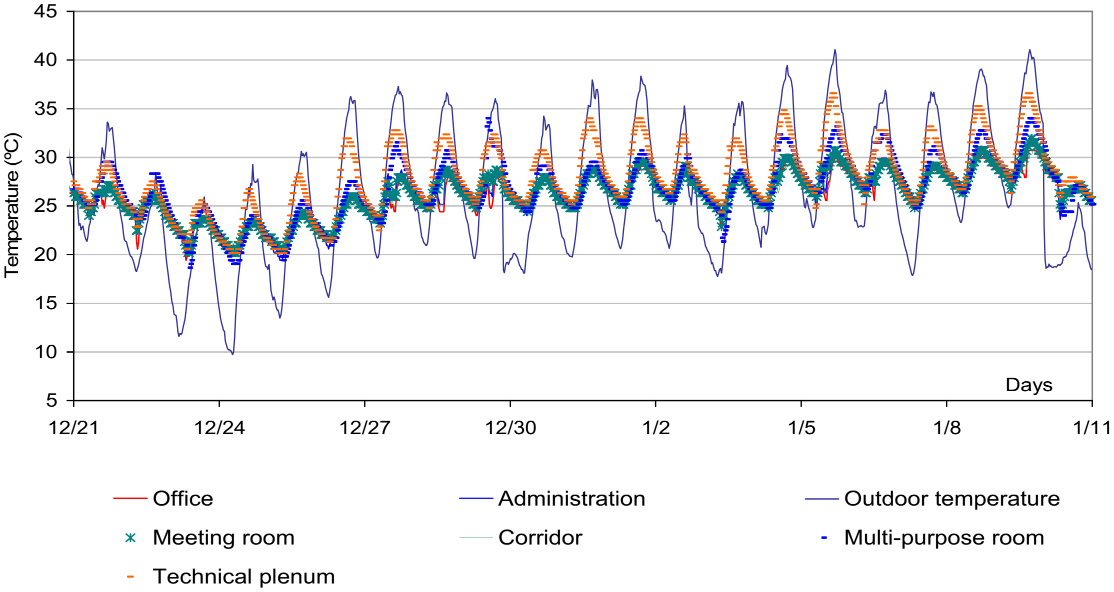


**Fig. 11.** Indoor temperatures of the functional areas and outdoor air temperature, for the period between December 25 2011 and January 9 2012.

not so different from that in other areas, the maximum temperature average was 3 °C above the maximum average in the rest of the building, and it was 1.6 °C below the temperature in the plenum, which reached maximum temperatures of more than 35 °C (Table 5). It should be said that this period coincided with summer holidays and there were two-worker shifts out of the eight technicians that work in the building. Also, the mosquito nets in the plenum's high windows had not been set yet, fact that prevented adequate natural ventilation as it had been stated in the original design. Table 6 shows that the indoor temperature average in the building was 26.9 °C, 1.7 °C below the outdoor temperature average (28.6 °C).

The last period under study went from March 26 to April 22 2012, characterized by clear sky days (Fig. 12). The occupants began to use auxiliary heating on April 23 (Fig. 13). The monitoring shows that no thermal stratification was observed among the functional areas. According to Table 6, the indoor temperature average was 2.8 °C above the outdoor temperature average. The temperature average in the north sector was 0.5 °C above that of the director's office, located in the south sector, which has indirect solar gain from the north through the plenum. The indoor temperature average remained constant, around 21 °C, and maximum values never went above 25 °C, during those days on which the outdoor temperature reached 30 °C.

## 3.2. Energy behavior

### 3.2.1. Winter

During winter, the study period included one week-end and an extended week-end during which the heaters, according to the gas meter records, were set to pilot. From August 10 until August 12, the outdoor maximum temperature was between 15 °C and almost 20 °C, a factor that surely lessened the effect of the wind and scarce solar radiation. The average gas consumption during the working days was 6.0 m$^3$ and 8.9 m$^3$ between 3:30 pm and 8:00 am. During the weekend, the outdoor temperature went down and continued to do so until August 22, when days began to experience the effect of southern winds and cloudy sky. Under those conditions, natural gas consumption during the working days increased up to 9.6 m$^3$ and 24.0 m$^3$ by the end of the day.

The experimental monitoring for the winter period, under use conditions, showed a real consumption – measured in August – that ranged from around 6–9.6 m$^3$ per day for less windy days and more windy days respectively. The results of the experimental monitoring show, on the one hand, that heaters were on during the night, and on the other, that the indoor temperature average was above the design base temperature, even when the mean air outdoor temperature was not so cold as that considered during the design stage. In this stage, the estimation of the natural gas consumption of the

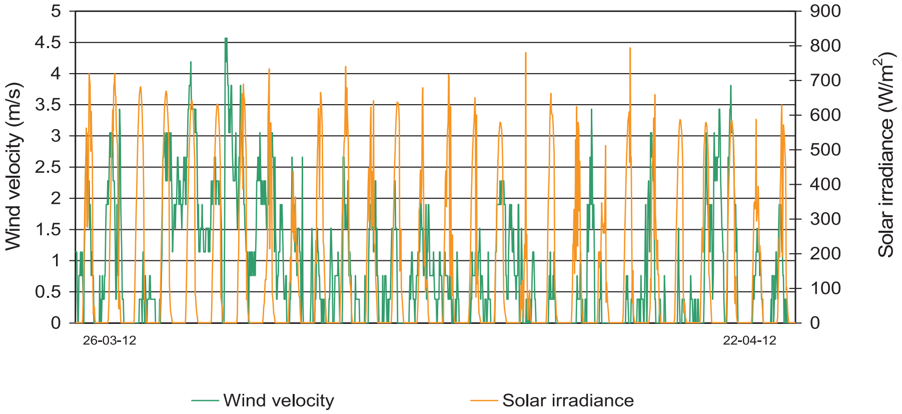


**Fig. 12.** Solar irradiance over horizontal surface (W/m$^2$) and wind velocity (m/s) for the period between March 26 and April 22 2012.

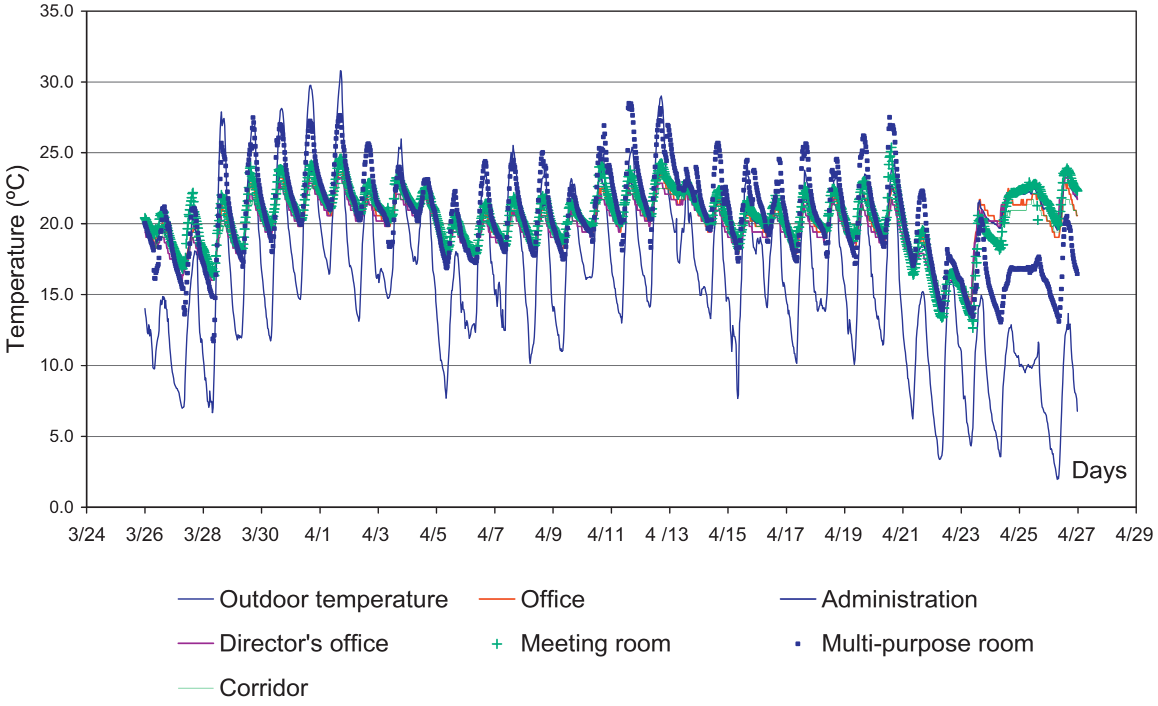


**Fig. 13.** Indoor temperatures of functional areas and outdoor air temperature, for the period between March 26 and April 26 2012.

building was 6.4 m$^3$, for a difference between mean indoor and outdoor temperatures ($\Delta T$) of 11.1 °C. In this stage, the simulation of the transient thermal behavior of the building was carried out through SIMEDIF software [20]. In the monitored period, for a $\Delta T$ of 9.9 °C, the daily average consumption was 7.8 m$^3$ for windy days in which the wind speed reached 18 km/h.

Heaters were on until October 18, consuming around 5 m$^3$/day during the working days. Heating natural gas consumption recorded during the winter of 2011 was 3383 m$^3$ (32,964 kW h if we consider that 1 m$^3$ natural gas = 8400 kcal). For a useful area of 269 m$^2$, 60% heaters' efficiency [21], and indoor average temperature of 20 °C, energy consumption was around 73.5 kW h/m$^2$. The thermal behavior is considered satisfactory and promising for low-energy consumption buildings. The energy savings of the study building with respect to those in a conventional INTA building in the same bio-environmental zone were 62.9% during 2011.

### *3.2.2. Summer*

The electricity consumption measured between December 1 2011 and March 30 2012 was 1668 kW h. Real daily records show that the electricity consumption average for night lighting was 8 kW h. The average consumption during the working days was 16 kW h, with maximum values of 21 and 23 kW h on December 27 and 28, 2011. Fig. 14 shows the office thermal behavior between December 26 and 30. The indoor and outdoor mean temperatures on December 27 were 25.5 and 28.7 °C, respectively. Values during the day were 25.9 and 28.5 °C. Cooling systems were turned on when the indoor temperature reached 28 °C, at approximately 11:30 AM, when the outdoor air temperature exceeded 30 °C.

The final use of energy consumption can be particularly difficult to determine in the case of electricity. But detailed monitoring and users involvement in monitoring allowed the authors to obtain some useful values. On December 27 and 28, mechanical cooling consumed between 17 and 19 kW h, respectively; values which correspond to 81% and 83% of the total daily consumption for working days. The ΔT (difference between indoor and outdoor temperature) were 3.2 and 2.6 °C on December 27 and 28. The rest of the energy consumed during the period corresponds to the consumption related to the office equipment. In terms of percentages, night lighting, mechanical cooling and office equipment consumed 27.6, 58.6 and 13.8% out of the daily electricity consumption. The energy savings of the building in this study with respect to a conventional INTA building in the same bio-environmental zone were 76.5% during the period between 21-11-11 and 23-3-12.

### *3.3. Thermal comfort conditions*

Thermal comfort is defined as 'that condition of mind which expresses satisfaction with the thermal environment' [22] and is a result of a combination/adaptation of parameters of both the environment and the human body itself. Fanger [23] proposed a method-the predicted mean vote (PMV) to predict the actual thermal sensation of people in an arbitrary climate where the variables might not satisfy the equation. The author determined the relation between the PMV-index and the predicted percentage of dissatisfaction (PPD). The International Standard ISO 7730, 2005 [24] uses these PMV and PPD indices to predict the thermal sensation of people exposed to moderate thermal environment, as well as to specify acceptable thermal environmental conditions for comfort.

Fig. 15 shows a scatter plot for the four selected monitoring periods and for the period of use with half-hourly records of temperature (horizontal axis) and relative humidity (vertical axis). It can be observed that the values of the areas of frequent use (offices and administration) fall within the comfort zone. In winter, the bioclimatic strategies used were appropriate to achieve a comfortable indoor environment. During the summer, some values in the technical plenum and multi-purpose room show overheating, but this does not occur in the functional areas of frequent use. Intermediate seasons do not show situations outside the comfort zone.

Fig. 16 shows the PMV and PPD for the environmental conditions of the office functional area for two values of metabolic rate M: 93 W/m$^2$ (standing and light activity) and 116 W/m$^2$ (standing and medium activity), and for two values of clothing Clo: 1 (between light and heavy clothing) and 0.5 (light clothing). The air

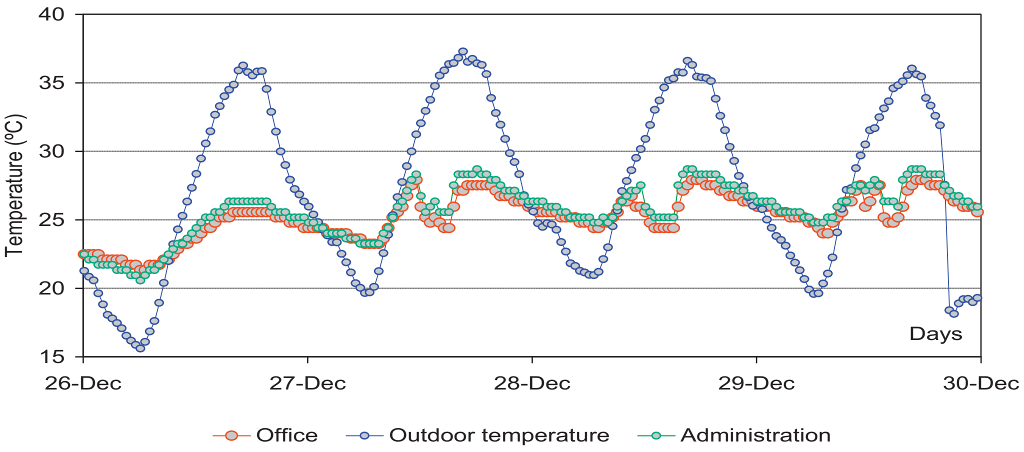
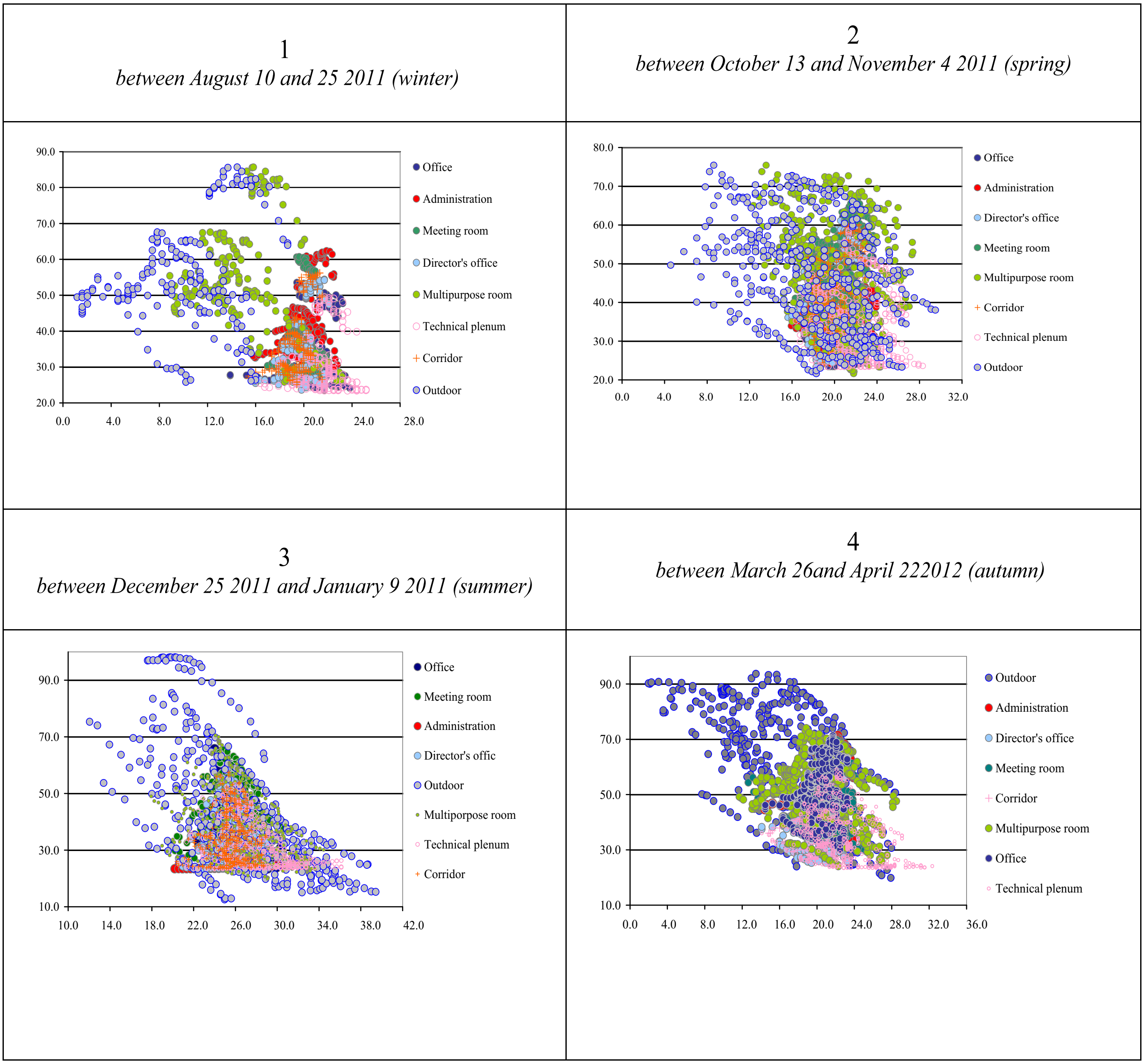


**Fig. 14.** Indoor temperatures of the office and outdoor air temperature, for the period between December 26 and 30 2011.


1
*between August 10 and 25 2011 (winter)*

2
*between October 13 and November 4 2011 (spring)*

3
*between December 25 2011 and January 9 2011 (summer)*

4
*between March 26and April 222012 (autumn)*

**Fig. 15.** Scatter graph between temperature (*x*-axis) and relative humidity (*y*-axis) of each monitoring period.

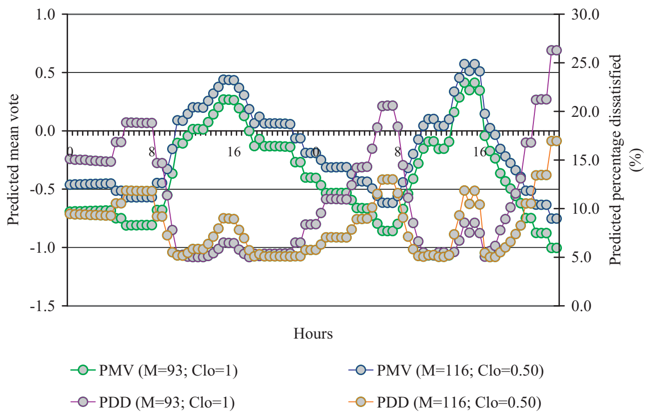


**Fig. 16.** Predicted mean vote (PMV) and Predicted percentage of dissatisfed (PPD) according to half an hour monitoring results in Office's funtional area during 18 and 19 August 2011 (working days).

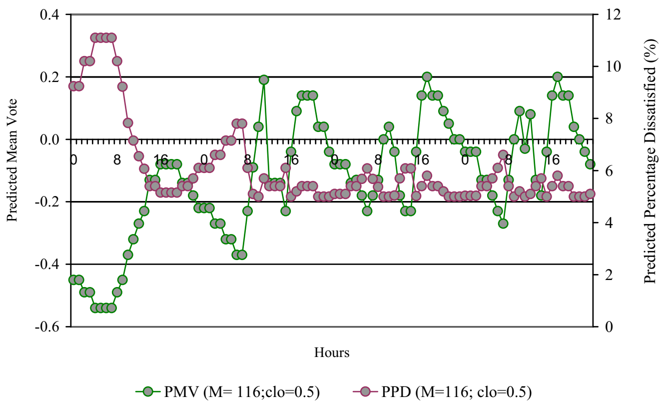


**Fig. 18.** Predicted mean vote (PMV) and Predicted percentage of dissatisfed (PPD) according half an hour monitoring results in Office's funtional area during 26, 27, 28 and 29 December2011 (working days).

temperature, relative humidity and indoor mean radiant temperature data correspond to the experimental results of half an hour monitoring. For this study, data from two working days (August 18 and 19, 2011) are considered, in which extreme weather conditions were very unfavorable, with strong southwest winds and low temperature of the outside air (Fig. 7).

During the period of use of the building (8:00 AM to 15:00 PM), the PMV lies in the range between −0.5 and 5. At 10:00 AM the PMV approaches 0 (neutral). At this time there is solar heat contribution to the indoor environment and the heaters are set to pilot according to users' opinions. The PPD ($M = 93$) is in accordance with ISO Norm 7730. For a higher level of activity and less clothing, the PPD value rises to 10%. The values correspond to an indoor temperature which ranged between 18.3 °C (RH = 42%) and 21.3 °C (RH = 35.4%) on day 18 at 7:30 AM and 15:30 PM, respectively. By day 19 the values were 18.3 °C (RH = 28.6%) and 21.7 °C (RH = 24.5%) for the same times.

During an extended weekend in August (20, 21 and 22) and for the two situations under study, the PMV is between −0.5 and −2.8 (value close to very cold). Activities ended at 15:20 PM on Friday. Since then and for the three-day period, roller shutters were lowered, not allowing the contribution of solar heat and the heaters, as explained in the preceding paragraphs, were set to pilot (Fig. 17). During this period the indoor temperature did not exceed 18.7 °C and dropped to 14.8 °C.

During the four selected days: December 26, 27, 28 and 29, PMV values indicate that a near neutral to slightly cool indoor environment prevailed. The PMV value, more pronounced towards −1, is observed in the early hours of the 26 and 27 when the indoor temperature was about 21.3 °C (RH = 23.4%) and the outdoor temperature was 15.9 °C. The maximum indoor temperature recorded was 27.9 °C (RH = 24.2%) with an outdoor temperature of 31.2 °C on December 27. According to what was stated in the preceding paragraphs, on December 27, the maximum air conditioning electricity consumption (21 kW h) was recorded to reach a temperature around 25 °C. For this situation, the PPD is 5% (Fig. 18).

Fig. 19 shows the PMV and PPD values for the extended weekend between December 30 2011 and January 2 2012. The building remained closed, roller shutters down, without natural ventilation and no air conditioning. Under these conditions and if the building were occupied the percentage of people in discomfort grows to 12% in January 2012 with an internal temperature of 29.1 °C (RH = 24.5%).

Table 7 shows the PMV and PPD values of average temperature and relative humidity for each of the experimental monitoring periods. The results obtained for the third period (summer) meet

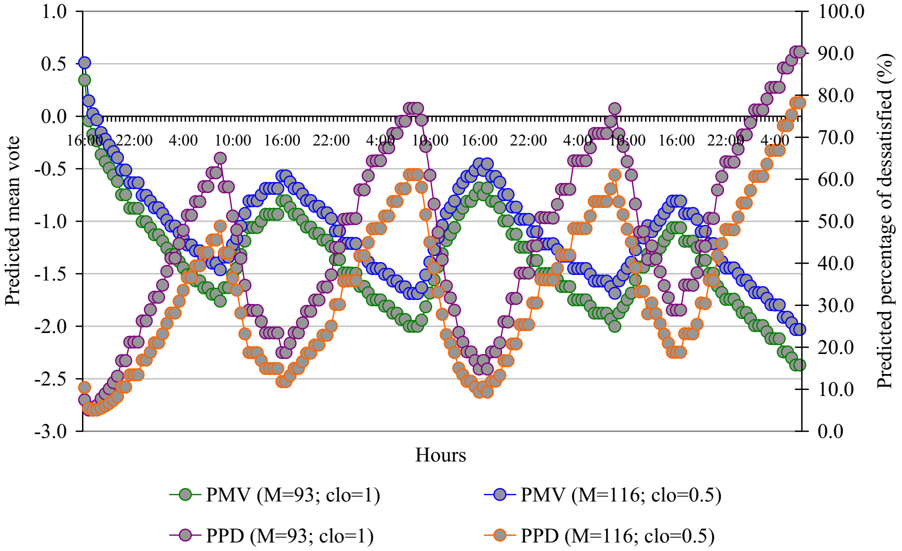


**Fig. 17.** Predicted mean vote (PMV) and Predicted percentage of dissatisfed (PPD) according half an hour monitoring results in Office's funtional area during 20, 21 and 22 August 2011 (extended week end).

**Table 7**
Predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) according to the average of half an hour thermal monitoring in the differents periods.

| *Monitoring period* | *Mean(according to Tables 3–6)* | | *Met* | *Clo* | *PMV* | *PPD* |
|---|---|---|---|---|---|---|
| | *Temperature* | *Relative humidity* | | | | |
| 1 | 20.2 | 34.2 | 93 | 1 | −0.47 | 9.7 |
| | | | 116 | 0.5 | −0.40 | 8.1 |
| | 19.0 | 39.4 | 93 | 1 | −0.80 | 20.2 |
| | | | 116 | 0.5 | −0.75 | 16.7 |
| 2 | 20.1 | 53.8 | 93 | 0.8 | −0.54 | 11.3 |
| | | | 116 | 0.5 | −0.52 | 10.6 |
| | 20.0 | 50.8 | 93 | 0.8 | −0.58 | 12.2 |
| | | | 116 | 0.5 | −0.54 | 11.3 |
| 3 | 26.4 | 35.0 | 116 | 0.5 | 0.12 | 5.3 |
| | 26.9 | 34.8 | 116 | 0.5 | 0.18 | 5.7 |
| 4 | 20.1 | 41.9 | 93 | 0.8 | −0.63 | 13.5 |
| | | | 116 | 0.5 | −0.60 | 12.5 |
| | 20.0 | 43.1 | 93 | 0.8 | −0.64 | 13.6 |
| | | | 116 | 0.5 | −0.60 | 12.6 |

*References:* Functional areas of permanent use (office, administration, meeting room, director's office and corridor) Building.
*Met:* 93 = Light activity; 116 = medium activity.
*Clo:* 0.5 = Light clothing; 0.8–1.0 = medium clothing.

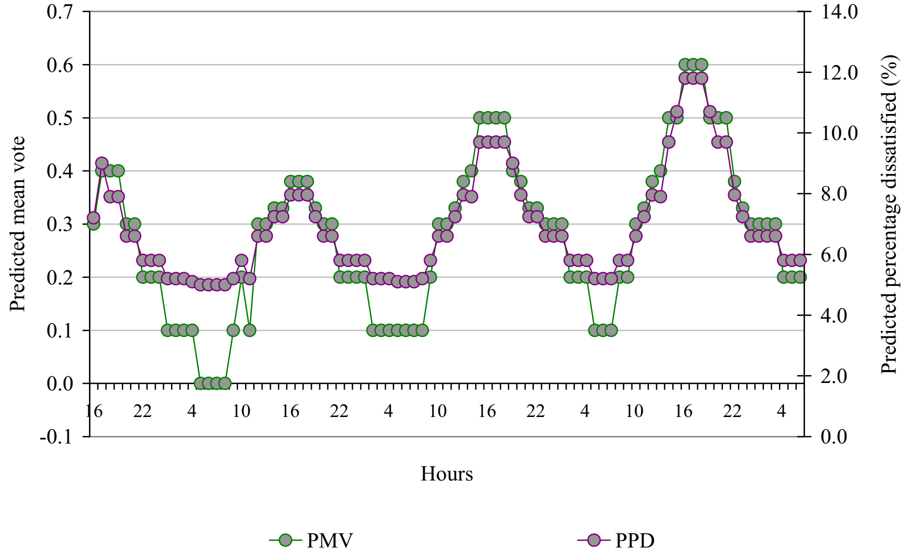


**Fig. 19.** Predicted mean vote (PMV) and Predicted percentage of dissatisfed (PPD) according half an hour monitoring results in Office's funtional area between 30 December2011 and 2 January 2012 (extended week end).

the requirements of ISO Norm 7730. The values show that there was no over-heating due to the architectural, technology and thermal design of the building (an aspect which constituted a major concern for project designers). In the other three periods PMV approached the neutral value and tended to lightly cool, situation that can be modified with a higher level of clothing.

## 4. Conclusions

The development of this work allowed us to meet the objectives: to describe the design and the post-occupancy evaluation of a new non-domestic solar building in a continental semiarid region of central Argentina, to analyze the building's hygrothermal and energy performance and to estimate the PMV and PPD.

Some concluding lessons can be learnt in terms of design strategies. As mentioned in the introduction, our previous experiences in bioclimatic buildings in the central region of Argentina show that the thermal behavior in the winter period is adequate but that overheating in summer is a problem to be faced. This aspect was a major concern for project designers of the studied building. The results of the experimental monitoring showed that there was no over-heating due to the architectural, technology and thermal design of the building. The experimental results showed that during winter the average temperature was 20 °C (the average outdoor temperature: 10.1 °C) and the heating energy saving was around 63% with respect to a conventional non-domestic building. Energy savings could be higher if the heaters were replaced by more efficient ones. In summer, the indoor temperature average in the building was 26.9 °C, 1.7 °C below the outdoor temperature average (28.6 °C). Cooling systems were turned on when the indoor temperature reached 28 °C, at approximately 11:30 AM, when the outdoor air temperature exceeded 30 °C. Cooling energy saving was around 76.5% with respect to a conventional non-domestic building. During winter and summer representative days, the PDD obtained met the requirements of ISO Norm 7730.

The solar collection area (area of effective glass) of around 12% of the building's useful area is a figure that provides a useful orientation to avoid the over-dimensioning of the heating and cooling systems used in other buildings in the same region and with similar envelope thermal resistance. The plenum, thought as a *'thermal steering wheel'*, allows for the building's operation in accordance with the different seasons and we believe that the incorporation of the plenum design was relevant. The incorporation of mechanical roller shutters with adjustable slats was also considered appropriate. In addition to reducing energy loss it has allowed to minimize the glare on workplanes.

According to the results, we consider that the building's thermal behavior that is described in the present paper is auspicious. Favorable results allow for a possible replication of the building, with appropriate changes, in other regions of the country with similar climates. The assessment and the approximations made in the early design stages were appropriate. From a technology perspective, the difficulties observed did not fall beyond those conventional buildings may present.

This study allowed the authors to know the building's thermal behavior, which proved to be satisfactory from the point of view of users and designers. It also helped to introduce suggestions for INTA's management officers. For instance, substituting electrical night lighting by renewable energy systems was recommended. A low-power wind-driven generator and a photovoltaic panel were suggested as well. Due to the randomized characteristics of winds in the area, a combination of both systems would meet both electricity consumption and the use of the region's available solar resource. A new monitoring will be carried out in 2016 as part of a new research project whose objectives are: to assess the thermal behavior with or without vegetation cover as well as the indoor illuminance on the workplane. A thermographic analysis will make it possible to detect energy losses and possible constructive pathologies.

By reducing buildings' energy consumption, a nation can reduce dependency on imported energy and strengthen its strategic position. Moderation of energy-end use in buildings will also reduce greenhouse gas emissions and pollution produced by the combustion of fossil fuels. This environmental advantage proves to be beneficial at both local and global levels. The region under study presents no technological barriers: there is appropriate technology to make buildings energy-saving, as well as experience in the construction and monitoring of bioclimatic buildings to prove it. Greater effort is needed on the part of society to accept this form of design as possible and urgent to meet the needs of future generations with equity and also preserving natural resources.

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