

Study of the energy consumption of a massive free-running building in the Argentinean northwest through monitoring and thermal simulation

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ABSTRACT

The investigation presented in this paper has three main objectives. The first one is to study, through a case study, if it is possible to acceptably predict the energy consumption of a massive residential free-running building, when the exact behavior of the occupants is unknown or actual indoor conditions are not monitored, assuming standard use and occupation schedules, for the dry climate of the Argentinean Northwest. The second objective of the paper is to detect the possible causes of differences between actual and predicted energy consumption through an exhaustive thermal monitoring and occupant's behavior, in order to obtain an improved model of the building giving more accurate predictions of the energy consumption. The third objective is to analyze the effect on the annual energy consumption of changing the massive envelope by a lightweight one. The comparison of real and simulated consumptions under comfort conditions defined by ASHRAE *Standard* 55 shows that simulations overestimated the energy consumption for heating and cooling. The main causes were detected from the experimental monitoring, indicating a lower use of the air conditioning equipment than the supposed initially. Simulations were improved to consider actual use and occupation conditions. Finally, an annual simulation of the improved model performed by changing the envelope material to a lightweight one showed that energy consumption for heating was increased, while energy consumption for cooling was decreased. In an annual balance, the massive walls are preferable over lightweight ones in arid sunny climates as in the Argentinean Northwest, giving energy savings of around 25%.

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1. Introduction

The assessment of energy consumption and indoor thermal comfort in buildings through computer thermal simulation has experienced a fast growing in the last years. In the beginning, most assessments were based on simulations of buildings under no-occupancy schedules. This simple model became obsolete when the increasing calculation power of PCs allowed the inclusion of complex occupancy schedules to account for interactions between user and indoor environment. This new approach was reinforced by investigations started in the early eighties that revealed the user behavior as one of the most important input parameters influencing the results of building performance simulations. Van Raaij and

Verhallen [1] discern five behavioral patterns (conservers, average users, spenders, cool dwellers and warm dwellers) that cause significant differences between predicted and actual energy use and indoor temperatures, as pointed out by Soebarto and Williamson [2]. Behavioral patterns are particularly important when passive-efficiency measures are used in the building design and/or for lightweight buildings [3,4] and they are linked to many factors, some of them being the thermal comfort perception of users and their adaptation capabilities. i.e., it is known that indoor temperature of free-running buildings are allowed to vary in a wider range without affecting the thermal comfort that buildings with mechanical air conditioning, due to the adaptive behavior of their occupants, as stated in [5]. This adaptive behavior is currently matter of study, because it depends on a variety of factors such as geographical localization, energy access, cultural background, social and economic level, energy cost, level of environmental awareness, and so on [6]. An example are the studies of Cao et al. [7] on thermal adaptability in China, that revealed higher tolerance of people in the hot environment than estimated by PMV (Predicted Mean Vote), and better adaptation of people to the cold environment

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in direct relationship with lower outdoor temperatures. Furthermore, the differences in thermal responses between respondents from North and South China showed that the different climates of people's native regions also affected their thermal comfort and adaptability.

Common interactions of an average user with the indoor environment of office buildings were studied empirically by several authors. Thus, in the current literature there are different available algorithms for office buildings that describe manual lighting controls, opening of windows, use of sun-shading devices, use of air conditioning equipment, clothing, etc. [8,9]. For residential buildings, studies were conducted in developed and developing countries to obtain algorithms or models describing "typical" occupancy levels [10], natural ventilation [11,12], and lighting and air conditioning use [13,14]. In the simulation programs, the description of occupancy patterns, use of lighting, opening of windows for natural ventilation, equipments, etc., in a very detailed way, is usually a time consuming task. As detected recently by Hoes et al. [4], the use of such detailed schedules and/or user patterns algorithms can be avoided when building design has low sensitivity to the user behavior. The authors focused on the questions of when it is useful to include a more detailed user behavior model (presence and user interaction with the building) in the building simulation process and how different building designs respond to differences in user behavior. The authors conclude that the selection of a particular model of user behavior, ranging from a simpler one to a more advanced one, depends on the required indicator, i.e., maximum and minimum indoor temperatures may be determined applying relative simple user profiles (with extreme values), while total energy use may require a more detailed modeling of user behavior. For example, Hens et al. [15] points out that when comparing calculated heating consumption in residential buildings assuming standard usage (based on EN-ISO 13790, heating season mean indoor temperature of 18.8 °C, with whole protected volume heated) with standardized measured data, it is common to find that measured consumption is a fraction only of what was calculated. Hoes et al. [4] also realize the fact that buildings with higher levels of thermal mass are less sensitive to changes in user behavior, while low thermal mass buildings with air conditioning or high temperature heating systems will respond directly to changes in presence.

In the last decade, several transitional and developing countries have undergone fast growth, which does not coincide with improvements in building techniques and codes that usually require research efforts and policy discussions within a longer time frame [16]. This is also the case of Argentina. Nationwide fuel prices are between 5 and 15 times lower than international prices [17], with natural gas being the cheapest per energy unit. Thus, the low energy bills discourage investments in technological improvements [18]. Furthermore, the subsidies are not income-sensitive and not equally distributed, i.e. all households enjoying natural gas pay the same unit price of heavily subsidized energy, which is probably the single, most convincing reason for middle-high and high income households not to choose better thermal performance buildings, even though they can afford them. In the Northwest zone of the country, the traditional envelope of residential buildings is made of ceramic hollow brick (0.18 m thick) plastered on both surfaces. The massive brick (0.3 m thick) with or without plaster is the second most used material, but the hollow brick is by far the preferred technology, because the wall construction is simpler, faster and more economic. No one of the mentioned technologies include thermal insulation. A ceramic wall 0.18 m thick has a thermal transmittance K of 2.23 W/m²K while a 0.3 m thick massive brick wall has a thermal transmittance of 1.83 W/m²K. The massive brick wall meet the level C (minimum) of the Argentinean construction codes IRAM Norm 11605 [19], while the lightweight hollow brick wall

does not meet the mentioned norm. Because it is not a national law, the Norm is not accomplished by the construction sector, nor even by the social houses built by the government itself. There is no knowledge of the effect on energy consumption of both technologies in the different climates of Argentina. Some studies were carried out for characterizing the thermal behavior of two massive walls, with and without thermal insulation [20], for the thermal behavior of social houses in Northwest [21] and for residential houses in La Pampa, in central Argentina [22], but still there is a lack of information on this subject.

The lack of codes regulating energy efficiency of buildings, the highly gas-dependence of the Argentinean energy consumption matrix (it depends more than 50% on natural gas), the lack of policy and investment on energy generation, and the fast grow of energy consumption in the last decades, make the energy situation of Argentina cause of deep concern. In the last years, the high consumption levels of natural gas during winter caused a strong restriction, between 20 and 50%, of the gas delivered to the industrial sector and to the power stations, in order to supply it to the top priority residential sector. In summer, the situation is not better, and the residential, commercial and industrial sectors are often affected by interruptions in the electricity supply. Around 22.5% of the delivered gas in Argentina is destined to the residential sector, while in the Argentinean Northwest this value is around 6% [23]. The energy demand of buildings experiences a fast growing in the last years that can be associated to an increase in the sells of A/C equipment. Between 2005 and 2010, the electricity consumption grew up to 38%, while the users' number growth was only 17% [24]. The average annual electricity consumption per capita in Salta city, in the Argentinean Northwest, was around 14,500 MJ/year in 2005 and 17,100 MJ/year in 2010.

In this context, the investigation presented in this paper has three main objectives. The first one is to study, through a case study, if it is possible to acceptably predict the energy consumption of a massive residential free-running building, when the exact behavior of the occupants is unknown or actual indoor conditions are not monitored, assuming standard use and occupation schedules, for the dry climate of the Argentinean Northwest. This is important for assessing the energy consumption of both, new and existent buildings, for which in general the actual occupant's behavior, ventilation schedules, use of heating/cooling devices, etc. are not known. In these cases, the common approach used in simulations is that the desirable indoor temperatures are taken according to the thermal comfort zone defined by the ASHRAE Standard 55 [25]. The second objective of the paper is to detect the possible causes of differences between actual and predicted energy consumption through an exhaustive thermal monitoring and occupant's behavior, in order to obtain an improved model of the building giving more accurate predictions of the energy consumption. The third objective is to analyze the effect on the annual energy consumption of changing the massive envelope by a lightweight one. The steps needed to achieve these objectives are: (a) to determine the historical 5-years energy consumption (gas and electricity) of the building and the "base" electricity and gas consumptions; (b) to simulate the bi-monthly energy consumption by using monitored meteorological data corresponding to a whole year, assuming the ASHRAE Standard 55; (c) to compare simulated and real bi-monthly energy consumption for this annual period and to quantify the difference; (d) to analyze measured hourly indoor temperatures in winter and summer periods in order to determine the possible causes of such differences, (e) to recalibrate the simulation model in order to reflect the actual use and occupancy of the building found during the experimental monitoring, and f- to quantify, for the improved model, the influence of a massive and a lightweight envelope in the annual energy consumption of the building.

2. Climate and building description

The city of Salta (24.8° South latitude, 65.5° West longitude, 1182 m over the sea level) is placed in the Northwest zone of Argentina. The climate is classified as sub-tropical with dry season, with thermal amplitudes higher than 14 °C. The annual average temperature (National Meteorological Service) is 16.3 °C and relative humidity is around 73%. In winter the average maximum, mean and minimum temperatures are 19.8 °C, 10.4 °C, and 4 °C, respectively, with clear sky days and high solar radiation levels (10.8 MJ/m²/day). In summer the average maximum, mean and minimum temperatures are 28.3 °C, 21.3 °C, and 18 °C, respectively, with a mean daily solar irradiance on horizontal surface around 19.2 MJ/m²/day. In the last years, maximum temperatures in summer usually overpassed 30 °C, with absolute maximum values that reached 37 °C.

The studied building is placed at 100 m over the city level in a residential neighborhood. The two-story house is inhabited by four people (two adults and two children), and it has a useful area of 180 m²: kitchen, living room, playroom, sunspace and a bathroom at the ground floor (124 m²); and two bedrooms (East, towards the street and West, towards an interior garden), a library, and two bathrooms in the first floor (56 m²). The house is exposed to outdoor air excepting the South surfaces that are shaded by a neighboring two-story house.

The vertical envelope is made of 0.3 m thick massive brick with plaster only on the internal side. The thermal transmittance of the vertical envelope is 1.83 W/m²K. Living room and bedrooms have roofs made of pine wood, insulation (expanded polystyrene of 0.025 m thick in the living and 0.05 m thick in the bedrooms) and orange French tile. The remaining roofs are ceramic slabs with a concrete carpet covered by an aluminized sheet, without thermal insulation. The double-contact carpentry of windows and doors is made of cedar wood and it has auto-adhesive stripping on the frame perimeters to prevent against dust and air infiltration. The sunspace carpentry is made of aluminum. Windows and glass doors are simple-glazed (3 mm thick uncolored glass), with the exception of the windows of Library and West Bedroom, both having hermetic double glazing (4 mm glass + 6 mm air + 4 mm glass). All windows have interior drapery for shading. The house has a ventilated covered garage that provides shade in summer and protection against winds.

The building air conditioning equipment includes three mechanical air conditioners (split heat pump type) for heating and cooling, all in the first floor: 3800 W in the East bedroom, 2600 W in the West bedroom, and 4100 W in the Library. The coefficient of performance COP of the cooling split units is 2.8 in cooling mode and 2.9 in heating mode and in summer the thermostats are set in 25 °C. Four gas heaters are installed in the Living room (8100 W), Playroom (5800 W) the West bedroom (6400 W) and the East bedroom (3700 W). Gas heaters are local units of direct gas combustion with gas exhaust, where outdoor air used in the combustion process. This type of gas air heaters are the only one allowed for bedrooms by the National Gas Regulating Entity. The units are connected to the main gas supply and they are turned on in the winter (and remain in pilot when they are not in use) and they are turned off in the spring. González et al. [26] measured a thermal efficiency of 0.6 for these units. Thus, in the bedrooms the air can be heated by the gas units or by the electric split heat pump units. In the West bedroom, the gas unit provides sufficient to reach thermal comfort so the heat pump unit is used very scarcely (one or two times a year). In the East bedroom, the gas unit is used during the day and the split heat pump unit is used during night, when the gas unit is not sufficient to maintain a comfortable temperature. When necessary, they are used simultaneously to obtain a quicker heating of the room, but this is very unusual.

3. Building energy consumption for space heating and cooling

3.1. Historical consumption of energy in the last 5 years and energy consumption in an annual period 2009–2010

Table 1 shows the real energy consumption of the building (gas and electricity) for the period between 2006 and 2010. A conversion value of 38.87 MJ per cubic meter of gas was used, according to data provided by the gas company). The total average annual consumption is around 58,400 MJ/year, from which around an 83% corresponds to gas (48,400 MJ/year) and 17% to electricity (10,000 MJ/year). The average standard deviation is 1500 MJ/bi-month for gas consumption and 200 MJ/bi-month for electricity, indicating that gas consumption is strongly seasonal, with a maximum during the winter months (July–August) around 5.8 times the usual summer value. It is noted that the electricity consumption is more uniform throughout the year, with maximum registers during summer (November–December) when the electricity consumption is 20% higher than usual.

The studied building is an example of the typical energy consumption of the residential sector in arid climates of Argentina. Similar consumption behaviors of Argentinean buildings were found in the studies [27] and [28]. At national level, the electricity consumption in times of extreme cold or hot weather, when dwellers make a massive use of air conditioners, is 50% higher and gas consumption in winter increases up to eight times the usual values for locations with cold winters [29].

The estimation of the energy consumed exclusively to heat and cool indoor air can be extracted from data of Table 1, by previously determining the “base” consumption of gas and electricity and subtracting these values from the average bi-monthly consumptions. The “base” consumption is defined as the energy consumed by the building without including heating and cooling [30]. For the studied building, the “base” consumptions are determined with the average the gas consumption in November–December of the last 5 years (when gas heaters are turned off) and with the average electricity consumption in September–October over the same years (when electricity is neither used for heating nor cooling). From Table 1, these values are 3044 MJ/bi-month for “base” gas consumption (49.9 MJ/day) and 1602 MJ/bi-month for “base” electricity consumption (26.3 MJ/day). Bezzo et al. [31] indicate that for outdoor mean temperatures higher than 20 °C (summer and intermediate seasons), the average “base” gas consumption in Argentina, corresponding to water heating and cooking of a typical family is 1.4 m³/day (54.3 MJ/day), that is close to the value obtained for this house. Finally, the average annual energy consumptions were obtained, resulting in 318.5 MJ/(year m²) for air heating and 13.1 MJ/(year m²) for air cooling, where the values are expressed per square meter of heated or cooled area (95 m² for heated area and 38 m² for cooled area). It is concluded that, from the annual gas consumption around a 62% is destined to space heating, while from the annual electricity consumption around a 5% is destined to space cooling.

The bi-monthly energy consumption of the building measured by the gas and electricity companies (Table 1) for an annual period since July 1st, 2009 to June 30th, 2010. The total annual consumption is around 57,700 MJ/year, from which around an 80% corresponds to gas (47,000 MJ/year) and 20% to electricity (10,700 MJ/year). The gas consumption has a maximum record during (July–August) that is roughly 5 times the “base” consumption. The electricity consumption is more uniform throughout the year, with maximum registers during the extreme outdoor conditions, that is, in summer (November–December) and winter (July–August), when the electricity consumption is 50% higher than the “base” consumption.

Table 1
Bi-monthly gas and electricity consumptions, 5-years average bi-monthly gas and electricity consumptions and standard deviation, in MJ/bi-month, for the period 2006–2010.

Period		January–February	March–April	May–June	July–August	September–October	November–December
2006	Gas	2937	3507	13439	17284	8206	3044
	Electricity	1780	1655	1531	1566	1602	1869
2007	Gas	2884	3222	15735	22321	10573	2795
	Electricity	1549	1371	1406	1406	1531	1513
2008	Gas	3079	3418	14774	14649	9719	3222
	Electricity	1816	1620	1477	1335	1673	1602
2009	Gas	3222	3346	9843	16874	6995	3186
	Electricity	1976	1744	1549	1513	1477	2207
2010	Gas	2599	4005	13368	15308	5518	2990
	Electricity	1816	1905	1709	1994	1744	2136
Average	Gas	2937	3507	13439	17284	8206	3044
	Electricity	1780	1655	1531	1566	1602	1869
SD	Gas	267	338	2581	3471	2350	196
	Electricity	178	214	142	303	125	356

3.2. Simulation with EnergyPlus for the period 2009–2010

Energy Plus (version 5.0) software [32] was used to simulate the transient thermal behavior of the building. This free software was developed by LBNL (Lawrence Berkeley National Laboratory) and it is currently the official software for building simulation of the USA Department of Energy. Energy Plus does not include algorithms describing user behavior; instead it allows the user to input very detailed schedules to account for user occupancy, on/off periods of electric and gas equipment, use of lights, etc. The monitored meteorological data corresponding to a whole year (July 1st, 2009 to June 30th, 2010) were used in an annual simulation of the heating and cooling loads of the building.

The following assumptions were made to perform the thermal simulation:

- The building was divided into 9 thermal zones, 5 at ground floor (Kitchen, Living room, Playroom, Bathroom, and Sunspace) and 4 at first floor (East bedroom, West bedroom, Dressing room including two bathrooms, and Library), as shown in Fig. 1.
- Thermal and optical properties of the building materials were obtained from the heat transfer literature.
- Monitored meteorological data (outdoor temperature, wind velocity and direction, relative humidity, and solar radiation on horizontal surface) were used. The data was collected since May 1st, 2009 to September 30th, 2010, at a 15 min timestep, by an on-site weather station whose sensors were previously calibrated at the INENCO laboratories. Automatic 12-bits data loggers were used to sense temperature ((accuracy: $\pm 0.35^\circ\text{C}$, resolution: 0.03°C at 25°C) and relative humidity (accuracy: $\pm 2.5\%$, resolution: 0.03%).
- Hourly normal direct and diffuse solar radiations were previously estimated from the global solar radiation on horizontal surface through the Liu–Jordan method and the Pérez model [33].
- Shading caused by surrounding building surfaces, overhangs and trees were considered. The deciduous foliage of neighboring trees was managed by defining solar and visible transmittances that vary during the year.
- All thermal zones were described by an air node representing the uniform temperature of the room volume.
- Constant infiltration of 1 air change per hour was set for all thermal zones connected to outdoors through windows and/or doors. In summer, occupants periodically ventilate their house. This purposeful flow of air from the outdoor environment directly into a thermal zone was simulated by using the simplified ventilation model *Wind and Stack with Open Area* provided by Energy Plus, which accounts for natural ventilation driven by wind and stack effects. In this model, the ventilation air flow rate is a function of wind speed and thermal stack effect, along with

the area of the opening being modeled. The natural ventilation flow rate can be also controlled by a multiplier fraction schedule applied to the user-defined opening area and through the specification of scheduled minimum temperatures (below which ventilation is shutoff), maximum temperatures (above which ventilation is shut off) and delta temperatures (temperature difference between indoor and outdoor below which ventilation is shut off). The temperatures can be either single constant values for the entire simulation or schedules which can vary over time. In the studied building, exterior windows were considered completely open (multiplier fraction = 1) during summer nights, and ventilation was allowed when indoor temperature exceeds 26°C and the difference between indoor and outdoor temperatures is higher than 2°C .

- Convective coefficients were set at $6\text{ W/m}^2\text{K}$ for all interior wall surfaces. The convective coefficients of exterior surfaces were auto-calculated by the software through a detailed model that accounts for orientation and wind velocity and direction.
- Floors are considered as three-layered elements (floor ceramic cover, concrete slab, and 1 m of soil) and the heat balance was calculated through FDA (Finite Differences Algorithm). This model was found to be more adequate for floors without thermal insulation, which has an important coupling with the soil, when ground temperature data in the site are not available. Building floors in Argentina are built commonly without thermal insulation; thus it is probable that the floor model used for the studied building will be adequate to simulate other buildings with similar floor characteristics.

To obtain an accurate thermal model of the building without the occupants, it was simulated under a no-occupancy schedule and with meteorological experimental data of a 15 days period, during which the house was unoccupied. The results of the simulated indoor temperature of each zone were compared with the measured air temperature and coefficients were adjusted until a good agreement was obtained. The differences between simulated and experimental data sets were 0.8°C in average, indicating that the thermal model is adequate to reproduce the building behavior. The results obtained for the adjustment between measured and simulated data for an unoccupied period was discussed in a previous paper [34], thus they are not repeated in the present article.

Once this initial thermal model of the building was tested and validated against experimental data, it was modified in order to include the internal heat gains in each zone (excluding the air heaters and coolers that were treated separately). A previous survey of the common activities and schedules of the family was made, in order to enter a schedule as detailed as possible. The internal heat gains in each building zone included: the metabolic heat rate (four people with full-time occupation), lights, electric appliances

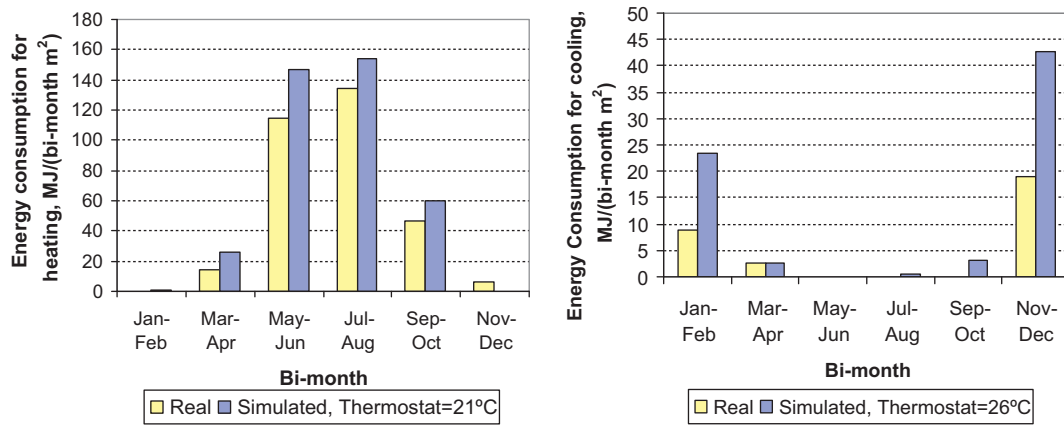


Fig. 1. Real and predicted bi-monthly energy consumption for heating (left) and cooling (right) per square meter of conditioned area, in MJ/m²·year. Simulations were performed for thermostat set-points temperatures of 21 °C (winter) and 26 °C (summer).

(2 PCs, 2 TVs, and 1 refrigerator) and heat from cooking. Comfort temperature limits recommended by ASHRAE *Standard 55* [25] are, in this case, 21 °C in winter and 26 °C in summer, for people in typical winter and summer clothing (0.9 clo and 0.5 clo, respectively) during primarily sedentary activity. These values were used as the heating and cooling set-points of the zone thermostats. Only the zones with installed air conditioning equipment (heaters or coolers) were thermostatically controlled, and only during the periods of time the zones were occupied by people. During unoccupied periods the building was simulated under free floating conditions. Thus, in winter the thermostatically controlled zones were the East Bedroom, West Bedroom and Living, while in summer they were the East Bedroom, West Bedroom and Library. The energy supplied to the heaters and coolers was estimated by supposing an efficiency of 0.6 for gas heaters and 0.5 for the A/C equipment. Simulated annual and bi-monthly heating and cooling loads are shown in Table 2, per square meter of heated or cooled area, together with mean indoor and outdoor temperatures. The simulated mean indoor temperatures ranged from 18.8 °C in winter to 28.9 °C in summer, with indoor thermal swings between 2 °C and 3 °C. These values together with an analysis of the hourly simulation during the whole year performed to detect the periods when the indoor temperatures were inside the comfort zone, indicate that the thermal comfort conditions of ASHRAE *Standard 55* were achieved only in intermediate seasons. This occurred in spring (September and first two weeks of October) and some weeks of autumn (in March).

3.3. Comparison between measured and simulated energy consumption of the building in the period 2009–2010

The energy consumed exclusively to heat and cool indoor air was estimated from data of Table 1, by subtracting the “base” consumptions as explained before. Because since 2010 both, gas and electricity are used for heating in the cold months (May–August), the difference between the electricity consumption and the “base” electricity consumption during these months is due to the use

of the electrical air heaters, thus it was included in the energy consumption for heating. The real annual energy consumption for cooling is 1000 MJ/year, while for heating it is 28,800 MJ/year. Thus, it can be concluded that, from the annual gas consumption (47,100 MJ/year) around a 61% is destined to space heating. This value is close to the value of 67% supplied by the gas company. In the same way, it is concluded that from the annual electricity consumption (10,600 MJ/year), around a 10% is destined to space cooling.

A computation of the annual energy consumption for air heating and cooling shows that 93% corresponds to heating. The comparison with the values predicted by EnergyPlus (Fig. 1) shows that the variation throughout the year of the energy consumption for heating, that is, the curve shape, is in agreement with the real trend. An overestimation of around 22% is observed between predicted and real consumptions in winter. In the case of the energy consumption for cooling, the simulated values are significantly higher than the real ones, particularly for the period November–December when the simulated value is more than twice the real consumption. In conclusion, simulations overestimated the energy consumption for heating and cooling in 22% and 135%, respectively. This situation can be explained by a lower use of the air heaters and coolers than supposed initially that can be caused by several factors, such as an intermittent use of air heaters/coolers instead a permanent use during a period of several hours, a higher tolerance to cold/hot indoor temperatures that influences the thermostat set-points; level of clothing different to the supposed by the model; an attitude of environmental consciousness that reinforces the use of passive strategies in summer and winter, etc. The sub-use of air heaters and coolers due to economical reasons was not included as a possible cause because the owners could afford the higher costs of obtaining thermal comfort. Thus, it was needed an analysis of the detailed hourly monitoring of the building under occupancy, in winter and summer periods, in order to give a deep insight of what is causing the differences between real and predicted energy consumptions, particularly during the summer. The results are presented in the next section.

Table 2

Bi-monthly heating and cooling loads and mean indoor temperatures obtained with EnergyPlus by using hourly monitored meteorological data for an annual period.

	January–February	March–April	May–June	July–August	September–October	November–December
Heating load [MJ/(bi-month m ²) of heated area]	0.0	18.5	104.9	110.0	42.9	0.0
Cooling load [MJ/(bi-month m ²) of cooled area]	15.5	1.4	0.0	0.5	1.9	28.6
Mean indoor temperature [°C]	27.1	23.2	18.8	19.0	21.8	28.9
Mean outdoor temperature [°C]	24.3	22.0	11.0	11.4	15.8	26.8

4. Summer and winter behavior: experimental monitoring and simulation

The house was monitored at a logging interval of 15 min, during 7 months, since January 7th to August 26th, 2010. In each room inside the building, one data logger sensing air temperature was placed at 1.5 m over the floor level. In the Living room, an additional logger was placed at 2.65 m over the floor level to obtain an averaged temperature of this double-storey volume. Two periods (one in summer, since January 26th to February 10th; and one in winter, since August 10th to 23rd) were selected to analyze the building thermal behavior. The on/off periods of A/C equipment and gas heaters, and periods of open/closed windows were carefully registered. The building was monitored under permanent occupancy, except for the period between January 16th and 29th when the owners went out for vacations. During this period, all windows, doors and curtains were closed and all electric and gas equipments remained off.

4.1. Summer thermal behavior

The period between January 26th and February 10th, 2010, was studied. The days were hot and mostly sunny, with high solar irradiance levels (around 1100 W/m^2). The maximum temperatures reached 36°C , and minimum temperatures oscillated between 18 and 23°C . The average temperature on the period was 27°C and the thermal amplitude was 13°C . Wind speeds were higher during the day, as usual, with a mean value of 4 m/s and dominant direction towards N–NE.

The results of the monitoring are shown in Figs. 2 and 3. The indoor temperatures at the first floor oscillated between 25°C and 30°C . In average, the building indoor temperature was 26.6°C and it never went down below 23°C . The average indoor temperature swing oscillated between 2°C and 3°C , with outdoor amplitudes of 13°C , realizing the effect of the massive envelope as moderator of the outdoor thermal swings. The highest temperatures were registered at the Sunspace, that oscillated between 27°C and 35°C , due to the direct solar gain incoming through the wide West glazed area (without solar shading) and to the heat conducted downward by the concrete roof, having no thermal insulation. This was also the zone with the highest thermal swing, which reached 8°C . Sunspace and Living room reached their maximum temperatures around 18:00. The lowest temperatures were registered at the Playroom, with a mean temperature around 25.3°C . This mean temperature was lower than outdoor temperature due to the effect of cooling through the thermal mass of the ground that acted as a thermal sink. The Playroom does not have direct solar heat gain and it is also the zone with the lowest envelope area in contact with outdoors. At the first floor, the East Bedroom and the Library reached their maximum temperatures at 20:00, while West Bedroom at 22:00. The shifts of indoor temperatures are in correspondence with the hours when mechanical air coolers are turned on or when fresh air from opened windows enters the spaces. Natural ventilation is used only during 2–3 h in the night, when outdoor temperatures are lower and the air is cleaner because the lower car circulation on the non-pavement street. Only the Sunspace, facing the interior garden, is ventilated all over the night.

The records show that occupants turn on the air coolers when indoor air temperature reaches 28°C and only if the zone is occupied. Usually this kind of higher indoor temperatures (e.g. around 28°C) are tolerated when air movement is promoted by ceiling fans or natural ventilation. In this building the air movement is promoted by using natural night ventilation. The periods of A/C use are short, usually less than 2 h. In the West Bedroom the A/C was used in the night and during the siesta (between 14:00 and 16:00). In the East Bedroom the use was restricted to the siesta, while in

the Library the A/C was used on the afternoon of some days. In average, the A/C equipment was used 1.3 h/day in the West Bedroom, 0.6 h/day in the Library and 0.6 h/day in the East Bedroom. Thermal simulation calculated average A/C use in this period of 9.8 and 11.8 h/day in East and West Bedrooms, and 4 h/day in the Library. Thus, it was confirmed that occupants made a lower use of the A/C equipment than the predicted by the simulation, and this lower use caused the indoor air temperature to be outside the comfort zone.

The percentage of hours with temperatures beyond 26°C and 28°C are shown in Fig. 4: in average, around 65% of the hours, indoor temperatures are higher than 26°C , and 16% of the hours are higher than 28°C . In the West Bedroom, East Bedroom and Library, around 85% of the hours the temperatures are higher than 26°C . The percentage of hours that auxiliary cooling energy will be needed to maintain the conditioned zones below 26°C during the periods the users occupy the zones are 41% for the West Bedroom (an average of 9.8 h/day of A/C use), 49% for the East Bedroom (11.8 h/day), and 13% for the Library (3.1 h/day). These values can be translated to electricity consumption by mean of the COP value and cooling power of each A/C unit, and by considering the period of use of each one, giving a daily electricity consumption for cooling of 106.7 MJ/day . If we use a comfort temperature limit of 28°C , these percentages of hours that auxiliary cooling energy will be needed are reduced to around 6%, 7% and 11% in the West Bedroom, Library and East Bedroom, respectively, giving a daily electricity consumption for cooling of 26.7 MJ/day . Then, it can be concluded that the consumption for cooling in this particular building in a hot day is reduced four times if the thermostat set-point is 28°C instead 26°C . Because on real occupancy of the house, the occupants tolerate temperatures up to 28°C without using air coolers, and simulations were performed with a limit of 26°C , it is clear that two reasons why simulation overestimates the cooling needs of the house are: the thermostat set-point, linked to a higher users' tolerance (28°C instead 26°C), and the use schedule in each zone, linked to the user's customs in the A/C equipment managing which causes indoor air to be clearly out of the comfort zone (behind 28°C) during long periods. Both, tolerance to higher temperatures and equipment management are characteristics of this particular family and cannot be generalized to all buildings in the zone without a previous statistical study on these topics.

4.2. Winter thermal behavior

The results of the monitoring are shown in Figs. 5 and 6. The 2010 winter was characterized by minimum exterior temperatures (-7.8°C) that were the coldest of the last ten years, with frosts and snow during July. The period between August 10th and August 23rd was selected to analyze the building thermal behavior. Minimum daily temperatures oscillated between 2°C and 13°C , with maximum temperatures between 13°C and 30°C . The days of the period were sunny, as usual in dry climates, with solar irradiance levels around 850 W/m^2 and high thermal amplitudes that reached 20°C (as in August 16th, 17th, and 18th). Massive buildings can temperate these thermal amplitudes more efficiently than lightweight buildings, which is one of the reasons why vernacular and current architecture designs include materials as adobe and massive brick walls. Two sub-periods can be distinguished in Fig. 5: the first one, from August 10th to 15th, with lower temperatures (mean temperature of 10°C , maximum temperature around 19°C), and the second one, from August 16th to 23rd, with higher temperatures (mean temperature of 17°C , maximum temperature around 30°C).

The registered on/off periods of the heating equipment shows that the use was not continuous through the day. The air heaters were turned off since August 18th, because of the warmer outdoor conditions. In the West Bedroom the use of the gas heater was

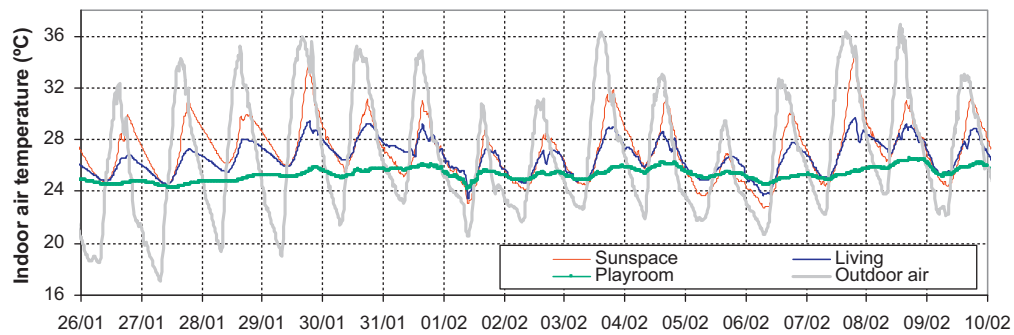


Fig. 2. Indoor temperatures of the zones at the ground floor and outdoor air temperature, for the period between January 26th and February 10th, 2010.

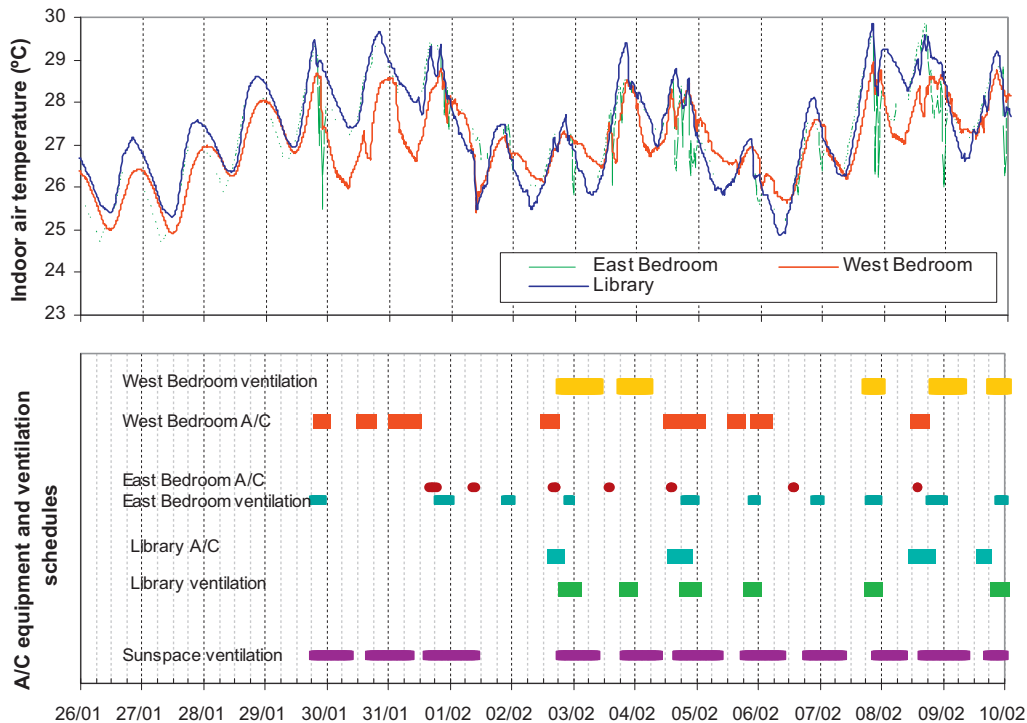


Fig. 3. Indoor temperatures of the zones at the first floor (top) and use schedules of A/C equipment and natural ventilation (bottom), for the period between January 26th and February 10th, 2010. The dashed bars correspond to operating periods.

limited to two hours in the night (22:00 to 24:00) and 1.5 h around the midday. In the Living room and Playroom the gas heaters were turned on early in the morning and they were turned off around midday. Playroom gas heater was turned on in the afternoon, since

17:00 to 22:00. In the East Bedroom both, a gas heater and an A/C electrical heater were used. It can be noted that both equipments were not used simultaneously, i.e., A/C was used all over the night with variable thermostat set-points between 17 °C and 21 °C

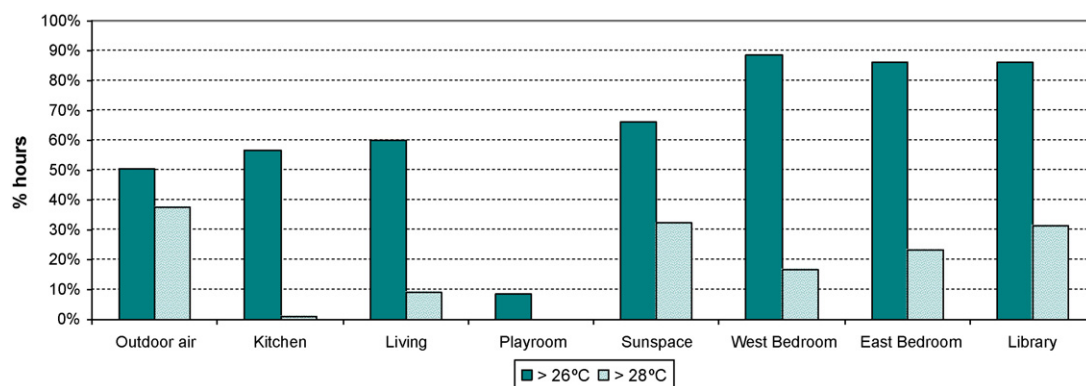


Fig. 4. Percentage of hours >26 °C and >28 °C for the monitored period (January 26th to February 10th, 2010).

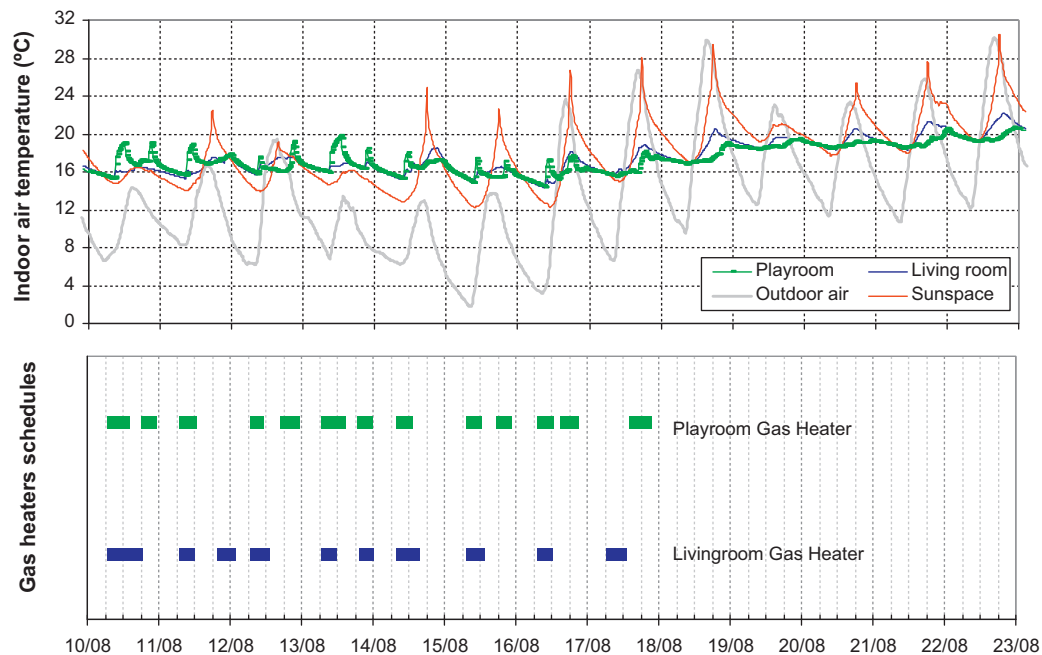


Fig. 5. Indoor temperatures of the zones at the ground floor and outdoor air temperature (top), and gas heaters schedules (bottom), for the period between August 10th and 23rd, 2010. The dashed bars correspond to operating periods.

(shown in the secondary axis of Fig. 6), while the gas heater was used usually during the siesta.

The mean indoor temperature was 17.6°C at the ground floor and 18.7°C at the first floor, with a mean outdoor temperature of 13.7°C. The maximum mean temperature was 19.6°C and it was registered at the East Bedroom where heaters functioned over all night. In average, the building indoor temperature was 17.8°C and it never went down below 14°C, excepting the Sunspace where temperatures reached 12°C during the night. The highest temperatures were registered at the Sunspace, that oscillated between 12°C and 30°C, due to the direct solar gain incoming through the West glazed area. It was also the zone with the highest thermal

amplitude, of around 12°C, because of the heat losses through the single-pane glazed area. The Sunspace, during the daylight hours (when it is used) does not need auxiliary heating if the day is sunny. Sunspace and Living room reached their maximum temperatures at around 18:00. The shifts of indoor temperatures in the Playroom and Bedrooms allow detecting the hours when the heaters are turned on, which were found to be in very good correspondence with the periods registered by the users. Since August 18th to 23rd, there was no use of auxiliary heating due to higher outdoor temperatures. In this sub-period, mean indoor temperatures were 18°C at the ground floor (20°C in the Sunspace) and 21°C at the first floor. The glass door connecting the Sunspace with the Living

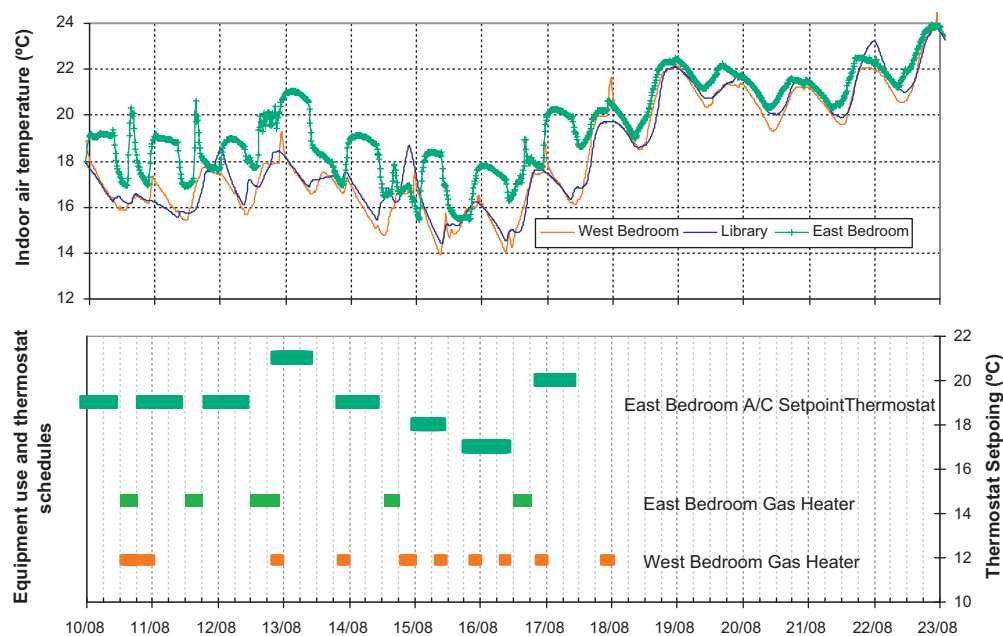


Fig. 6. Indoor temperatures of the zones (top) and heaters schedules (bottom) at the first floor for the period between August 10th and 23rd, 2010. The dashed bars correspond to operating periods.

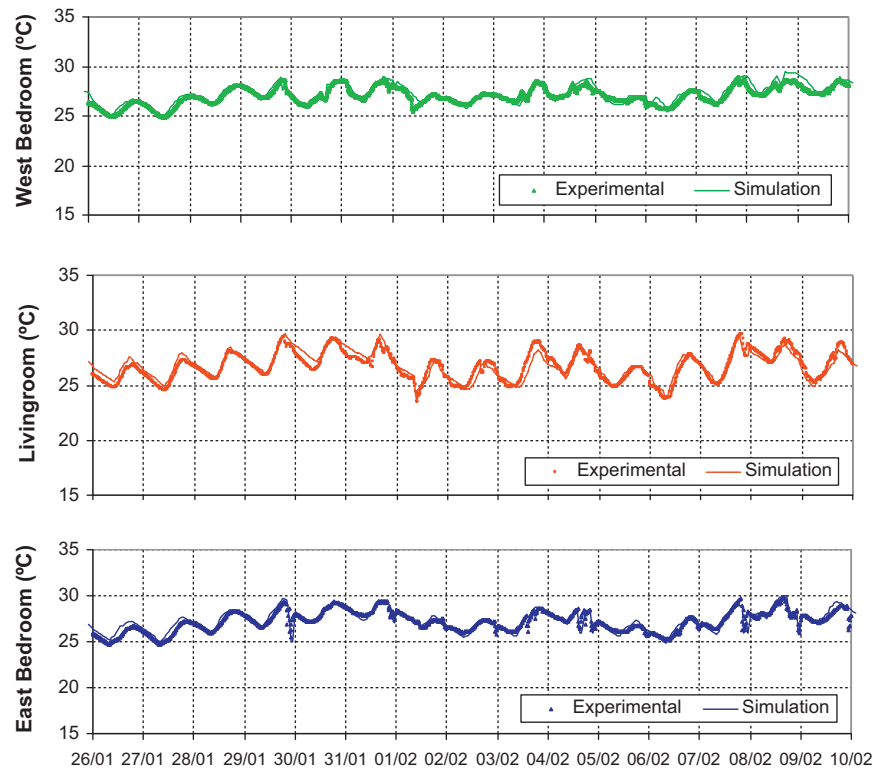


Fig. 7. Simulated and experimental indoor temperatures of the zones for the summer period between January 26th and February 10th, 2010.

room allows the users to drive the hot air of the Sunspace into the Livingroom. When this door is opened between 15:00 and 20:00, the temperature in the Living raises 2 °C. As explained, the thermal mass of the building tempered the outdoor thermal swings

and contributed to minimize the use of the heaters. An average on the period shows that the heaters were used 2.2 h/day in the Living room, 2.2 h/day in the Playroom, 4.3 h/day in the West Bedroom, and 7.4 h/day in the East Bedroom. EnergyPlus estimated an

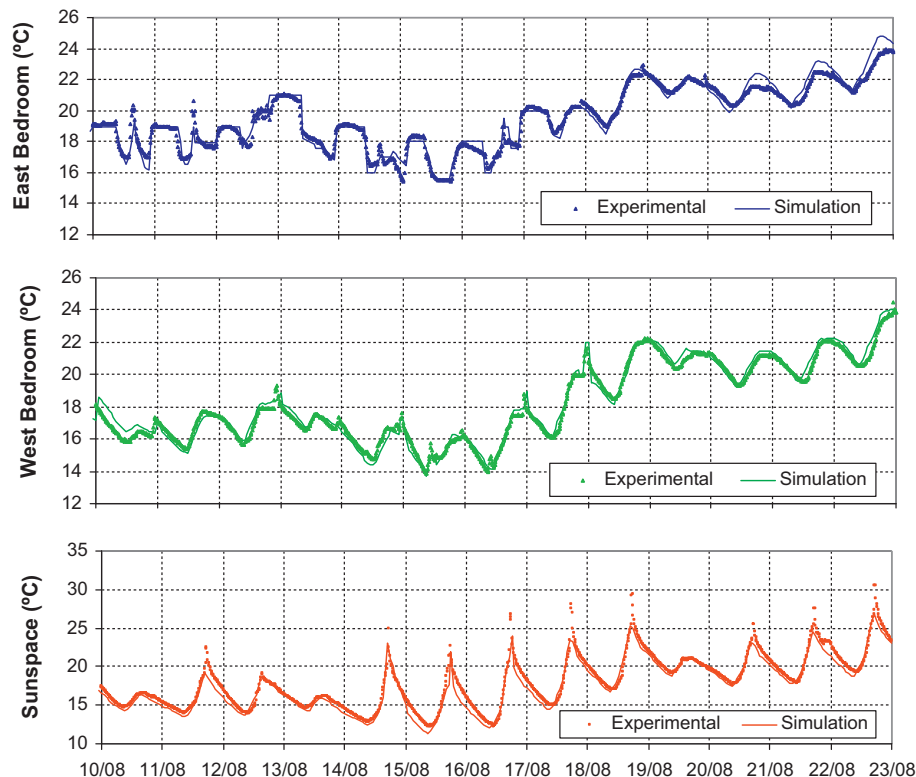


Fig. 8. Simulated and experimental indoor temperatures of the zones for the winter period between August 10th and 23rd, 2010.

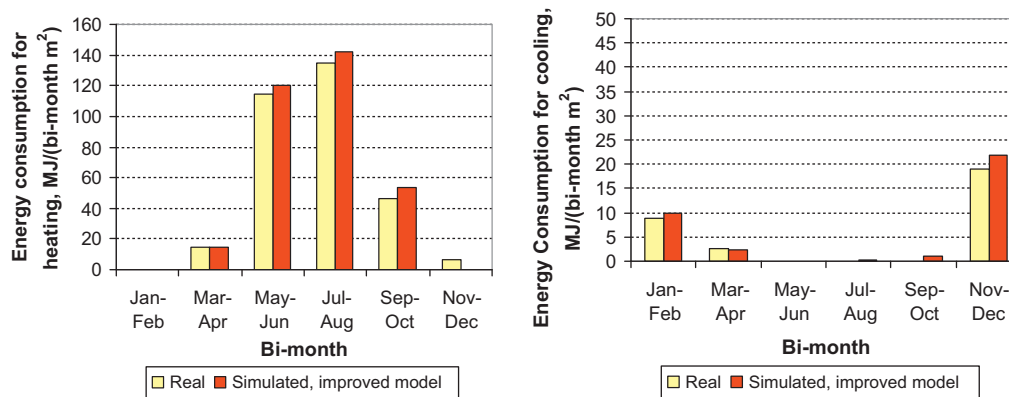


Fig. 9. Real and predicted bi-monthly energy consumption for heating and cooling per square meter of conditioned area, in MJ/m²year. Simulations were performed for the improved building.

average use of heaters in this period of 9.4 hours/day in the East Bedroom, 7.8 h/day in the West Bedroom, and 8.8 hours/day in the Living room. As in summer, it was concluded that occupants made a lower use of the heaters than the predicted by the simulation, and this lower use caused the indoor air temperature to be outside the comfort zone.

4.3. Simulation under actual use conditions

In order to reflect the actual use and occupancy of the building found during the experimental monitoring, new simulations were performed with refined input data. Thus, new hourly schedules of open/closed windows for natural ventilation, on/off periods of heaters and coolers, and variable thermostat setpoints were defined that followed the real management of equipment and ventilation shown in Figs. 3, 5 and 6. The simulations were made for the two previously studied periods (summer and winter) and good agreement between experimental data and simulation was obtained. The simulated and experimental temperatures of three selected zones are shown in Figs. 7 and 8. A good agreement between experimental and simulated data sets was found, with differences below 1 °C.

Once the model was recalibrated, new annual simulations were done to obtain improved energy consumptions for heating and cooling. The results are shown in Fig. 9, showing a significant improvement of the predicted consumptions: simulations predict an annual energy consumption for cooling of 36 MJ/m² of conditioned area (real consumption was 31 MJ/m²), and an annual energy consumption for heating of 331 MJ/m² of conditioned area (real consumption was 317 MJ/m²). Thus, simulations overpredicted 16% the energy consumption for cooling and only 5% for heating,

showing that it was possible to successfully recalibrate the model of the building under actual use conditions.

4.4. Effect of the thermal mass in the energy consumption

The Argentinean Norm IRAM 11605 (2002) [24] establishes three levels for the maximum values of thermal transmittances of walls and roofs: A (recommended), B (medium) and C (minimum), for winter and summer conditions. These maximum values depend on the outdoor design temperature of the zone. For Salta city, the outdoor design temperatures are: 6.3 °C (mean design temperature) and −0.8 °C (minimum design temperature) for winter, and 20.9 °C (mean design temperature) and 30.6 °C (maximum design temperature) for summer. The maximum values of thermal transmittances of walls are 0.38 W/m²K (level A), 1.00 W/m²K (level B) and 1.85 W/m²K (level C) for winter, and 0.5 W/m²K (level A), 1.25 W/m²K (level B) and 2.00 W/m²K (level C) for summer.

A 0.18 m thick ceramic wall has a thermal transmittance K of 2.23 W/m²K while a 0.3 m thick massive brick wall has a thermal transmittance K of 1.83 W/m²K. The massive brick wall meet the level C (minimum) of IRAM Norm, while the lightweight hollow brick wall does not meet the IRAM Norm. An annual simulation was performed by changing the envelope material from massive brick (0.03 m thick) to lightweight hollow ceramic brick (0.18 m thick). The results are shown in Fig. 10. As expected, the energy consumption for heating was found to be lower with the use of 0.3 m thick brick walls, because the capacity to storage the solar heat gain is higher in a massive envelope. On the opposite, in summer the energy consumption for cooling was seen to increase a moderate amount for massive walls when compared with the lightweight

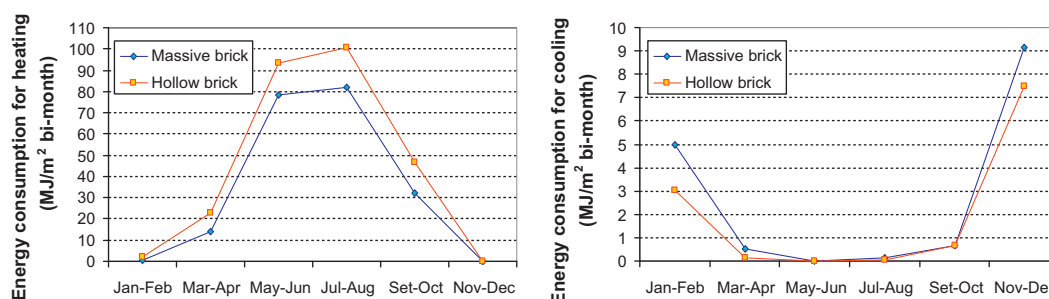


Fig. 10. Energy consumption for heating and cooling for two different building envelope materials: massive brick (0.3 m thick) and ceramic hollow brick (0.18 m thick).

envelope, because heat is stored during the day in the massive walls and released back to indoors during the night. This behavior agrees with those found by Zhu et al. [35] for buildings in the dry desert climate of Las Vegas, that is characterized by high ambient temperatures during the day and high solar irradiance levels. It is concluded that the annual balance gives that massive walls are preferable over lightweight ones, due to the climatic conditions of the zone: the annual energy consumption is 222 MJ/(m²·year) for the building with massive brick and 278 MJ/(m²·year) for the hollow brick envelope, that is, an increment of around 25% in the annual energy consumption.

5. Conclusions

The historical 5-year energy consumption (gas and electricity) of the building, the “base” electricity gas and electricity consumptions, the actual and simulated bi-monthly energy consumption for heating and cooling through the software EnergyPlus for a monitored whole year meteorological data under the comfort conditions defined by ASHRAE *Standard* 55 and under actual use conditions, the measured hourly indoor temperatures in winter and summer periods, and the influence of a massive and a lightweight envelope in the annual energy consumption of the building, were analyzed in detail.

The historical annual energy consumption of the building (gas and electricity) for the period between 2006 and 2010, per square meter of useful area was 328 MJ/m²·year, from which around an 83% corresponded to gas and 17% to electricity. Gas consumption was strongly seasonal, with maximum values during winter 5.8 times the usual value, while electricity consumption was more uniform throughout the year, with maximum registers during summer when the electricity consumption is 20% higher than usual. The average annual energy consumptions indicated that a 62% was destined to space heating, and 5% to space cooling.

Based on a validated physical model of the building, an annual simulation of heating and cooling loads of the building was performed with EnergyPlus, using monitored meteorological data, schedules describing the usual lifestyle of a typical four-people mid-income family, and comfort temperature limits of 21 °C in winter and 26 °C in summer recommended by ASHRAE *Standard* 55. This procedure was selected because it is the logical assumption when the exact behavior of the occupants is unknown or actual indoor conditions are not monitored. Only the zones with installed air conditioning equipment (heaters or coolers) were thermostatically controlled, and only during the periods of time the zones were occupied by people. The comparison of real and simulated consumptions showed that simulations overestimated the energy consumption for heating and cooling in 22% and 135%, respectively, indicating that the use of the air heaters and coolers was lower than supposed. Detailed monitoring in winter and summer periods was used to detect possible causes of this behavior and to recalibrate the simulations to consider actual operating conditions.

The detailed monitoring showed that in summer, the building mean indoor temperature was 26.6 °C and it never went down below 23 °C. The occupants tolerated temperatures up to 28 °C without using air coolers and not up to 26 °C, as supposed in the simulations performed following the ASHRAE *Standard* 55, because the use of natural ventilation promoted the air movement. In winter, the mean indoor temperature was 17.6 °C at the ground floor and 18.7 °C at the first floor, with a mean outdoor temperature of 13.7 °C. In both periods, the use of heaters and A/C equipments was intermittent and lasted usually less than 2 h in summer and 4.5 h in winter (excepting the heater in the East bedroom). The use of heaters and coolers was lower than the predicted by simulations and it explained why simulation overestimated the cooling and

heating loads. Tolerance to low/high temperatures, heaters/coolers schedule use, occupation, clothing, etc. are characteristics of this particular family and cannot be generalized to all buildings in the zone without a previous statistical study on these topics.

The improvement of the simulation results considered the actual schedules of ventilation and use of air conditioners and gas heaters. Simulations predicted an annual energy consumption for cooling of 36 MJ/m² of conditioned area (real consumption was 31 MJ/m²), and an annual energy consumption for heating of 331 MJ/m² of conditioned area (real consumption was 317 MJ/m²). Thus, simulations overpredicted 16% the energy consumption for cooling and only 5% for heating, showing that it was possible to successfully recalibrate the model of the building under actual use conditions.

The annual simulation performed by changing the envelope material to a lightweight one showed that energy consumption for heating was increased, while energy consumption for cooling was decreased, because of the capacity of massive walls to store energy during the day and release it during the night. In an annual balance, the massive walls are preferable over lightweight ones in arid sunny climates as in the Argentinean Northwest, giving energy savings of around 25%. The effect on lowering the outdoor thermal swing of the massive envelope was highly beneficial both, in winter and summer, because the large thermal amplitudes of outdoor air were reduced from 13 to 15 °C to indoor temperature swings of 2–3 °C.

Results obtained for the studied building indicate that, even with a deep and previously validated knowledge of the building thermal response under a non-occupancy schedule, an accurate prediction of the energy consumption based exclusively on ASHRAE *Standard* 55 comfort limits is highly difficult. Occupant management has a significant effect on simulation output and suggests that recommendations for building operation based on the assumption of passive occupants may be sub-optimal. Thus, it should be considered that the heating/cooling load values obtained by simulation are of limited application and they can not be representative of the real consumption at all, if the user behavior schedule does not closely represent the real behavior of the building occupants. The assumption that building occupants are passive with respect to their indoor environment is clearly unrealistic, and therefore recommendations for building operation based on this assumption are limited. Improved predictions of building consumption and the understanding of the relation between building and user can be reached by including user behavior models with higher resolution and higher complexity. An extensive field and statistical studies are needed to obtain adequate models for different countries and climates, in order to apply them in the estimation of energy consumption by thermal simulation and to advance the goal of design more energy efficient and comfortable buildings.

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