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Analysis of the energy performance strategies in a historical building used as a music school

Carolina Aparicio-Fernández [a,*], M Eugenia Torner [b], Mar Cañada-Soriano [c], José-Luis Vivancos [d]

[a] Building Technology Research Centre, Universitat Politècnica de València, 46022, Valencia, Spain
[b] Department of Continuous Medium Mechanics and Theory of Structures, Universitat Politècnica de València, Camino de Vera s/n, 46022, Valencia, Spain
[c] Applied Thermodynamics Department (DTRA), Universitat Politècnica de València, 46022, Valencia, Spain
[d] Project Management, Innovation and Sustainability Research Centre (PRINS) Universitat Politècnica de València, 46022, Valencia, Spain

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ABSTRACT

Energy consumption in public education buildings depends on use and occupancy. To improve energy performance, energy audits are essential to identify specific solutions for each building. In this study, we conducted an energy audit of a historical building used as a public education centre. We collected gas and electricity bills and recorded indoor temperatures for over a year to determine heating and cooling set points and the schedules. Our analysis showed that 47.42% of the electricity bills were unused. To reduce energy demand and improve thermal comfort, we both developed and validated a Building Energy Modelling (BEM) approach using TRNSYS18 and weather data during year 2021. The BEM model allowed us to propose efficient measures to meet the Standard Passive requirements. Our results demonstrate the effectiveness of energy audits and BEM modelling in reducing energy consumption in public education buildings.

1. Introduction

Energy consumption in buildings has been an issue of growing global interest in recent decades. The building sector is one of the largest energy consumers in the European Union (EU), accounting for approximately 40% of final energy demand and 36% of carbon dioxide (CO_2) emissions (Li et al., 2019). The Climate Change Conference (COP21) in Paris in 2015 aimed to limit the temperature increase to 1.5 °C by the end of this century, reducing global emissions by more than 50% by 2023 and working towards carbon neutrality by 2050. In recent years there has been a commitment to modernise the existing building stock by making it more sustainable and decarbonised. The United Nations through a roadmap published in 2020 set out the guidelines for existing buildings to achieve zero emissions, along with efficient and resilient buildings by 2050, recommending a renovation rate of 3% per year and 30% improvement in 2030. The European Directive 2012/27/EU, which is currently in force with the latest consolidated version of 2021 ((EU), 2021), promotes energy efficiency improvements to ensure in 2030 a headline target of 32.5% at least. To achieve this, one of the proposals in the building sector is that each Member State must renovate 3% of the total floor area occupied by administrative departments with a total useful area of over 500 m^2. On 15th December 2021, the European Commission published a proposal to revise the Energy Performance of Buildings Directive as part of Fit for 55 (Tenhunen, 2021), which aimed to reduce emissions by 55% below 1990 levels by 2030. It introduces several new definitions such as “Zero Emission Buildings (ZEB)" ((EU) C, 2019a; (EU) C, 2019b) with high levels of renewable energy production and near-zero energy consumption to decarbonise the building stock. Through this, it was agreed that all Member States must ensure that all public buildings achieve at least a class E certificate by 2030.

Since 35% of the EU’s building stock is over 50 years old and therefore, inefficient (Filippidou and Jimenez Navarro, 2019), making them as efficient as possible is a key EU objective. The end uses of existing buildings are diverse, and they often change over the years. In this sense, the Building Stock Observatory established in 2016 ″provides a better understanding of the energy performance of the building sector through reliable, consistent and comparable data” (Arcipowska et al., 2014). This report states that non-residential building stock is about 25% of the total stock, of which 42% of the buildings were built before 1970, that is, prior the widespread implementation of energy efficiency measures. Besides, only 9% of the non-residential stock has been renovated. For Spain, less than 0.1% of the building stock has been renovated according to ZEBRA 2020 project (Toleikyte, 2016). Thus, it is the EU’s country with the lower building stock renovating rates, presenting even

* Corresponding author. Universitat Politècnica de València, Camino de Vera S/N, 46022, Valencia, Spain.
E-mail address: caap@csa.upv.es (C. Aparicio-Fernández).

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low rates in non-residential existing buildings. In this sense, Spain has been creating several standards in recent years to reduce the energy demand of buildings, mainly focused on requiring the increase of the thermal insulation. It should be noted that the energy performance of the building stock built before 1979 was considered without thermal insulation, from 1980 to 2006 thermal insulation systems and other energy efficiency measures were gradually applied, and from 2007 to 2019 technologies and products to reduce energy consumption were developed and applied. Regarding historical buildings in the EU and specifically in Spain, 24% of the renovated stock takes place in non-residential buildings, of which, 16% is for educational purposes, the second higher type of non-residential buildings after offices both in the EU and Spain (BPIE. Europe' s buildings under the microscope, 2011).

Energy efficiency in historical buildings is a growing concern, and preserving cultural heritage has an impact on their life cycle energy consumption (Atmaca et al., 2021). However, when historical buildings are involved, it is challenging to adapt either active or passive energy efficiency strategies to meet current standards (Lerma et al., 2021; Cho et al., 2022). Among passive design strategies, building volume, orientation or daylighting cannot be changed unless the building is redesigned. However, other ones such as adding insulation, extra ventilation, or adapting schedules or set points in the cooling or heating system can be indeed considered (Jie et al., 2018; Lidelöw et al., 2019). On the other hand, active strategies are related to equipment or facilities responsible for improving comfort conditions but also for achieving the reduction of their final energy consumption (Lidelöw et al., 2019; Alhazzaa, 2023). When the energy use in buildings is assessed, dynamic thermal simulations are often considered (Li et al., 2021; Nagy and Ashraf, 2021). Specifically, in historical buildings, the main scope when simulation software are used, is to evaluate the energy behaviour of the building along with the assessment of energy interventions compatible with current regulations (Cumo et al., 2022; Vallati et al., 2022). In this regard, the data related to the building such as the building envelope materials, thermal loads, or the heating and cooling systems' operation, play an important role in the accuracy of the results (Akkurt et al., 2020). However, in many cases, part of the information must be estimated since obtaining real data for long periods is not only hard, but also it is often incomplete or limited.

In order to reduce global CO_2 emissions, saving energy in the public sector as in the case of historical buildings with the possibility of reuse is of paramount importance. Retrofitting solutions suitable for the purpose of this study have been presented in previous studies, such as energy retrofitting taking into account both the historical value and the indoor environment, as well as the analysis of the energy reduction of different technologies, including renewables (López-Ochoa et al., 2019; Jesús et al., 2018; Atiba et al., 2019; Sanchez-Ramos et al., 2019).

This paper focuses on the assessment of the energy behaviour of a historical building used as a music school. Several studies (Rospi et al., 2017; Campelo-Pérez et al., 2019), have established the conditions for adequate comfort and air conditioning for students in other disciplines. Given the particular activity carried out in music schools, parameters such as humidity and temperature must be considered of vital importance. For this purpose, one-year data were used to validate an energy model approach by means of TRNSYS18 (Klein, 2018a). In this sense, to dispose of real data regarding both weather parameters and energy behaviour of the building brings added value to studies on this area. Finally, seeking a reduction in energy consumption, both active and passive strategies compatible with the current directives have been evaluated (Vázquez-Torres et al., 2023).

2. Methodology

The methodology used in this study is shown in Fig. 1, which is divided into four sections according to the steps regarding energy consumption retrofitting.

Energy audit. This first step consists of data collection to obtain all the necessary information to analyse the building under study. It is a fieldwork carried out on site and refers to the architecture, the technical installations and the energy consumption based on current and measured data (temperature and relative humidity) collected on site.

Results of the audit. A detailed analysis of the consumption and measured data allows us to draw a reliable picture of the energy performance of the building along with to identify the most tangible and significant opportunities for improvement.

Energy simulation. This step consists of running a volumetric model from the data collected during the audit. Then, the model's validation provides a reliable picture of the overall energy model, allowing us to identify the most significant parameters for improvement.

Potential savings. Once the model has been validated, potential savings are applied based on the previous parameters and finally, the results are reported.

3. Case study: data collection for energy audits

3.1. Architectural description of the building

The building chosen for this study dates from 1921 and it is located in Carcaixent, Valencia (Spain). It was originally built as a hospital, and until it was later refitted as a professional conservatory of artistic education managed by the Department of education of the Valencian Region, it has undergone very few modifications. Although different actions have been carried out to improve accessibility, the same infrastructures of the old hospital have been maintained, including the chapel currently used as an audition room.

The building has three floors with 28 classrooms, 1 auditorium, 4 offices for management and coordination of the centre, a rehearsal room, audition room, teachers' meeting room and different storage rooms. The most important architectural data are shown in Table 1.

Fig. 2 shows floor plans of the building where different uses are indicated. The constructive typology of the building follows the architectural framework of its original construction. Its walls are made of masonry approximately 50 cm thick and its horizontal structure is composed of wooden beams and girders with ceramic interjoins. The coatings used in the building are plaster inside and cement mortar outside and its roof is gabled, with traditional ceramic tiles. A typical and traditional construction method was used throughout the building. In Fig. 2, it is possible to see the main exterior facades which have elongated openings on the ground floor and first floor, while on the second floor the windows are squarer and smaller, typical are the chambers placed behind the tiled roof. Inside the building, as can be

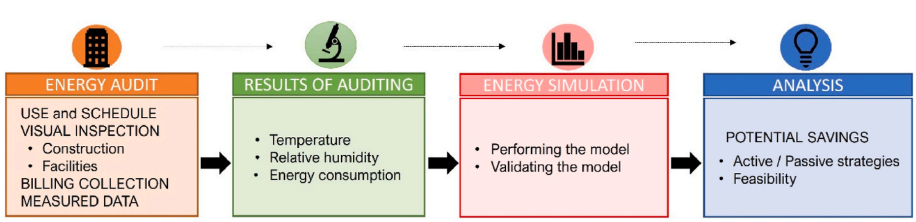


Fig. 1. Methodology divided into four sections according to the steps of energy consumption retrofitting.

Table 1
Architectural data of the conservatory of professional artistic education, Carcaixent (Spain).

Localization	39°07′21.3″N 0°27′09.8″W
Usage	Educational facilities
Land register data (CODE)	0236601YJ2303N0001GG
Floor area (m^2)	1196 m^2
Built area (m^2)	2705 m^2
Construction's year	1921
Orientation	Main facade-Northeast Side facade-Northwest
Occupation	58 Teachers and 400 students
Zone description	Hall Reception office 28 Classroom Concerts Hall Rehearsal room Offices management and coordination Meeting room Stores
Schedules	9:00–15:00 management 15:00–21:00 music school

seen in Fig. 3, there is a central courtyard which brings light to the corridors of the centre. The typology of the openings facing this courtyard is different from those of the facades, these being openings that are wider than tall with semi-circular arches. The orientation of the courtyard is South and East, enabling large openings that allow sun and light to enter inside the corridors.

3.2. Visual inspection

Once the floor plans were established, a study was made of the constructive parameters and the characteristics of the facilities in order to gain a better understanding of the building. To this end, an audit was carried out based on the data set out in Table 2.

Heating system. Natural gas is used to supply a boiler that heats the entire building through water radiators. Thus, it is a centralized system that heats the whole building at the same time. The boiler is switched on manually and daily 7 months of the year: January, February, March, April, October, November, and December. The boiler is a ROCA MODEL CPA 300 with a nominal power of 348.9 kW, and it was installed in August 2000. The central heating system is manually switched on at 15:00 and off at 20:00, so the building is heated by this system for 5 h on teaching days and only if needed.

Conventional electric radiators are also used for heating both in the administration office at the entrance (ground floor) and in the teacher's office (first floor). This system is only used when the gas boiler is not connected or when there are no students in the building but some areas demand heating.

Cooling system. Individual air conditioning systems were installed in

Fig. 3. Facades of the conservatory of professional artistic education, Carcaixent (Spain).

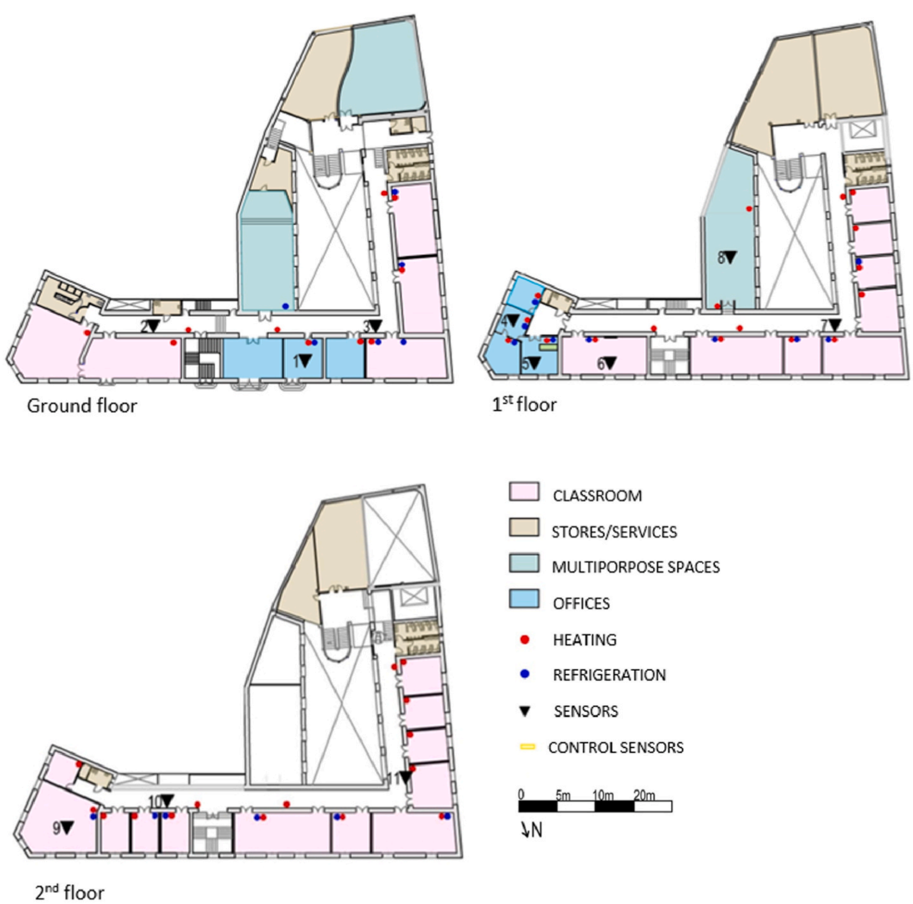


Fig. 2. Floorplans for the conservatory of professional artistic education, Carcaixent (Spain).

Table 2
Audit data (constructive and technical data).

Auditing technical data	
Walls	Thickness and materials
Windows	Frame and glass
Electricity	Tariff type
	Consumption divided by time slots and months
Natural gas	Monthly energy consumption
Lighting	Type, zone location
DHW + HEATING	Centralized control system
	Type of system
	- Gas boiler
	- Electric radiators
COOLING	Heat pumps and air conditioning

the administration office, classrooms, and teacher offices. It is a split system with indoor and outdoor units of more than 10 years old. Each area connects the air individually depending on demand. Heating and cooling capacity was 3.2 and 2.5 respectively when they were new. EER/COO is a 3.13/3.71 Mitsubishi model. Spaces with heating and cooling system are shown in Fig. 2.

Building envelope. As it was mentioned in the previous section, this work analyses an historical building with a traditional constructive system. Although a new refurbishment was carried out 10 years ago, the envelope was merely repaired but not insulated. Walls for the external and internal layers are solid masonry and there is no insulation inside. Wall thickness depends on the floor, being 60 cm on the ground floor (U-value = 2.143 W/m^{2}K) and 40 cm on the second floor (U-value = 2.523 W/m^{2}K). The roof shape is a gable roof and the area under the roof is habitable, which is made of concrete slabs and ceramic tiles (U-value = 1.81W/m^{2}K). The floor on the ground floor is covered with marble tiles over a concrete base (U-value = 2.155 W/m^{2}K). Additionally, the internal walls are made of compact bricks with plaster board (U-value = 2.458 W/m^{2}K). Original windows are single glazed 6 mm with frames made of wood whose U-value are 5.7 W/m^{2}K and 2.2 W/m^{2}K respectively. Only the windows corresponding to the external façade on the first floor were changed into windows with an aluminium frame and thermal bridge and double glazing 4-12-4 whose U-value are 3.2 W/m^{2}K and 1.4 W/m^{2}K, respectively.

3.3. Billing information

Natural gas consumption is not reflected on each monthly bill, since the company uses a standard model considering first the average and then in summer, they do a real reading of the gas meter to correct the real consumption. Therefore, only the total consumption for the whole year was considered for the gas bills.

Electric bills have also been analysed. The model used for the electricity billing system depends on the time of the day. It introduces three equal time periods of 8 h each establishing different prices giving consumers a chance to save money if the use of their appliance is outside the peak hours. The cheapest period is the off-peak or valley and it ranges from midnight to 8:00 when the building is completely closed and with no use. The most expensive is the peak period which ranges from 10:00 to 14:00 and from 18:00 to 22:00. The rest corresponds to the average price time and with the flat rate period ranging from 8:00 to 10:00, from 14:00 to 18:00 and from 22:00 to midnight. Although since July 2021 the electricity supplier changed the billing system slightly, the work has been considered as described above for the sake of simplicity.

3.4. Collected data (Indoor: Temperature, humidity; outdoor: weather)

Low-cost monitoring equipment was used to measure the internal parameters. This equipment is made up of a mini-PC control and a storage community, 12 Si7021A20 wireless digital sensors from Silicon Labs™, which can be used to measure temperatures ranging from −40 to 125 °C, with a resolution of 0.02 °C and an accuracy of ±0.4 °C and recording average values every 10 min. The sensors have been individually calibrated for temperature and the calibration data is stored in the non-volatile memory of the device. This ensures the sensors exchangeability, without the need for recalibration or changes of the software system as was shown in a previous work (Aparicio-Fernández et al., 2021).

In this work, the data was collected during a period from May 4th, 2021, to March 3rd, 2022 (a total of 303 days). Eleven sensors were placed inside the building and since the building area is large, they were placed on the three different floors: 3 of them on the ground floor (GF), 5 on the 1st floor (FF) and 3 on the 2nd floor (SF), see Fig. 2. All of them were placed in safety zones to prevent troubles with students and they were also grouped according to the floorplan location given in Fig. 2.

Boxplots display batches of data obtained. Five values from a set of data are conventionally used: the extremes, the upper and lower hinges (quartiles), and the median (McGill et al., 1978). The two 'hinges' are versions of the first and third quartile, i.e., close to quantile. Distributions were compared in terms of differences between medians and/or between interquartile ranges (IQR) so the notches extend to ± 1.58 IQR/sqrt(n). They are based on asymptotic normality of the median and roughly equal sample sizes for the two medians being compared and are said to be rather insensitive to the underlying distributions of the samples. The idea is to provide roughly a 95% confidence interval (interquartile range from 2.5% to 97.5%), for the difference between two medians.

Weather data used was obtained from a weather station located in the same location (Carcaixent) by the Spanish Meteorological Agency (© AEMET). Summer of 2021 was hot and mostly clear, and winter was warm, windy and not very cloudy. Graphs in Fig. 4 show the average monthly weather data collected through 2021 in Carcaixent. The coldest month is January with an average temperature of 9.97 °C and the hottest month is July with 26.73 °C which is hot considering that temperature can rise over 40 °C. Relative humidity during all year ranges between 70% and 80% most of the time. Wind rose is used to show wind cardinal direction and speed for each period, and it shows that 30% of time the wind blows in South direction with low velocity (between 0 and 2 m/s 22% of the time). Moreover, solar irradiance in horizontal surface was included to show that is a sunny place during all year. In this sense, a typical warm Mediterranean climate is considered in Carcaixent (Csa Köppen-Geiger classification).

4. Results of auditing

4.1. Bills

For electricity consumption, the company which supply electricity, each month provides a bill with the real consumption for this month. Different pricing depending on the daily supply schedule is used by the company. In 2021 two different ranges of bills were used by the company. From January to May they considered 8 h for each range of consumption (peak, flat and off-peak) and from June to December the company increased the range for peak time to 9 h and reduced the flat time to 7 h. This change is reflected in the total consumption where the flat consumption is reduced in the last part of the year increasing the peak time consumption.

Fig. 5 shows that the flat time corresponds to the period with higher consumption, since the schedule for the school during the afternoon ranges from 15:00 to 21:00 using more hours for this period. This effect changes in the second part of the year when bills were changed obtaining similar values between peak time and flat time. Moreover, it can be observed that consumption increases in winter season, because the building is open for information during the morning, and, consequently, there are more lighting hours and electric heating. The gas boiler, conversely, is not connected until the afternoon when students have classes.

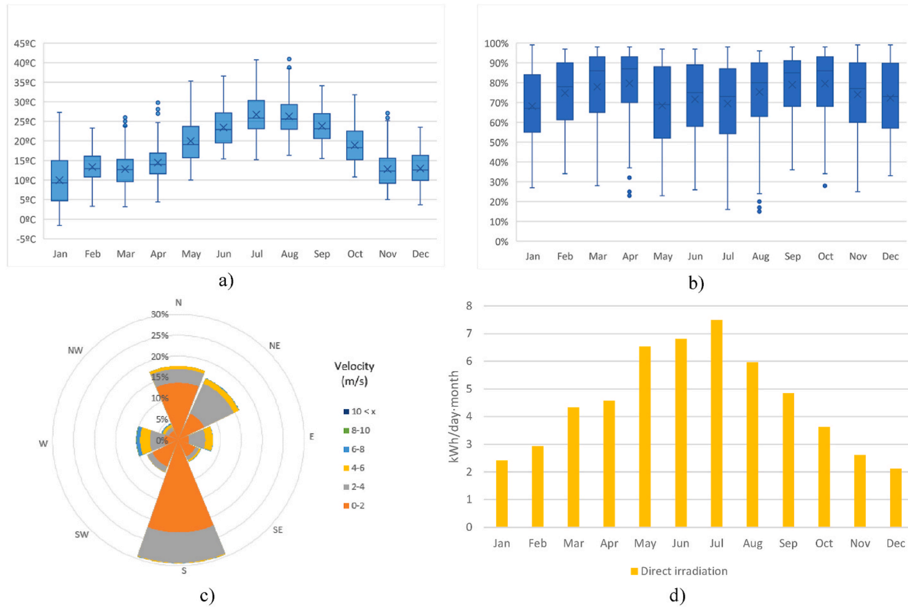


Fig. 4. Monthly weather data through 2021 in Carcaixent: a) temperature, b) relative humidity, c) wind rose (direction and velocity) and d) incident irradiation on a horizontal surface for each month.

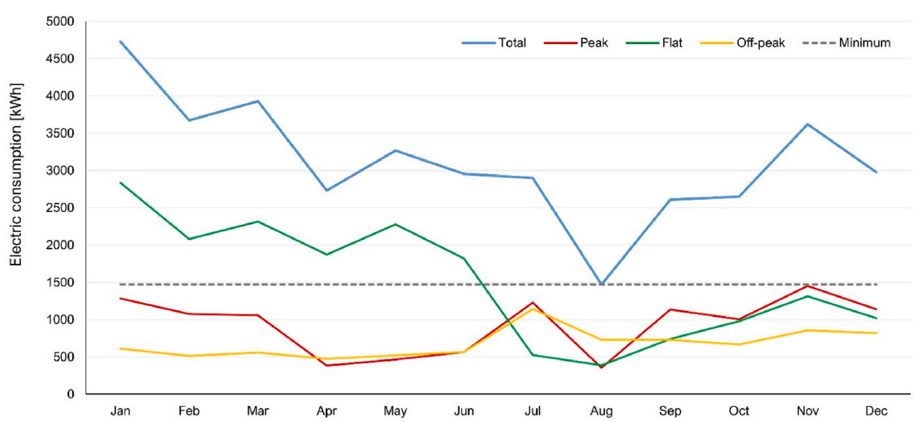


Fig. 5. Electric consumption (kWh) by the bills during year 2021.

The total electricity consumption in 2021 was 37508 kWh and the minimum consumption during the analysed period corresponded to August 2021 with 1472 kWh. Thus, the consumption in August has been considered as the residual consumption of electricity produced in the building due to different appliances, engines or food and coffee vending machines, that are always connected, even during holiday periods. This allows us to consider that if the building is not open and in use, the consumption could be reduced by 1472 kWh for the 31 days in August, which would be possible to extrapolate to the rest of the holiday periods. It is also logical to consider that the consumption produced in August is the minimum that will be produced throughout the year when the appliances, engines and machines will also be switched on.

Natural gas is supplied to the building to fuel the gas boiler in order to heat the building. The company do not read the real consumption on the gas meter each month because in summer when the heating system is not used, the company has already billed it. For this reason, in order to know the energy used from natural gas, the total amount for the whole year was used. The total gas consumption in 2021 was 86393 kWh/year, and this is the value used in this paper to validate the model. Since central heating system in the building uses gas, the difference between the gas and the electricity consumption is obvious.

4.2. *Indoor temperature*

Floorplan location for the sensors is given in Fig. 2 and its description in Table 3. Hence, each sensor code (sensor description) assigned in Table 3 determine its situation (Ground Floor: GF, First Floor: FF, Second Floor: SF), the zone it occupies inside the professional conservatory of artistic education (administration: adm, corridor: corr, office: off, dance: danc, meeting: meet) and its orientation (N: North, S: South, W: West).

To obtain a representative value for the setpoint temperature, in the winter period, a selection of measurements was taken using thermal variations on sensors in the working schedule (from 8:00 to 20:00). In Fig. 6, for the winter period, a thermal variation in temperature due to the heating system was noticed, specifically, the maximum, which corresponds to 20:00 h, a time when the heating is turned off. In the second-floor sensors temperatures showed a disturbance as if they would had been affected by solar radiation.

In the summer period, a selection of measurements was taken using hourly thermal differences in sensors to obtain a representative value for the setpoint temperature. In Fig. 6, for the summer period a thermal variation in temperature due to the cooling system was observed. There is no pattern, as every room had a completely different behaviour. These

Table 3
Summary of set points for heating and cooling period. (*) Indicates that there is no Air Conditioning Unit in this room.

Sensor Number	Sensor description	Days for heating setpoint	Days for cooling setpoint	Mean of maximums Heating (°C)	Mean of minimums Cooling (°C)
1	GFadm	64	23	24.1	27.0
2	GFdanc	28	*	19.9	–
3	GFcorr	11	*	20.0	–
4	FFoffW	55	19	20.7	27.8
5	FFoffN	56	6	20.9	27.5
6	FFclass	56	3	21.0	–
7	FFcorr	56	*	21.4	–
8	FFmeet	55	0	19.5	–
9	SFclass	56	0	20.2	–
10	SFcorrS	29	*	19.1	–
11	SFcorrW	11	*	18.1	–

differences are due to occupation, i.e. in the ground floor administration offices there was a minimum at midday between 14:00 and 15:00, when they had left the office and turned off the cooling system, whereas in the dance room results revealed a different behaviour pattern.

Individual air conditioning systems were only installed in the administration office, classrooms, and teacher offices. Each area connects the air individually depending on the demand. It can be observed in "FFclass" that only 3 days in the whole period, the air conditioner was switched on (or windows opened), so it is not representative. On the other hand, in both "FFmeet" and "SFclass", no downward peak corresponding to the air conditioner start-up can be identified.

4.3. Indoor thermal variation (ΔTdin)

Differences in indoor temperature on the sensors from 20:00 to 8:00 during the winter period analysed, were obtained for each sensor. These values (indoor thermal variation from 8:00 to 20:00) were analysed using a boxplot test (section 3.4). Thus, on days when heating was switched on, a positive difference was obtained. Eventually, setpoint values were retrieved, resulting that a mean of maximum daily temperature for days when differences in the indoor temperature on the sensors from 20:00 to 8:00 were higher than median. For sensors on the second floor when maximum daily temperature was caused by solar radiation, instead of the maximum the temperature at 20:00 was used. Readings for hourly difference in the indoor temperature on the sensors during the summer period for each sensor were obtained. These values (hourly temperature differences) were analysed using a boxplot test (section 3.4).

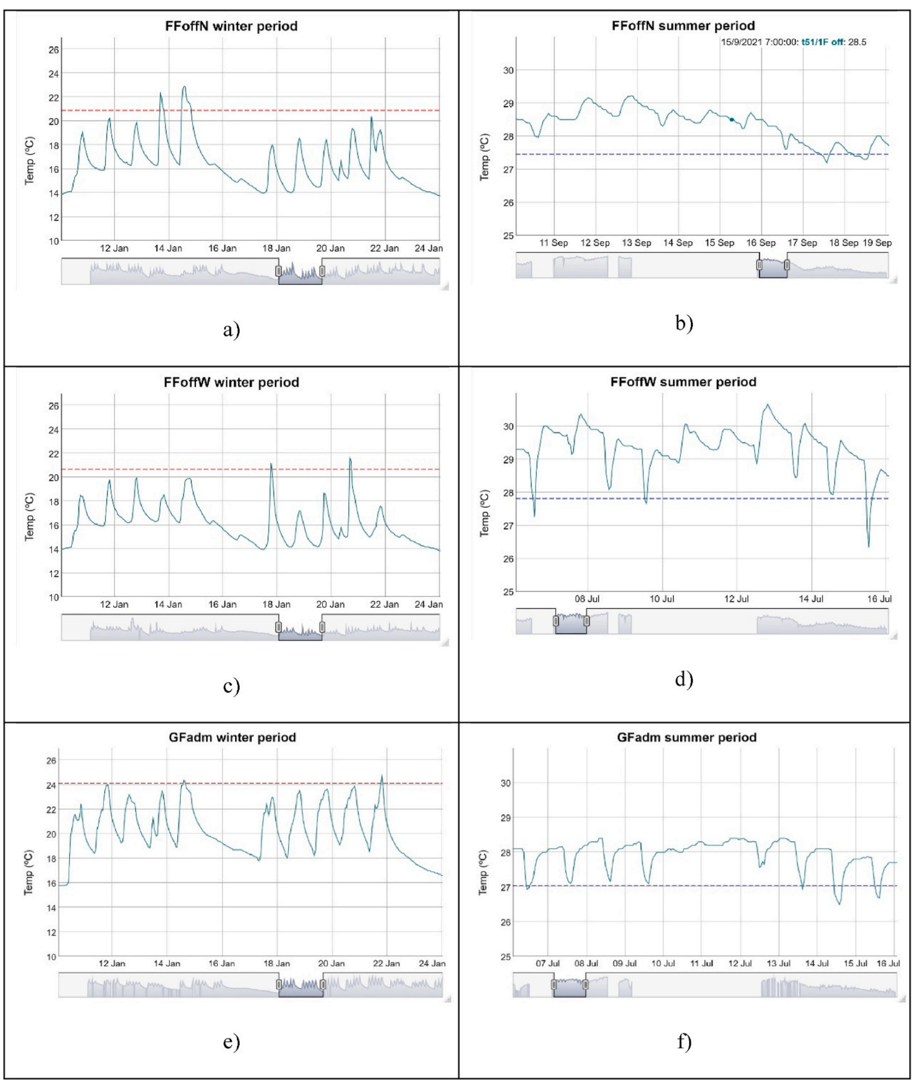


Fig. 6. Temperatures recorded in winter period and setpoint at a) FFoffN, c) FFoffW and e) GFadm, Temperatures recorded in summer period and setpoint at b) FFoffN, d) FFoffW and f) GFadm.

Hence, on days when cooling was switched on, it resulted in a negative difference. In summer, the period from 5th July to 19th September was used for the setpoint. To obtain a representative value for the setpoint temperature, a selection of measurements was chosen, using for this purpose hourly thermal variations on sensors. Setpoint values were obtained, resulting in a mean of minimum daily temperature for days when hourly temperature differences of sensors were lower than the lower whisker, that corresponds to values outside the 95% confidence interval (outlier values). In July and September there are no regular classes, then, students only attend certain special sessions. Hence, in these situations, classrooms would be used only on days with a specific activity and schedule and those activities make up 30% of the use of spaces and of regular schedules. With the collected data, different schedules were retrieved for the classroom, the teaching office or administration office for the period ranging from July and September for air conditioning (when still there were no regular classes for students). Offices on the ground floor are occupied from 9:00 to 21:00, which corresponds to the period when the cooling system is regularly on, then it is connected 12 h/day. Offices on the first floor for teachers also have a cooling system which is switched on at 9:00 and off at 14:00 regularly from Monday to Friday, thus it was switched on 5 h/day during the morning. Also, it can be observed that average temperature in classes and the corridor is higher on the Second Floor where the roof has a great impact on this surface due to the solar gains. In the corridors there is a large area with single glazing so that the incoming radiation may have a greater impact on the temperature. Moreover, since there is no cooling system in those spaces the only way to control the high temperature is by natural ventilation.

5. Energy simulation calculations. TRNSYS

Since the analysed building is affected by a large number of surrounding influences, its energy analysis proved to be complex. The TRNSYS18 program (Klein, 2018b) was used to develop the model, introducing, for this purpose, all the different variables collected in the building such as constructive and technical data.

5.1. Model

First, a geometrical model was developed with the TRNSYS plug-in for Google Sketchup as it is shown in Fig. 7. This is a quite useful tool for architecture since it enables the definition of a 3D model in which different volumes and glazing areas can be defined along with shadowing effects. This 3D model is generated as an "idf" (intermediate data file) extension which can be then imported into TRNSYS18 to create a 3D Building Project (multi-zone).

Hence, a "multi-zone building" type 56 is generated which aims to model the thermal behaviour of the building divided into different thermal zones. In Fig. 8 the different thermal zones are showed according to their use and heating and/or cooling demand. As it is described, this building presents 12 thermal zones on the ground floor and 11 for the 1st floor with a total area of 899.38 m^2 for each floor, and the 2nd floor with a total area of 809.85 m^2 consists of 10 thermal zones.

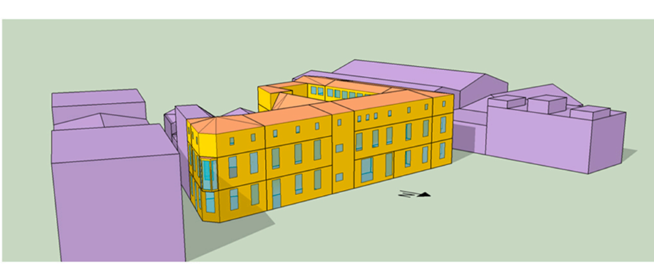


Fig. 7. Geometrical model developed with Sketchup corresponding to the assessed building.

Then the information regarding the building such as the envelope' thermal properties, routines, heating, or cooling demand or lights must be defined for each thermal zone by using the TRNSYS sub-program TRNBuild.

On the other hand, Type 15-6 was used to define the weather data, using for this purpose © AEMET data from 2021. In this sense, weather information considered for the simulation comprises: solar radiation in horizontal (W/m^2), temperature (°C), relative humidity (%), wind velocity (m/s) and wind direction (°; degrees). In order to introduce these parameters as an excel or text file, Type15-6 was replaced by Type99.

Regarding the occupancy schedule, Christmas, Easter, local holidays, and summer holidays were considered and for each different zone within the building, the schedule could be defined. In terms of occupancy, in this work, a distinction has been made between corridors, teachers' offices, reception, and classrooms. During working days, the building is open from 9:00 to 21:00 (12 h/day) for reception and teachers' offices and from 15:00 to 21:00 (6 h/day) for classrooms and corridors). During holidays, the building is completely closed, and no activity is carried out inside. Moreover, for Friday's classes the presence of only half of the normal student occupancy has been considered. Therefore, in 2021 the occupancy was 217 days for staff and teachers' offices, and 157 days for classes from Monday to Thursday and 26 days for classes on Fridays, making a total of 183 days. Hence, for 148 days the building was completely closed and without activity inside. The occupancy of the building considered was 3 administration staff, 58 teachers and 400 students and the distribution was calculated for each and defined in Type56. The total number of students attending the school was 200 students each day except for Fridays when it was 100. This proportion was the same for teachers and the administration staff was constant every day.

Therefore, the collected data was used to find the set point and to check the schedule at which the heating system is switched on/off. For heating demand, the time that students are inside (6 h/day) for 7 months was considered. For the administration office the schedule is 12 h/day, therefore the days when there are classes, an extra of 6 h/day heating was needed in this area which was supplied by electric radiators.

The cooling system is connected only four months a year and the set point used was 26 °C. Those months are May, June, July, and September, and only in May and June when there are classes. For cooling demand, the administration office has been considered using a different schedule. Since each room has its own system, the air conditioning was only connected when demanded.

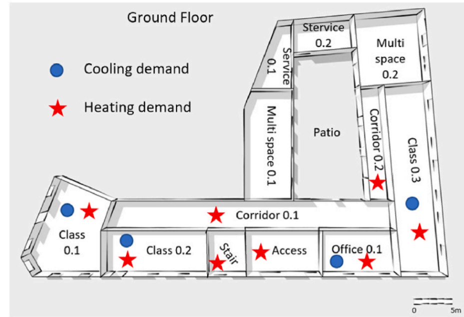
Also, internal gains were considered for occupancy, lighting, computers, and other elements. LED tube lighting of 9 W and average of 5 W/m^2 were used in all the rooms, which were only connected when there was occupancy.

Infiltration was considered with a constant value of 0.55 h^{-1} (Sherman and Matson, 2002) for an historical building, since windows are old and the window-wall ratio is more than 50% considering all the facades. Ventilation was also considered as a controlled parameter that depends on human action by opening the windows. This is because in this building no mechanical air renewal system is installed and, therefore, ventilation is directly related with the use of the building. In this way, it is also important to remember that after the lockdown period in Spain, public buildings must have windows open whenever they were occupied. In this way, the minimum ventilation required is 0.6 h^{-1}, but 1.2 h^{-1} and 1.8 h^{-1} were also analysed (Ji et al., 2020).

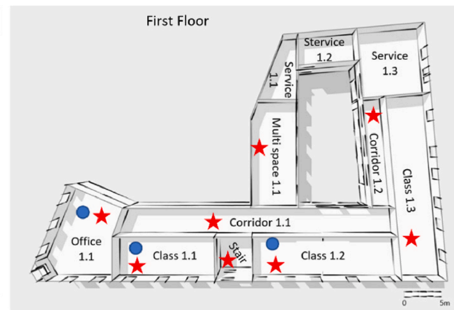
Thus, the total number of days considered for heating, cooling, or lighting are described below. The total days for cooling demand in the students' and staff area are 65 and 87, respectively. Although there are no classes in either July or September, the staff are in the building to prepare the courses. For heating, the gas boiler is connected for 130 days in the afternoon. Finally, the lighting demand for the whole year was considered, but as in the case of cooling, staff use the building more days than students do.

Fig. 9 shows the layout of the model developed in TRNSYS in which

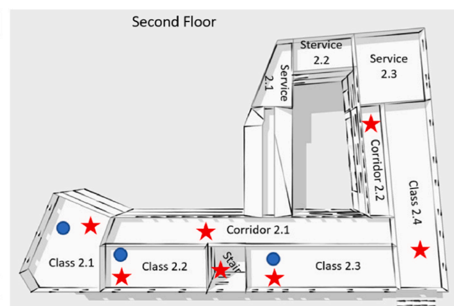
	Thermal zone	Area (m^2)	Heat	Cool
Ground floor	Class 0.1	102.22	Yes	Yes
	Class 0.2	79.91	Yes	Yes
	Stairs	29.4	Yes	No
	Access	57.61	Yes	No
	Office 0.1	57.53	Yes	Yes
	Class 0.3	149.23	Yes	Yes
	Multi space 0.1	89.53	No	No
	Multi space 0.2	83.71	No	No
	Corridor 0.1	139.62	Yes	No
	Corridor 0.2	44.93	Yes	No
	Service 0.1	31.97	No	No
	Service 0.2	33.72	No	No
	TOTAL GF (m^2)	*899.38*	*660.45*	*388.89*



	Thermal zone	Area (m^2)	Heat	Cool
1st floor	Office 1.1	102.22	Yes	Yes
	Class 1.1	79.91	Yes	Yes
	Stairs	29.4	Yes	No
	Class 1.2	115.14	Yes	Yes
	Class 1.3	149.23	Yes	No
	Multi space 1.1	89.53	Yes	No
	Corridor 1.1	139.62	Yes	No
	Corridor 1.2	44.93	Yes	No
	Service 1.1	31.97	No	No
	Service 1.2	33.72	No	No
	Service 1.3	83.71	No	No
	TOTAL 1F (m^2)	*899.38*	*749.98*	*297.27*



	Thermal zone	Area (m^2)	Heat	Cool
2nd floor	Class 2.1	102.22	Yes	Yes
	Class 2.2	79.91	Yes	Yes
	Stairs	29.4	Yes	No
	Class 2.3	115.14	Yes	Yes
	Class 2.4	149.23	Yes	No
	Corridor 2.1	139.62	Yes	No
	Corridor 2.2	44.93	Yes	No
	Service 2.1	31.97	No	No
	Service 2.2	33.72	No	No
	Service 2.3	83.71	No	No
	TOTAL 2F (m^2)	*809.85*	*660,45*	*297.27*



TOTAL BUILDING	**2608.61**	**2070.88**	**983.43**

Fig. 8. Thermal zones defined in the 3D-model and their area for heat and cool demand implemented.

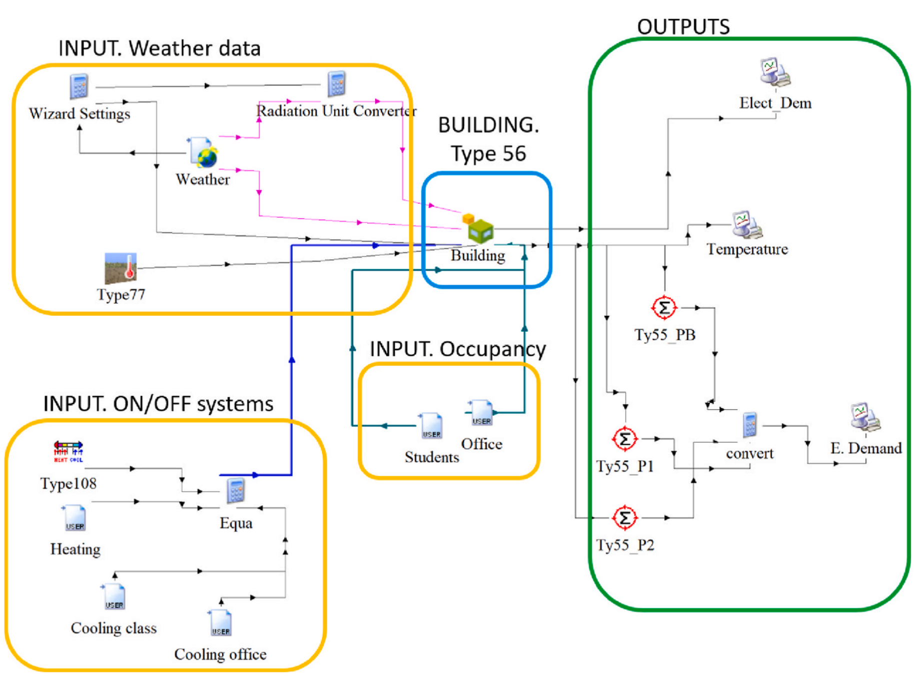


Fig. 9. Building simulation diagram in TRNSYS of the analysed building.

the different types mentioned throughout the section along with the inputs and outputs can be observed.

5.2. Energy simulation and validation

Total energy demand for cooling and heating was used to validate the model with TRNSYS 18. To establish the final model, 3 variables were considered: ventilation rate inside the building, set point for cooling and heating, and efficiency for the heating system.

Quantification studies were carried out via an experimental design applied to create a system of three variables/three levels. By using the experimental design (MODDE 8.0), it was possible to generate the quantity of samples. The final set included 12 experiments at low, medium, and high levels. Then, 12 models were simulated, and the results showed that the set point for heating at 21 °C, the ventilation of 1.2renov/hour and the boiler's efficiency of 75%, fit the model. These results have been compared with the gas bills (86393 kWh/year) which can be seen in Table 4.

The cooling system in this building has been developed considering individual heat pumps for each room, and since it is not a centralized system, the connection of each engine depends on the users. On the one hand, this makes it impossible to define power consumption due to the connection of the air conditioning in summer. On the other hand, it is worth mentioning that there are a lot of appliances connected to the electric network and it is impossible to calculate the energy consumed by each element exactly from the data obtained in the bills. Hence, the main goal regarding the electricity, was to find out the amount of electricity used for the cooling system and, thus, to validate the model.

With TRNSYS18, the Type 32 (SQHEAT) was used to obtain the sum of sensible heating demand for a group of air nodes with a total area of 1822.2 m^2 corresponding to the area heated by the centralized system gas boiler. The total heating demand is used to compare the gas needed depending on the efficiency of the boiler. This result has been compared with the gas bills, as we can see in Table 4. For the selected model, the total energy demand to heat the building was 63026.55 kWh/year and considering the efficiency for the gas boiler of 75% 84035.40 kWh/year was obtained, which is the closest result to the total gas consumption obtained from the bills of 86939 kWh/year. Fig. 10 shows the total energy consumption required to heat all the spaces occupied when the school is open according to the results obtained with the developed model in TRNSYS. In this sense, the electric consumption is divided into the different systems considered.

Energy demand for cooling was difficult to control due to there are many energy-consuming appliances in the assessed building. Type 33 (SQCOOL) was used to obtain the sum of sensible cooling demand for a group of air nodes that correspond with the areas where the cooling system is considered and the efficiency of the heat pump considered is 75%. The model selected considered a ventilation of 1.2 h^{-1} so a cooling demand of 4842.36 kWh was obtained in the building from May to September excluding August when the school is closed for summer holidays. Also, from the simulation with TRNSYS the energy demanded for lighting, computers, and other appliances according to the values considered in the model was obtained. With the considered model, it can be stated that 47.48% of the total energy consumption is residual consumption (1472 kWh/month) and 52.52% corresponds to electricity consumption from lighting, computers, other appliances and heating and cooling systems. The heating system is also considered because the administration staff's working timetable is longer in time than the schedule taken into account for the heating system, which would mean that during the morning the administration staff connect the air conditioning to supply the demanded heat energy. Thus, following this hypothesis, we conclude that the consumption for lighting is 14.96%, computers is 10.29% during the year, heating is 10.88% and cooling is 17.17% with a total electric consumption obtained in the model is 37608.43 during 2021.

Table 4
Results for heating energy consumption of 12 models in TRNSYS.

Model	Ventilation [h^{-1}]	Setpoints [°C]	Boiler's efficiency [%]	Gas consumption [kWh/year]
1	0.6	20–26	95	51 547.17
2	0.6	20–26	75	65 293.08
3	0.6	21–26	95	61 704.68
4	0.6	21–26	75	78 159.27
5	1.2	20–26	95	54 708.42
6	1.2	20–26	75	69 297.33
7	1.2	21–26	95	66 343.74
8	**1.2**	**21–26**	**75**	**84 035.40**
9	1.8	20–26	95	57 900.18
10	1.8	20–26	75	73 340.22
11	1.8	21–26	95	80 552.82
12	1.8	21–26	75	102 033.57

6. Upgrading the school performance. Saving measures according to the audit

This section seeks to implement in the TRNSYS model, the energy savings based on the data obtained from the bills (gas and electricity) in order to convert the school into a passive building. Passive House Standard consider a maximum energy demand for cooling and heating of 15 kWh/m^2. Thus, the main goal in this chapter is to consider the viability of this parameter in a historical building used for educational purposes (Institute, 2021). Since the total area of the building to heat is 2070.88 m^2 and considering the energy demand in the selected model is 63026.55 kWh/year, it would mean that the total energy demand for heating in our building is 30.43 kWh/m^2. On the other hand, since there are no splits in the corridors, the cooling area considered is 983.43 m^2 and the energy demand for cooling in the selected model is 4842.36 kWh/year, therefore the total energy demand is only 4.92 kWh/m^2 according to the data obtained from the model in TRNSYS. Thus, taking these results into account, several passive strategies may be considered in order to reduce the energy demand for heating, as it has been proposed in previous works (Gil-Baez et al., 2019; Park et al., 2020; Pérez-Andreu et al., 2018). All chosen strategies are related to the reduction of energy consumption in the validated model. The viability of the strategies in the model considered must apply to a historical building, which means that window dimensions on the façades cannot be modified. Regarding the building envelope, the quality of windows, the tiled roof, insulation on walls, and floor on the ground could be improved for the envelope in order to reduce the energy demand. The second passive strategy to be contemplated is natural ventilation in summer along with improving infiltration if new windows are considered. Two different scenarios were analysed for the natural ventilation when outdoor temperature is between 21 °C and 25 °C. The first scenario with air renovation of 0.6 h^{-1} and the second with 3 h^{-1}.

In Table 5 the results for the chosen strategies reducing the energy demand in our building are summarized. The first improvement consists of replacing the current windows with single glass, along with improving both the frame and the glass. Moreover, the roof was insulated reducing the U-value to 0.313 W/m^2K. These two improvements would reduce the current infiltration in old or historical buildings such as this since infiltrations usually occur through windows and roof. The third improvement was to reduce infiltration to 0.03 h^{-1}. In this case the heating energy demand is reduced to 20.69 kWh/m^2year which is closer to the Standard Passive, and for cooling 5.54 kWh/m^2year was obtained. This improvement resulted in a total energy saving of 18.8% which is not enough for a passive building. Accordingly, other improvements were evaluated. Among them, walls and floor insulation were simulated in order to improve indoor thermal conditions and to reduce heating energy demand, although a large financial investment would require. In this case 11.34 kWh/m^2year is demanded for heating, thus achieving the standard passive, and thus reducing the energy demand by 55.2% compared to the initial value. In this sense, it can be observed that all

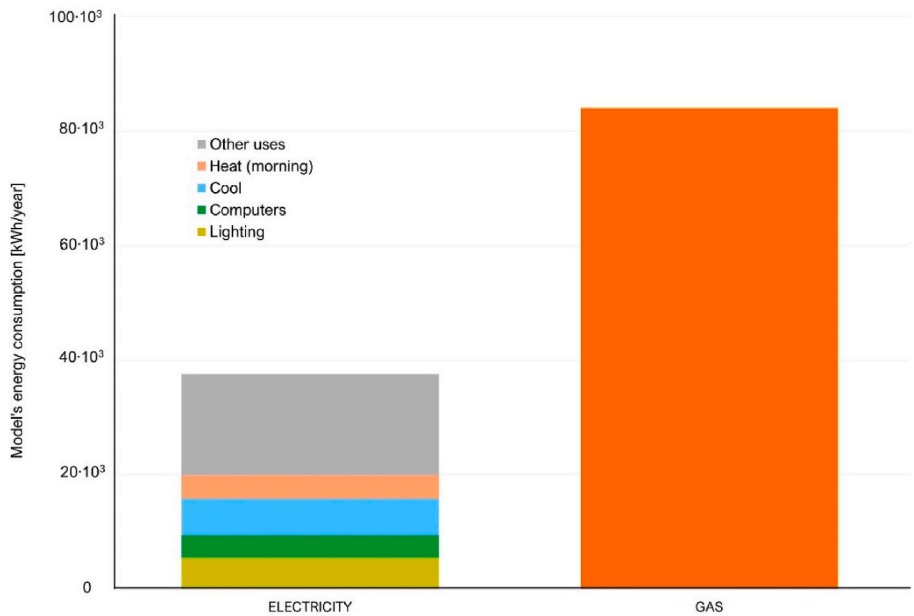


Fig. 10. Energy consumption obtained with the validated model with TRNSYS.

Table 5
Results for heating energy demand with the 7 improvements proposed in the model.

Strategy	Strategy description	Validated model	Improvement implemented
Initial	Validated model U-value [W/m^{2}K]		
01	Window frame/glass U-value [W/m^{2}K]	5.3/2.2	2.2/1.96
02	Roof insulation U-value [W/m^{2}K]	1.81	0.313
03	Infiltration [h^{-1}]	0.55	
04	Walls insulation U-value [W/m^{2}K]	2.149/2.523	0.38
05	Floor insulation U-value [W/m^{2}K]	2.155	0.313
06	Ventilation [h^{-1}]	1.2	0.6
07	Ventilation [h^{-1}]	0	3

actions taken to reduce heating energy demand have led, in turn, to an increase in the cooling energy demand. Hence, in order to reduce the cooling demand, two new actions related to natural ventilation were also considered during the corresponding period. On the one hand, natural ventilation using the windows would be considered when the external conditions are suitable, that is, in our case, when external temperature is between 20 °C and 25 °C the natural ventilation is considered. On the other hand, extra ventilation is added to the regular ventilation considered in the initial model. The other strategies, depend on the installations and facilities in the building in order to improve the efficiency of the systems. Once the lowest heating and cooling demand was achieved, other improvements in the current facilities could also be carried out such as replacing the boiler whose efficiency is 75% in winter or replacing it with a heat pump in summer.

Fig. 11 also represents graphically improvements over the initial validated model. It is easier to see that the best improvement to reduce heating demand is to insulate the envelope (roof, walls, and floor) and insulating the floor presents the highest reverse effect on the cooling demand by increasing it.

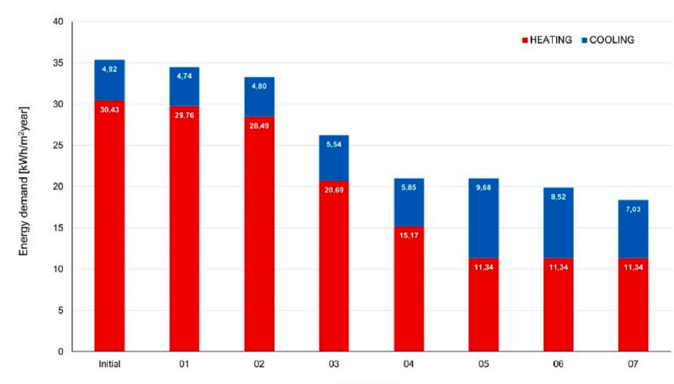


Fig. 11. Energy demand obtained with TRNSYS considering saving strategies.

7. Conclusion

Public buildings used for educational purposes must meet minimum requirements for both comfort and minimum consumption. In this sense, when an energy audit is carried out, the particularity of each building and users must be taken into account (Chung and Yeung, 2020). This work has shown that the analysed building is far from complying with current regulations, which lead us to carry out a specific study of the operational characteristics of the building and, to make concrete proposals aimed to both reduce energy consumption and to improve users' comfort. Educational building in a Mediterranean climate has a regular use from September to June, therefore during the hottest period, the building is closed, which makes that the highest energy demand is for heating and the best passive strategies to reduce energy consumption will be for winter.

Collecting data of indoor temperatures allowed the determination of setpoints in heating or cooling demand periods. Hence, through the data analysis, setpoints in summer and winter periods were established. Collecting data on gas and electricity bills is essential to analyse the current operation of the building and to make concrete proposals aimed to reduce energy consumption effectively. It is important to have the actual monthly consumption values, which is not the case for gas bills. Consideration of the residual consumption of 1472 kWh each month implies that it is unknown where a total of 47.48% of the electrical energy consumed has taken place (see Fig. 5). For this reason, it would be interesting to make an exhaustive study considering all the appliances connected to the electrical network to know where the highest consumptions occur. An inspection of the envelope by means of infrared thermography should be also considered in future works, through which thermal bridges or other faults could be detected. This may allow the subsequent implementation of the simulation model to be more realistic.

The analysed building is complex because it is affected by a lot of surrounding factors and providing an energy analysis has proved difficult. TRNSYS18 software was used to develop the model by introducing all the different variables collected in the building along with real weather parameters obtained over a year. Developing a model that allows us to reproduce the performance of the building is fundamental to make improvement proposals. In this case, the main objective was to reduce the energy demand in an educational building achieving both better thermal comfort and reducing consumption using passive strategies, in our case 55.2% of the energy demand can be reduced. Improving the thermal conditioning installations results in direct reduction in energy consumption, although the investment and the impact on the building is very high. The installations require proper use and maintenance, as well as renovation. Thus, performing this analysis in all existing public buildings which do not comply with current regulations it is highly recommendable since efficient measures to bring the building within the parameters of Standard Passive could be proposed.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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