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Building energy audit, thermal comfort, and IAQ assessment of a school building: A case study

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ABSTRACT

In France, the total heated surface area of educational buildings represents 19.5% of non-residential buildings, with an average total final energy consumption of 142 kWh/m^2/y. Of this, the energy usage for heating is 97 kWh/m^2/y. To save energy, building energy assessment seeks a trade-off between energy savings and the indoor environmental quality (IEQ) of the buildings. A long-term post-occupancy study was conducted on a two-story educational building with a total floor area of 3200 m^2 located in Troyes, France. The Building Management System (BMS) programme was used to analyse the energy consumption for a period of three years from January 2015 to December 2017. Although the building complies with High Environmental Quality (HQE®) standards, the post-occupancy energy demand exceeded the predicted consumption levels owing to the auxiliary equipment. Furthermore, the indoor air quality (IAQ) was assessed by monitoring and analysing CO_2 levels, which were satisfactory for 95% of occupancy period. Moreover, further investigations were performed in the building's foyer, area where indoor thermal comfort was assessed experimentally and numerically. Subjective evaluation was also conducted according to survey questionnaires completed by 41 students between the ages of 17 and 22. The results indicate that increasing the indoor temperature by 1 °C can improve the indoor thermal sensation but led to increased energy consumption of about 12%.

1. Introduction

To address global warming, several plans and commitments have been signed by international energy and environmental organisations to reduce greenhouse gas emissions generated by the use of fossil fuels. Currently, most countries are moving towards a policy of energy saving by acting on energy consumer sectors such as transportation, industry, householders and services, and agriculture sectors. Using nearly 50% of the natural resources, 40% of the energy, and 16% of the water, householder and services is the largest consumer of all energy sectors [1].

According to the statistical pocketbook published in 2018 by the European Commission regarding the energy and environment statistics in the EU-28 member states [2], the EU final energy consumption for 2016 in the buildings sector amounted to 39.6% of the total EU-28 final energy use. Regarding the percentage of final energy consumption of buildings to the total energy consumption, the member states with the highest final energy consumption in the residential and tertiary sector include Estonia, at 55%; Hungary and Croatia, at 51%; Denmark and Lithuania, at 50%; Poland, at 48%; and France, at 46%.

Therefore, energy efficiency is one of the energy policy challenges regarding the EU's Energy Performance of Buildings Directive (EPBD) [3]. The energy demands for general electricity, heating, lighting, and air conditioning have increased owing to the growth and increasing needs in population and construction. During the period 1994–2016 the energy demands in the building sector increased by 11% [2]. In contrast, this increasing change requires the use of minimum energy consumption. From this perspective, user behaviour plays a crucial role owing to consumers' peculiarities and the effects of indoor environmental conditions on their health and productivity [4], particularly in non-residential buildings [5,6].

At 10% higher than that in residential buildings, the total energy consumption in non-residential buildings in France is substantial [7]. Since the 1990s, institutional organisations such as the ministries of industry, environment, and housing; the French Environment and Energy Management Agency (ADEME); and the Scientific and Technical

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Center for Building (CSTB) have been mobilised to act according to environmental concerns. Their aim is to change public opinion on energy usage and to encourage a paradigm shift in the behaviours and attitudes of consumers in non-residential buildings [8].

Indeed, since January 2013, all newly constructed buildings must comply with French building regulation RT 2012 [9], which states that the total primary energy consumption (Cpe) should not exceed a value which is adjusted to consider geographic location, usage, net surface area, CO_2 emissions, and other factors. Cep includes heating, cooling, domestic hot water use, and ventilation and auxiliary equipment including fans and heating system pumps and excludes appliances and lab facilities [9]. To fulfil the trade-off between energy saving and environmental performance, the maximum indoor temperature should be at 19 °C in winter and 26 °C in summer season, and the total glazing area should represent more than 16% of the total heated floor area [9].

In addition to the RT 2012 regulation, High Environmental Quality (HQE®) certification has been set up in France to extend the requirements toward occupants' health and wellbeing concerning envelope materials, water, and waste management; this designation is more suitable for non-residential buildings [10]. An award of HQE® certification, which is similar to the Leadership in Energy and Environmental Design (LEED®) standard in the United States (US) and the Building Research Establishment Environmental Assessment Method (BREAM®) standard in the United Kingdom (UK), aims to encourage many energy saving initiatives and promote sustainable quality in building constructions.

Among the concerned buildings, academic buildings house the largest occupied indoor environment after homes, making them particularly relevant to the issues of energy and indoor environmental quality (IEQ) [8,11]. Such buildings require more attention because of the large numbers of people they can accommodate with different purposes such as teachers, researchers, and students engaged in space-time activities Additionally, the number of topics related to an energy audit and the IEQ in academic buildings are not comparable to those applied to offices, hospitals, and other buildings. Zomorodian et al. [12] revealed that only 48 papers on the topic of thermal comfort in school buildings were published from 1969 to 2015.

Recent studies conducted on academic buildings focus on energy-related topics or IEQ-related issues; very few evaluate energy and IEQ simultaneously [8]. For energy-related issues, numerous studies on academic buildings have reported a gap between predicted and actual energy consumption [1,5,6,13–17]. Gupta et al. [1] revealed that in the UK, actual energy consumption in such buildings is usually twice the predicted amount owing to various problems such as improper installation, poor-quality materials, and poor quality control. In such cases, the expectations of the educational buildings' occupants are not met, and it is important to conduct energy monitoring. Data analysis helps in making recommendations towards improving the energy efficiency [1]. Bengerth et al. [13] conducted an energy audit over three years and a building energy simulation of a LEED® certified dining hall at the University of Maryland's campus in College Park. The analysis of the measured data from the Building Automation system revealed that the final energy usage of the considered building was more than 50% higher than that of a typical building owing mainly to the electricity usage. Simulations of energy-efficiency measures (EEM) predicted savings of nearly 60% of the current total building energy consumption or $231,632 per year.

The findings of the above studies have also been reported in other research; all highlight the fact that although technological advances have been made, a substantial gap remains between the actual performance and design expectations [5]. Pegg et al. [16] performed a long-term post-occupancy evaluation of five secondary schools in England which were considered as low-energy buildings whereby actual consumption data, computer energy models, long-term light level samples, energy audits, and interviews with facility staff were used. Research has shown that buildings can use twice the amount of their theoretical energy performance and that very little interconnection exists between the design estimations and the actual energy consumption of the monitored buildings. Van Dronkelaar et al. [17] elucidated that such a gap can be decreased to a large extent if actual operating conditions are used in the building simulation or if the building's purpose is considered. A comprehensive review of recent works related to energy metering of academic buildings has been reported previously [5,16,17].

The related IEQ concerns for academic buildings have also addressed in the literature, and its measurement processes are well established [18]. Good thermal comfort and IAQ, which improve the performances of students and researchers and minimise health risks, is required in academic buildings [19]. Ricciardi et al. [20] conducted both subjective and objective evaluation of indoor environmental performance in seven classrooms at the University of Pavia, Italy. The authors considered 'global comfort' to include thermal, acoustic, and lighting comfort. The best correlation with the experimental results were chosen, and 10 indices were proposed on the basis of a new questionnaire which asked people to suggest ideal comfort conditions. However, in case of uncomfortable classrooms, students were unable to make environmental changes during the lectures and tended to accept the undesirable environmental conditions rather than attempting to achieve the necessary conditions for comfort [21]. In India, a study conducted in 30 classrooms in 3 university buildings during the summer season revealed that students preferred a change of clothing to adapt to changes in indoor and outdoor climatic conditions. Moreover, when an increase in indoor and outdoor air temperature occurs, 50% of students preferred to open windows as the primary thermal adaptation method, 40% opted to open doors, and 100% desired to control the air speed by operating ceiling fans [21]. Thus, it is important to use suitable heating, ventilation, and air conditioning (HVAC) systems that improve the wellbeing of occupants. In Brazil, de Abreu-Harbich et al. [22] analysed the impact of three ventilation system types including an air conditioner, an evaporative cooler, and natural ventilation on thermal comfort and thermal perception according to in situ measurements and surveys. Under extremely hot conditions, the evaporative cooler was the best solution according to in situ measurements. In that context, according to the calculated indices using the Fanger method, it was found that the results underestimated the students' perceptions. Vilcekova et al. [23] highlighted the relationship between IEQ and performance of school building occupants in Slovakia. In their study, objective measurements demonstrated low lighting quality, high levels of CO_2 concentration, and acoustic discomfort. These observations were also confirmed by a questionnaire which concerned a total of 34 students and 5 pedagogical staff members at the school. Reports of several Sick Building Syndrome (SBS) symptoms were confirmed among pupils and employees including fatigue, heavy-headed feeling, headache, difficulty in concentration, eyes and nose irritation, and sore throat. A recent study showed the effect of CO_2 on work performance based on decision-making skill in which subjects were exposed to various concentrations of CO_2 [24]. The above studies are non-exhaustive; more recent works concerning the correlation between IEQ and student performance are given in Ref. [25].

However, few works based on existing state-of-the-art techniques simultaneously address the issues concerning long-term energy audits, IAQ assessment, and thermal comfort evaluation in academic buildings, particularly in Western European countries. These factors are highly important for post-occupancy evaluation of a new construction designed to be a low-energy consumption building according to the standard. We believe that it is necessary to consider all of the aforementioned aspects simultaneously to understand and outline the relationships of these aspects and to determine whether the gap between the office design expectations and the actual energy consumption affect the IEQ.

Located in the southern part of Troyes city in France, the ex-Ecole Polytechnique Féminine (EPF) School of Engineering has taken serious measures against wasting energy. The school aims to make reductions of 20% in its total energy consumption and 50% in its greenhouse gas emissions by 2025 and is committed to improving the IEQ of the occupants. The EPF building was designed to consume less energy and is equipped with sub-meters and sensors that are linked to a Building Management System (BMS).

The major goals of the EPF in reducing its energy consumption are also used as a method of reducing the school's annual power bill, which is increasingly expensive. The challenge to develop renewable energy on campus is a step towards green energy and an energy transition. Moreover, facilities management and energy services development enable a substantial number of jobs to be created. However, large challenges are associated reducing both heating and electricity consumption to save energy.

Although energy saving efforts have been made by the EPF School of Engineering, large amounts of electricity and heating are still wasted. The air handler units often work for 24 h 7 days a week in unoccupied rooms. Thus, an energy audit is expected to identify the problematic areas and to measure the economic and environmental impacts.

In this study, we perform a building energy audit during a three-year period from January 2015 to December 2017. The analysed data, extracted from a database website of the BMS, includes all the building's relative energy consumption. Furthermore, data concerning the IAQ as well as the thermal comfort of the occupants during the winter season are analysed and discussed. A simulation is conducted using a developed Modelica® model, which is an object-oriented modelling tool designed to provide quantitative outcomes of thermal comfort, and the results are compared with the measurements and the survey answers. This study offers an overview of the building's energy audit and evaluates both the IAQ and the thermal comfort; moreover, it may serve as a case study for newly constructed academic buildings.

As shown in Fig. 1, the work methodology follows three steps, from the information gathering to the alternative solutions. Firstly, the energy audit begins with an initial building walkthrough led by the technical staff of the facilities management. This tour gave us privileged access to facilities management areas such as mechanical rooms, equipment rooms not usually offered for public access, and the building's space-type documents. Based on these technical elements, analysis of the actual building's energy systems consumption obtained from the BMS was conducted. Then, the IAQ assessment of three teaching rooms based on the CO_2 measurement was performed. Finally, the occupants' thermal comfort in the café and seating space was studied and analysed during the winter season by using experiments, survey, and Modelica® numerical modelling.

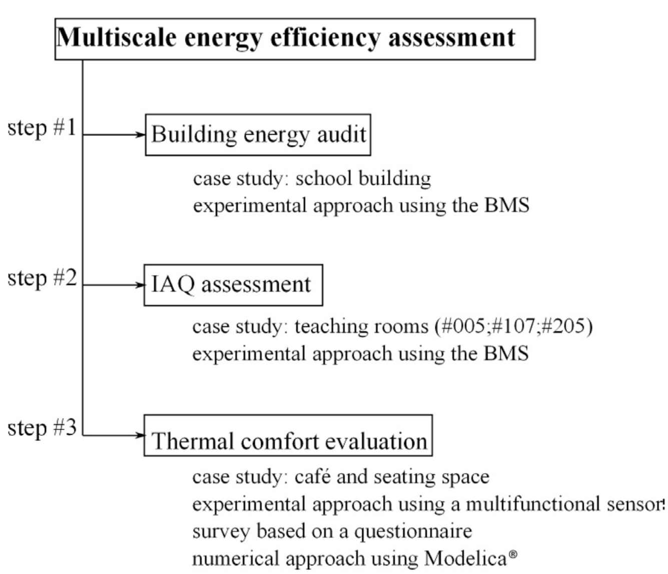


Fig. 1. Schematic diagram of the proposed methodology.

2. Building overview

2.1. Case study building details

The building was designed to be an exemplar engineering school building for graduate engineering students in the fields of buildings and smart cities. It was designed with the dual purpose of an educational environment and an experimental case study in order to analyse its energy consumption and IEQ. The building was designed to be a low energy consumption building to meet the French standard requirement RT2012. Constructed in 2014 in Troyes, France, the building has a net surface area of 3200 m^2 spread over three levels (Fig. 2). The ground floor (GF) contains an amphitheatre, a café, students' open-work spaces, an atrium/exhibition area, association offices, computer teaching rooms, and a storage room containing the first Air Handler Unit (AHU). The first floor (1F) includes offices, teaching rooms, a kitchen, a meeting room, a server room, and a storage room containing the second AHU. The second floor (2F) includes teaching rooms, offices, a meeting room, and a storage room containing the third AHU.

The building staff undertook several actions to implement an improved sustainable policy. Many facilities were integrated to reduce the building's energy consumption and to favour the thermal comfort of the students. The building is linked to an urban heating network which provides hot water to the 8.8 MW biomass boiler using wood and straw. The building is heated by an underground floor heating system, radiators, and a dual-flow ventilation system which contains three AHUs integrating heating coils to enable heating and ventilation. The outdoor air, which is supplied to the building through a Canadian well, is naturally preheated in winter at 9–11 °C even if the outdoor temperature is a negative value. The preheated air flows through an enthalpy wheel that plays the role of a heat recovery system to reach the set-point air supply temperature of 20 °C. If necessary, the hydraulic heating coil engages to attain the set-point temperature. In summer, the outdoor air is naturally precooled to 16–18 °C through the Canadian well before it is supplied to the building. In addition, the AHUs are not equipped with cooling coils.

Both the heating and ventilation systems are controlled by a BMS which incorporates an array of air temperature and CO_2 sensors installed at various building locations. Such environmental data is collected in 1-min increments from sensors and is transmitted to the BMS, which enables the staff members to receive feedback on the building performance and occupancy rate. For example, for collected data regarding the CO_2 concentration, the staff should be aware of whether the space is occupied. RT 2012 limits CO_2 concentrations of < 400 ppm for unoccupied space, 400–1000 ppm for occupied space, and > 1000 for over-occupied space. In the case of over-occupied spaces, the air volume flow rate is increased by action of the AHU fan rotation to maintain a CO_2 level less than 1000 ppm.

The building was oriented to maximise daylight and winter solar access in the room spaces. A 20 kWc share of power is produced by the 128 m^2 photovoltaic (PV) panels, which are installed on the roof and are south-oriented. Further, rainwater is collected and filtered for sanitary water use. Table 1 shows the physical characteristics of the buildings, and Fig. 3 illustrates the layout of the GF, 1F, and 2F floors of the building.

2.2. BMS description

By activating and deactivating the HVAC system, a BMS controls the input set-points such as temperature, air volume rate, CO_2 rate, and other parameters. Regarding facility management, the second role of the BMS is to monitor and control the energy systems and the IAQ by using a server with a database. In this system, an array of sensors connected to an Internet-capable network that are located throughout the building gather and send data to the BMS. The data collected by both air temperature sensors and CO_2 rate sensors are

(a) (b)

Fig. 2. EPF school building: (a) northeast view; (b) inside view.

post-treated to analyse the IAQ of the building and the thermal comfort.

Moreover, BMS software enables the facilities operations to be visualised in real time. If the sensors report data that falls outside predefined conditions, an alarm will be activated by the BMS. For example, the BMS might activate an alarm if the CO_2 rate exceeds 1500 ppm. Fig. 4 shows two screenshots corresponding to the AHU located in the GF and the primary hot water network which provides the heating system.

3. Utility analysis

The utility analysis evaluates the total energy sources used by the electrical and heating systems. To determine the impact of the weather on energy usage allowing an objective comparison of the three-year audit, at least three key weather factors should be considered: outdoor temperature, global solar radiation, and heating degree days (HDDs). HDD are the sum of the average daily differences between the outdoor temperature values and 18 °C by considering that heating is not needed when the outdoor temperature is 18 °C. A greater HDD value relates to a greater need for heating.

Weather data are collected by a weather station in Barberey located 11.5 km from the building and are displayed online free of charge [26]. The online database is updated hourly and offers comprehensive and accurate information suitable for scientific purposes. These weather data were helpful for analysing the space heating and electricity needs over the three-year study period.

Fig. 5a shows the average monthly outdoor temperature and HDD charts, and Fig. 5b presents the hourly accumulation of monthly global solar radiation. The weather was relatively the same over the three

Table 1
Brief description of the building.

Location	Troyes city, France (latitude 48.2° N, longitude 4.07° E)
Area	External area of 4142.6 m^2; total heated floor area of 3200 m^2 (three levels)
Dimensions and heights	L × l: 37.16 m × 37.16 m; floor-to-floor = 2.54 m
Operating hours	Monday to Friday 08:00 to 21:00 (UTC + 01:00); 220 students and staff members in 2015, 281 in 2016, and 315 in 2017. Designed maximum occupation of 699 people
Construction elements	**External walls** U-value = 0.19 Wm^{-2}K^{-1} constituted by concrete wall, oriented strand board (OSB) and 20 cm mineral wool (λ = 0.04 Wm^{-1}K^{-1}) from outside to inside **Roof** U-value = 0.13 Wm^{-2}K^{-1} with heavyweight concrete and 19 cm Polyurethane insulation (λ = 0.025 Wm^{-1}K^{-1}) **Floor** U-value 0.05 Wm^{-2}K^{-1} **Internal walls** U-value = 4.1 Wm^{-2}K^{-1} **Double glazing** with U_g = 1.1 Wm^{-2}K^{-1} and U_w = 1.5 Wm^{-2}K^{-1}, SHGC = 0.63, transmissivity > 0.7; equipped with internal and external shadings **Global envelope building** U-value = 0.361 Wm^{-2}K^{-1}
Air tightness	Intended air permeability (not achieved) = 0.7 m^{3}h^{-1}m^{-2} at 4 Pa.
Rainwater collection	Rainwater harvesting collector for WC use coupled to the filtration system and installed on the roof; estimated water consumption of 389 m^3/y. Rainwater collector volume V = 20 m^3 covering 95% of the WC water needed.
PV system	128 m^2 (20 kWc) of 80 PV panels on south face of roof occupying an area of 2800 m^2.
Internal gains	Appliances load = 2 Wm^{-2}; occupants seated quietly = 108 W/person (1.0 Met); normal office clothing (1 clo)
Lighting system	High-efficiency LED bulbs with daylight sensing override and occupancy sensors in all rooms.
Building Energy systems	**Heating system** powered by 8.8 MW biomass boiler. The building is equipped with radiators. Supply water temperature is a function of outdoor temperature; underground floor heating system are also present. Set point temperature at 20 °C. Indoor air temperature controlled by the BMS. **Ventilation system**, coupled to the Canadian air well, contains three AHUs, a dual-flow ventilation system equipped with enthalpy wheels, and heating coils. Supply air temperature provided at 20 °C; air volume flow rate is set to 1080 or 4676 m^{3}h^{-1} for the GF and 7498 or 8499 m^{3}h^{-1} for the 1F and the 2F depending on the occupation rate. The air volume rate is controlled by the BMS according to data collected from the CO_2 sensors.
Canadian well	Six cast iron tubes embedded 3 m in the soil, each 30 cm in diameter; length = 60 m; total length = 360 m; occupied area = 234 m^2. Canadian well provides air to AHUs. Air is preheated to 9–11 °C in winter and 16–21 °C in summer. No cooling system is present in the building.

Fig. 3. Building floor plan: (a) GF; (b) 1F; (c) 2F

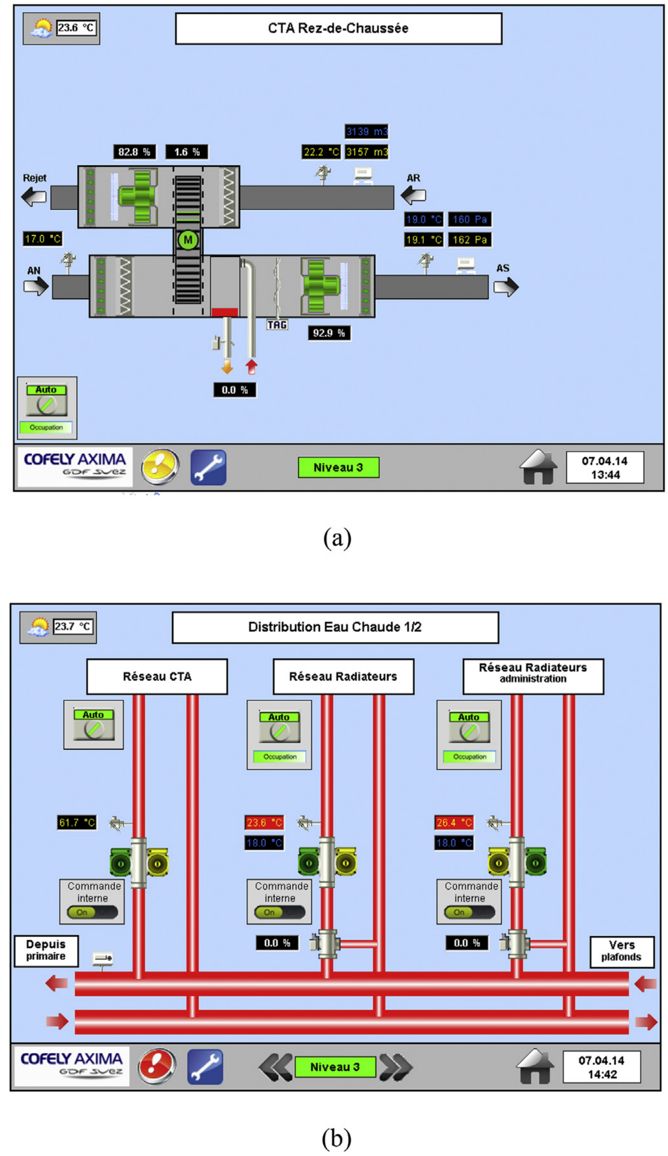


Fig. 4. BMS screenshots. (a) AHU located in the GF; (b) hot water network for heating.

years except for the solar potential, which varied monthly. Thus, except for the heating demand and PV electricity production, which is depicted on an annual basis, the averaged three-year monthly electricity consumption were considered, specifically AHUs and lighting. Table 2 summarises the total HDD and hourly cumulus solar radiation over the three-year study period.

Fig. 6 shows the building heating energy consumption over the three years, which demonstrates that the heating energy usage matched the expectations according to the weather data. The monthly energy usage was highest in winter months, with peaks in December and January caused by high heating demands. The lowest energy consumption occurred during the shoulder seasons, and usage in summer was neglected. The trend analysis shows that the energy consumption was relatively stable between 2015 and 2017. Interestingly, with essentially the same HDD in 2015 and 2016, which corresponds to March, the energy consumption through heating in 2016 was higher than that in 2015. This could be attributed to the presence of higher solar radiation during March 2015 (Fig. 5b), which indicates that the building is well oriented for receiving solar radiation. The same observation was noted for April 2016 and 2017. The heating demands corresponding to April 2016 and April 2017 were about 15 MWh and 13 MWh, respectively, which represents 13% energy savings.

Electricity, including air ventilation and lighting, showed the greatest consumption with an average annual bill of 19,000 €, followed by heating at 12,830 €. The averaged monthly electricity usage is shown in Fig. 7. The average electricity consumption increased from 6.95 MWh in August to 13.57 MWh in December. Greater electricity consumption was recorded in winter and shoulder seasons compared with that in the summer. These results could be correlated to summer vacation, in which students were present, and administrative and facilities staff members had lower attendance. It appears that larger share in total electricity demand is attributed to usage of AHUs, appliances, and auxiliary equipment, the latter of which represents mainly the heating system pumps and ventilation fans excluding AHUs. The amount of the energy use corresponding to lighting was low compared with other consumption owing to low-energy LED bulbs with daylight

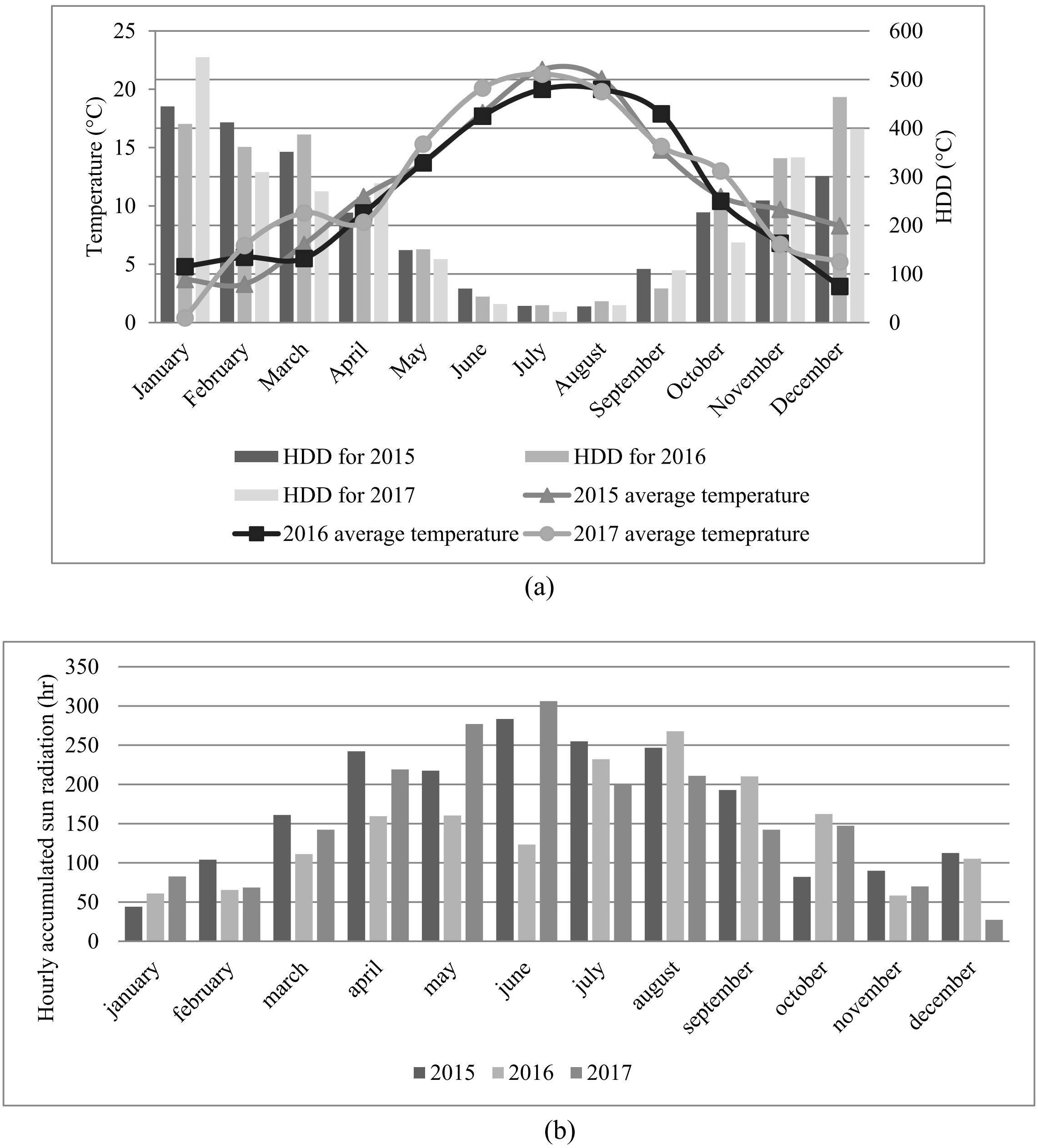


Fig. 5. Three-year averaged weather data [26]: (a) averaged outdoor temperature and HDD; (b) hourly accumulation of monthly sun radiation.

Table 2
Total HDD and hourly accumulated sun radiation over the three-year study period.

	2015	2016	2017
Total HDD (h)	2612	2810	2649
Total sun radiation (h)	2032	1717	1893

sensing overrides and occupancy sensors in installed classrooms and offices. Unlike the heating utility, in which energy consumption depends on the weather only, lighting usage depends on weather, including solar radiation, as well as occupant number. Thus, the solar radiation in January 2015 was less than that for January 2016, which is counterbalanced by the fact that in 2016, 281 students and staff members were involved compared with 200 in 2015, amounting to a 30% increase. As a result, the lighting energy use was 1.87 MWh in 2015 and 2.15 MWh in 2016, representing a 15% increase in energy consumption.

To illustrate the lighting use among building levels and outside, Fig. 8 presents the averaged three-year monthly electricity usage for lighting regarding the ground floor (GF), the first floor (1F), the second floor (2F), and outside. Owing to the occupancy rate, 2F had the largest share of lighting consumption followed by GF and 1F. This result occurred because 2F has more open and teaching spaces for student attendance according to the floor plan illustrated in Fig. 3 even though the most of these spaces are well oriented. Lighting usage was higher for GF than for 1F because the daylight potential is less important, and most of teaching rooms in GF are north-oriented.

The assigned monthly electricity consumptions owing to AHUs corresponding to GF, 1F, and 2F are shown in Fig. 9. The usage was higher during winter and spring (November to May) compared with

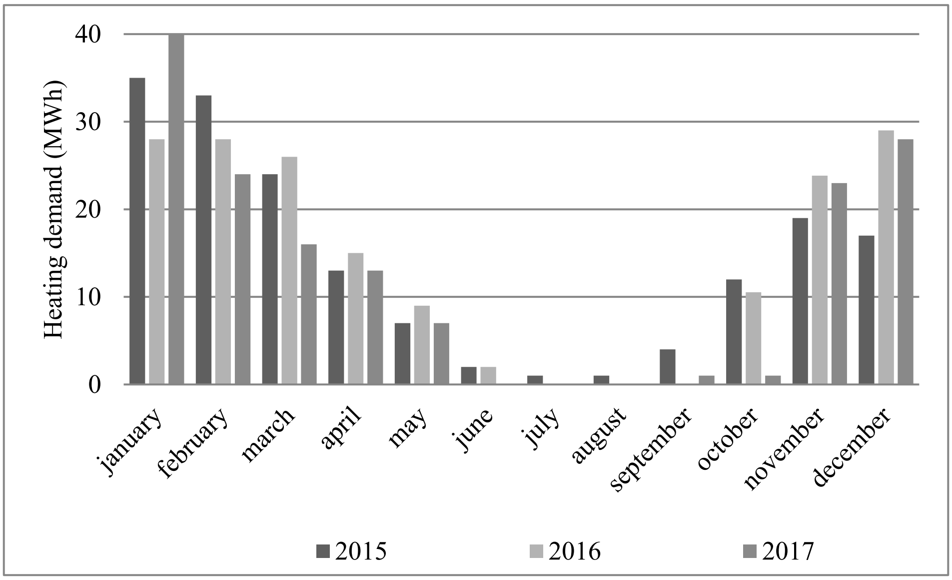


Fig. 6. Three-year monthly heating demand.

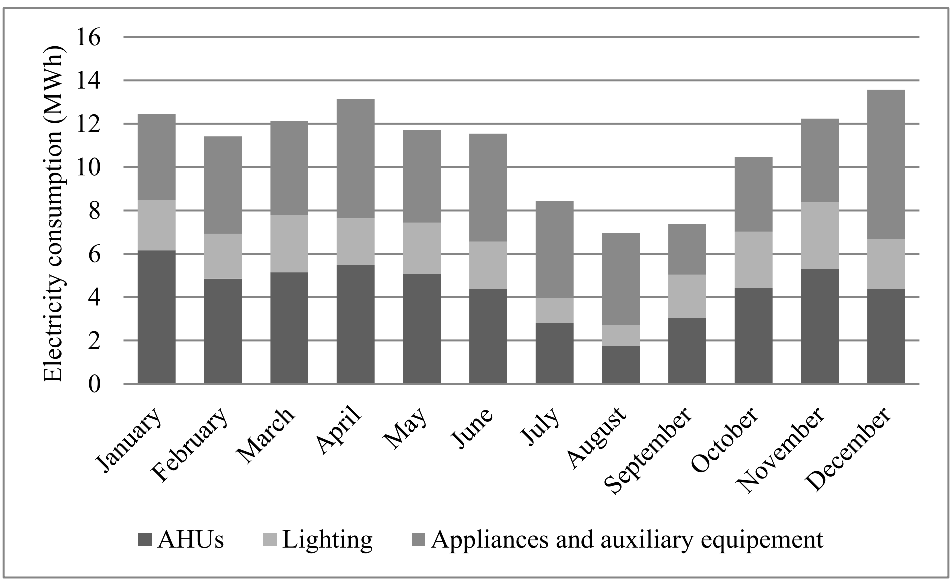


Fig. 7. Average of the three-year monthly electricity consumption.

that in summer as a result of the vacations. The AHU providing air to both 1F and 2F was consumed to a larger extent than those for GF and the amphitheatre because of the high renewable air demand.

The 80 PV panels have performed well, with PV-generated electricity making up 18%, 16%, and 19% of the electricity used in the building in 2015, 2016, and 2017, respectively. It should be noted that in April and September 2015 the electric inverter was powered off for one and two weeks, respectively. Fig. 10 depicts the PV production charts over the three years. As expected, the electricity production matched well with accumulation of monthly solar radiation presented in Fig. 4.

Energy benchmarking is a method of comparing the energy performance of the studied building with the general energy consumption threshold of buildings with similar characteristics. This technique enables building owners and managers to assess the energy performance of existing buildings. Moreover, benchmarking helps a firm to improve its market competitiveness among commercial buildings and cities with energy efficiency goals.

The initial objective of the programme was to design a building according to the benchmark Trés Haute Performance Energétique (THPE®), i.e. a 20% reduction in energy consumption compared with the benchmark threshold HQE®. Both the bioclimatic provisions and the introduction of renewable energy at the building level have made it possible to go beyond this requirement to reach the RT 2012 mandate, which allows for energy reductions of 30–50% compared with the HQE® benchmark in terms of primary energy.

Primary energy consumption measures the total energy demand including losses during transformation, from energy extraction to end-use final consumption. Thus, coefficients must be applied to consider these energy losses. In France, a coefficient of 2.58 is used to calculate the primary energy from the final energy for the electricity; 1 is used for renewable energy and for gas or biomass.

For comparison of the total building energy consumption against RT 2012 and the HQE® requirements, a summary is depicted in Table 3. Indeed, RT 2012 recommends a maximum energy consumption of 78 kWh/m^2/y for new school buildings located in the eastern France,

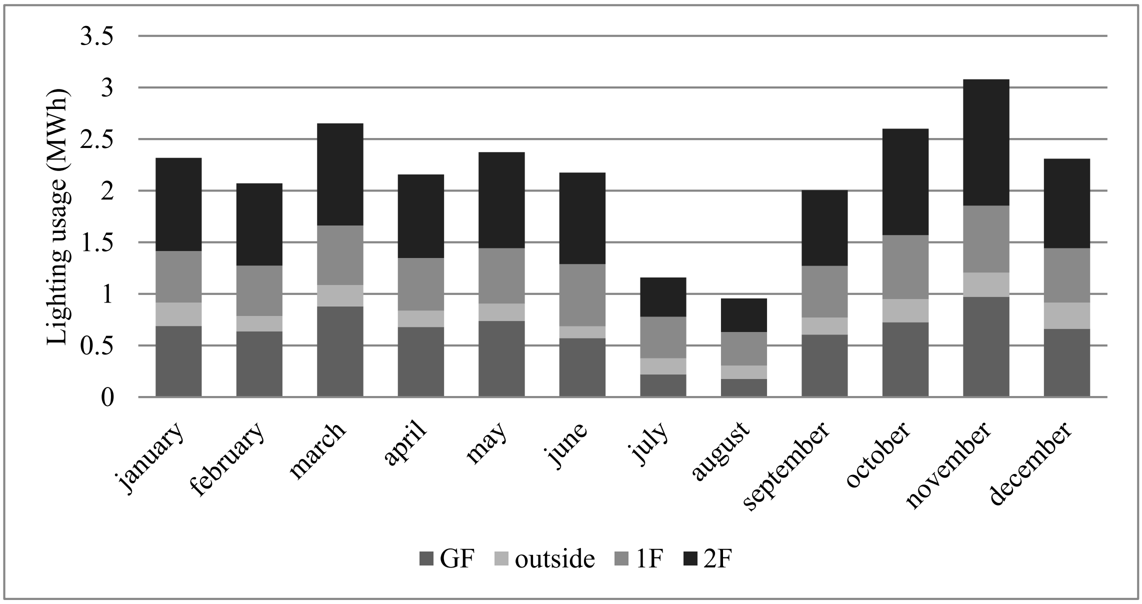


Fig. 8. Average of the three-year monthly electricity consumption through lighting.

whereas the corresponding value for new office buildings is 84 kWh/m^2/y. As shown in the table, the total energy consumption exceeded the RT 2012 requirements. Electricity accounted for the greatest consumption of the building during the three-year study period. It should be noted that PV production covers only the lighting electricity demand.

The design-office assessment produced a rapid initial estimate of the breakdown of the energy use based on metered energy use and sub-metering data. A comparison of the energy use of the building, for the three-year energy audit, with the design estimate regarding RT 2012 regulation and HQE® benchmark is shown in Fig. 11. It should be noted that the calculations do not account for all energy systems and include only heating, ventilation and auxiliary equipment, internal and external lighting, and PV electricity production.

Regarding the HQE® standard, no discrepancy was noted between the benchmark requirements and the total actual metered energy use. Indeed, although the actual energy use for ventilation and auxiliary equipment was higher than the HQE® requirements, the heating and lighting uses were lower than the requirements. However, the total energy use was underestimated according to RT 2012 regulation, at 78 kWh/m^2/y. The total actual energy appeared to be higher than the requirements by a mean factor of 1.33, which shows that the heating demand was essentially the same over the considered three years because the HDD was the same.

This gap is attributed to several aspects that were not considered in the design estimate such as air leakage, thermal bridges, and indoor temperature regulation. In fact, the set-point temperature was often maintained at 20 °C in the building even though the RT 2012 regulation recommends 19 °C, upon which the design estimate is based. The gap of 1 °C dramatically affected the energy consumption which could be quantified. Moreover, because air tightness testing was not mandated, this test was not conducted. It appears that the air passes through openings to cause heat loss. Thermal imaging conducted in the café and seating space (Fig. 12), which is a highly glazed room, showed numerous thermal anomalies resulting from design detailing and installation during construction. Moreover, it is difficult to quantify the amount of heat loss owing to thermal bridges in transient conditions. Further, occupant behaviour in over-occupied rooms or offices, such as

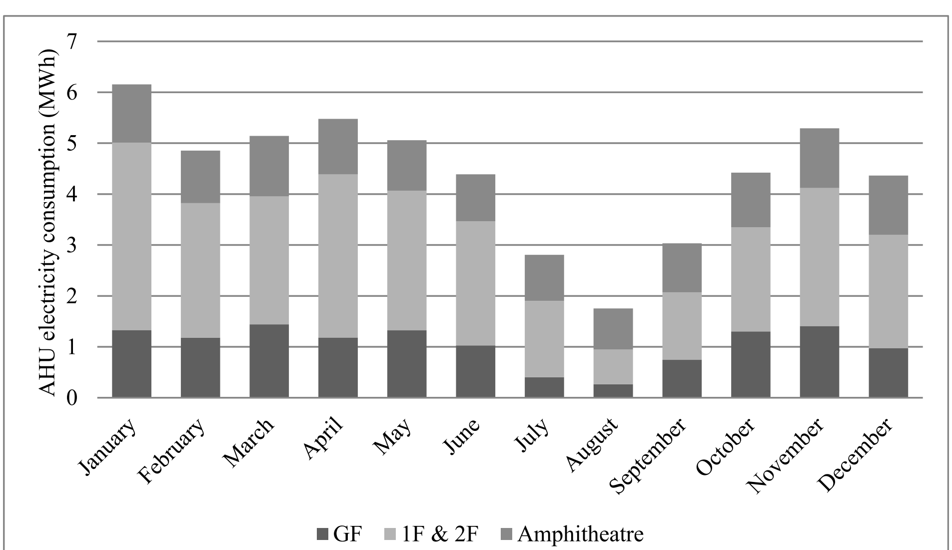


Fig. 9. Average of three-year monthly AHU electricity consumption.

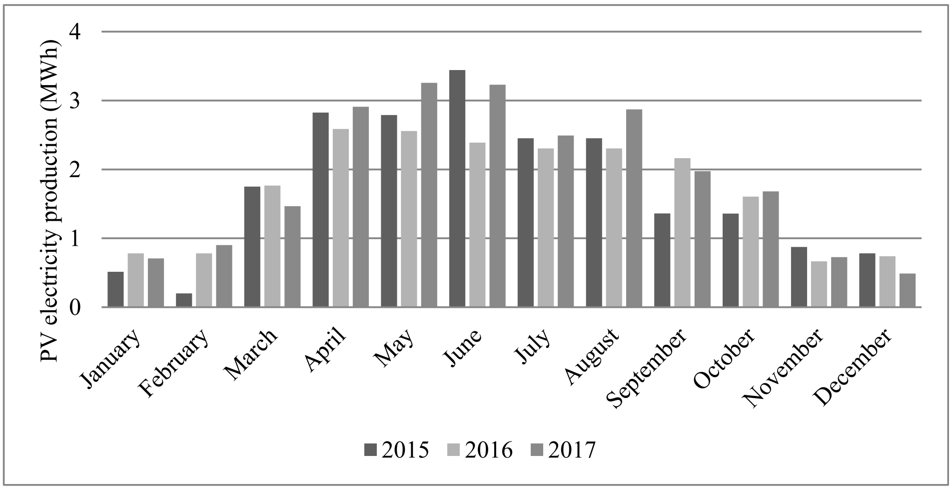


Fig. 10. Three-year monthly PV electricity production.

Table 3
Total energy consumption.

Utility energy use (kWh/y)	2015			2016			2017		
	Final energy	Primary energy	Quota %	Final energy	Primary energy	Quota %	Final energy	Primary energy	Quota %
Heating	168000	168000	52	171360	171360	50	153000	153000	47
Ventilation	58800	151704	47	60324	155636	45	60324	155636	47
Lighting	20939	54023	17	26496	68360	20	30140	77761	24
PV production	−20808	−53684	−17	−20645	−53263	−16	−22707	−58585	−18
Total (kWh/m^2/y)	100		100%	107		100%	102		100%

opening windows on a cold day, leads to more heating and ventilation energy consumption.

Similar to the heating utility, the ventilation and auxiliary equipment usage also high. This occurred because the volume flow rate of the AHU is controlled according to the CO_2 rate, which varies frequently. This caused the fans and enthalpy wheels to restart, which consequently leads to an increase in power consumption. Moreover, it is worth noting that the pressure drop owing to the tubes in the Canadian well was not considered in the estimation even though it significantly affects the energy use.

Although the hourly accumulated solar radiation over the three-year study period was essentially similar, the increase in the occupant number affected the lighting frequency use. In addition, the management staff members noted that the occupancy sensors installed in the teaching rooms are not well regulated and optimally placed. In fact, a person passing through a corridor is detected by the sensors when the doors of teaching rooms are open even during non-occupancy periods. Moreover, when a person enters the atrium, the occupancy sensors located in 1F and the 2F turn activate the lighting automatically in all corridors of such floors. These could be reasons for the gap between the estimation and the actual lighting energy use.

4. Indoor air quality

The IAQ has a significant effect on the wellbeing of the administrative staff and students. Healthy buildings lead to motivated occupants in a workplace, reduced employee absenteeism, and improved occupant productivity and satisfaction [27]. According to EN 15251 standard [28] regarding non-residential buildings, the air volume rate per person should be set to 36 (m^3.h^{-1}), 25.2 (m^3.h^{-1}) and 14.4

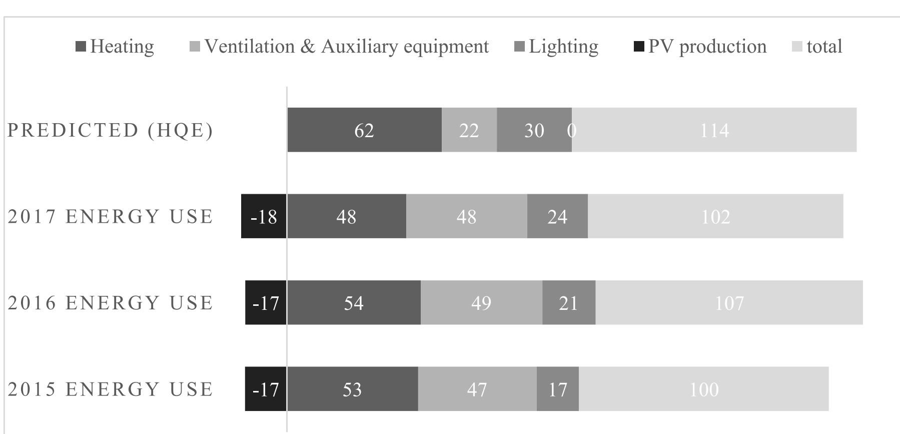


Fig. 11. Actual total annual energy use (kWh/m^2/y) compared with predictions regarding the RT 2012 regulation and HQE® benchmark.

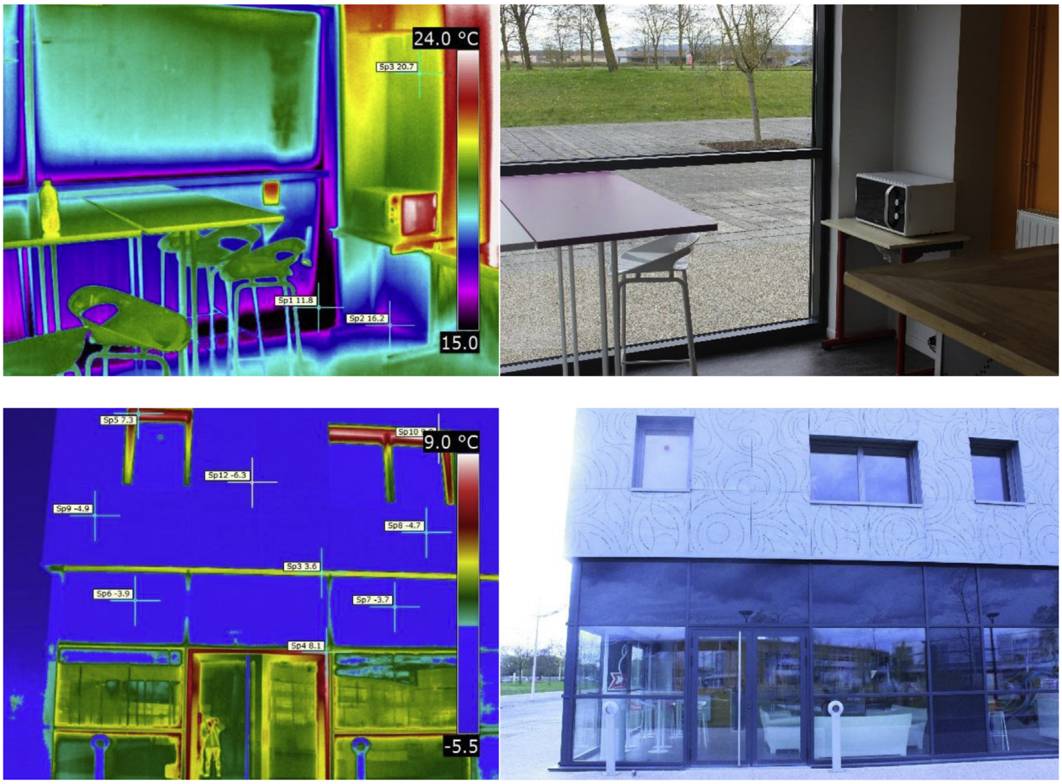


Fig. 12. Air leakage and thermal bridges caused by openings in the café and seating space.

Table 4
CO_2 rate required by EN 15251 standard for EPF building.

Non-residential building categories (EN 15251)	Minimum required VFR ($m^3.h^{-1}$)/person	Maximum occupant number (LVFR)	Maximum occupant number (HVFR)	Upper CO_2 limit (ppm)
Cat. I	36	238	366	< 670 (350 + 320)
Cat. II	25.2	340	523	< 820 (500 + 320)
Cat. III	14.4	596	915	< 1120 (800 + 320)

($m^3.h^{-1}$) which are associated with forecasts of 15% (category I), 20% (category II), and 30% (category III) of persons dissatisfied (PD), respectively. Table 4 depicts the required IAQ in terms of upper CO_2 limit according to the European benchmark requirements for our case study. The fan velocities of the AHUs servicing GF, 1F, and 2F were usually set to maintain a CO_2 rate less than 1000 ppm. As shown in the table, both the low value of volume flow rate (LVFR) of 8578 $m^3 h^{-1}$ and the high value of volume flow rate (HVFR) of 13175 $m^3 h^{-1}$, corresponding to both total minimum and maximum air volume flow rates (VFR) provided by the HUs, were used to estimate the maximum occupant number for the building. The upper limit of the CO_2 rate was calculated according to the EN 15251 method, which takes values corresponding to 350 ppm, 500 ppm, and 800 ppm (categories I, II, and III, respectively) added to the outside CO_2 rate which theoretically corresponds to the CO_2 value of an unoccupied space. Based on our measurements, we found an average value of 320 ppm in the unoccupied space.

Although the building was designed to receive a maximum of 699 people, the maximum count in our study was 315. In such a case, the CO_2 rate for inside spaces should be theoretically maintained at less than 820 ppm (category II with LVFR) to meet the EN 15251 recommendations [28]. Moreover, it is possible to check the data provided by the BMS to determine whether the CO_2 rate exceeds the recommended upper limit, particularly during regular courses offered between 00:80 and 18:00 (UTC + 01:00). Beyond this time range, students entered the building at random times to work without a defined schedule. Fig. 13 presents measurements regarding the CO_2 rate

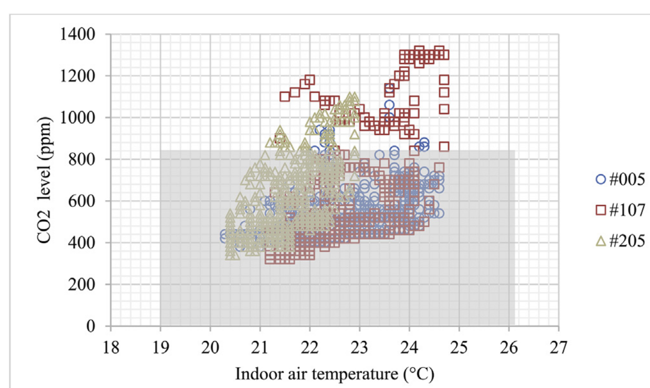


Fig. 13. Temperature and CO_2 rate measurements in teaching rooms measured on 22–26 January 2018: (a) #005; (b) #107; (c) #205.

and the indoor air temperature in west-oriented teaching rooms with the same usage, where #005, #107, and #205 are located in GF, 1F, and 2F, respectively. Such measurements were recorded in 2-min intervals from 08:00 to 21:00 (UTC + 01:00) during a typical winter week in January 2018.

The temperatures were between 20 °C and 25 °C, which is acceptable regarding the RT 2012 requirements. During periods of high occupancy, the CO_2 levels could exceed 820 ppm. However, such a case

Fig. 14. (a) Outside view of the foyer, located at the southeastern part of the building; (b) inside view.

occurred only between 1% and 5% of occupancy hours; thus, the air quality was considered to be satisfactory regarding the CO_2 rate owing to the air VFR controlled by the AHU.

5. Thermal comfort

Students occupying the area that includes the café and seating space, referred to as the foyer, reported a significant difference in temperature from that in other parts of the building and indicated dissatisfaction in the thermal conditions even though the air quality was acceptable. The foyer, located in the southeastern part of GF (Fig. 14), is a communal place of life in which students meet every day to eat, rest, and do activities. The foyer has a floor area of 58 m^2 and south- and east-oriented glass façades of about 31 m^2, including 13 m^2 for the former and 18 m^2 for the latter.

In order to confirm this fact, questionnaires were prepared and collected from 41 students between the ages of 17–22 during three days in November 2014. Students used a predicted mean vote (PMV) for seven grades of a thermal sensation scale ranging from −3 to +3 [29–31]. As shown in Fig. 15, only 56% of the students reported a neutral feeling in the foyer at the time of the survey, whereas 39% conveyed a slightly cool feeling, and % felt slightly warm. In addition, the students were asked to express their satisfaction by answering the following question: Are you satisfied with the indoor conditions when attending the foyer? Representing 34.1%, 14 students reported dissatisfaction with the indoor thermal conditions of the foyer. Fig. 15 shows the students' responses as a function of thermal sensation vote, where a neutral thermal sensation corresponds to the highest satisfaction assessment. An important inference is that the students expressed the most dissatisfaction, about 70%, when they felt slightly cool. This may have occurred because the students became acclimatised to neutral or slightly warm thermal conditions in winter owing to the wide use of heating systems. Thus, the results show that some students experience thermal discomfort in the foyer during winter. This could be correlated to the presence of the highly glazed envelope because frequent changes in the outdoor climate affect the mean radiant temperature. For example, high-intensity solar radiation may lead to high radiant temperature values, and low outdoor temperature with low solar radiation could lead to lower radiant temperature. Because the radiant temperature has a major influence on thermal comfort, this may have caused the aforementioned thermal discomfort.

Furthermore, the foyer was considered for investigation and analysis of the occupants' thermal comfort by means of in situ measurements and numerical simulation. Measurements were fulfilled to confirm the students' complains and to understand the impact of physical and human parameters on thermal discomfort. The numerical study may be complementary to measurements and may be used as a fast and simple tool to predict occupants' thermal comfort by testing several scenarios such as a regulated heating system, a decreased area of glazing, and treatment of the thermal bridges.

An experimental investigation of occupants' thermal comfort within the foyer was conducted to calculate and analyse the PMV and predicted percentage dissatisfied (PPD) indices in order to evaluate the thermal comfort level in that area. In this regard, a multifunctional sensor developed by Institut d'Electronique et des Systèmes (IES) was used to monitor the environmental parameters of the foyer such as room temperature, mean radiant temperature, relative humidity, and air velocity and to calculate and visualise in real time the indices of thermal comfort (PMV and PPD). In this system, a sensor, shown in Fig. 16, transmits the data to a work station using Wi-Fi. During data collection, the measurements made by the sensor are recorded as data frames in a text file that are directly used to plot the evolution of the

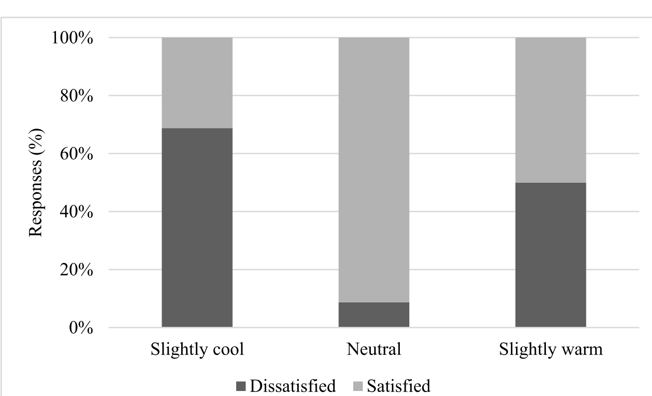


Fig. 15. Relationship between thermal sensation and thermal satisfaction.

Fig. 16. Multifunctional sensor.

Table 5
Multifunctional sensor characteristics and experimental cycles.

Parameters	Range of variation	Accuracy
Ambient temperature (°C)	[-40.0, 123.8]	± 0.4
Mean radiant temperature (°C)	[0, 100]	± 0.4
Relative humidity (%)	[0, 100]	± 3
Air velocity ($m.s^{-1}$)	[0.05, 5.00]	± 0.05 for [0.05, 1.00] ± 0.15 for [1.00, 5.00]

Experimental cycles					
	12/11		13/11	14/11	
	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5
Start hour[a]	10:47	14:46	08:21	10:01	14:31
End hour[a]	11:29	18:36	08:55 (+1 day)	11:49	14:31

[a] (UTC + 01:00).

different physical quantities during the series of measurements. This same interface also enables modification of complementary parameters such as metabolic rate and clothing insulation to calculate the PMV and PPD. The activity levels of the students were evaluated by asking the students to complete the following sentence: 'I go to the foyer for:' The answer choices were eating, relaxing, working, discussion. In addition, the students were given the opportunity to choose more than one answer. The results revealed that an overwhelming majority of the students chose eating, relaxing, and discussion, at 26%, 39%, and 39%. We assumed that these answers could indicate sedentary activity (1.2 met); thus 1.2 met ($70\,W\,m^{-2}$) could be representative for the students' activity levels. The clothing level was assumed to be $0.155\,K\,m^2\,W^{-1}$ (1 clo) for typical winter clothing. Table 5 summarises the sensor characteristics and the five measurement cycles conducted from Wednesday, 12 November, until Friday, 14 November 2014.

Dymola® was used to develop the case study model and to conduct the simulations. Fig. 17 describes the interaction among the sub-models (Fig. 17a) and shows the Dymola® model (Fig. 17b). Both Modelica® Buildings Library and Modelica® Standard Library were used for this purpose. The MixedAir component of the Rooms package [32] was used to illustrate a single room with an unlimited number of opaque constructions.

The thermal properties of the interior walls, ceilings, floors, and glass façades were represented by using the OpaqueConstructions and GlazingSystems components of the HeatTransfer package. The mechanical ventilation system of the foyer was implemented into the model by using FlowControlled_m_flow of the Fluid package [33]. The ConstantEffectiveness heat exchanger of the Fluid package was used to depict the heat recovery system. The heating system was modelled by using RadiatorEN442_2 of the Fluid package, which represents a radiator that can be used as a dynamic or steady-state model. Moreover, DaySchedule was used to represent the occupancy profile in the foyer and was connected to the inlet connector qGai flow of the MixedAir model to add the internal radiative, convective, and latent heat gains. The ReaderTMY3 component of the BoundaryConditions package [34] was used to represent the outdoor weather conditions. Detailed descriptions and the development of the global model, the components used, and the validation process are presented in Ref. [35].

The predicted PMV and PPD were compared with the calculated indices by using the measured data and the survey. The average values of PMV and PPD obtained for the five experimental cycles are presented in Fig. 18. In general, all of the obtained average values of PMV were negative and fell outside the acceptable comfort range [-0.5, +0.5]. The obtained values of PMV from our developed model averaged −1.2. Therefore, all of the obtained average values of PPD were above the recommended comfort range of 10%. The obtained average values of PPD from the Modelica® model averaged 33.69%. These results indicate that the indoor thermal environment of the foyer was cold and that the simulation and calculated results were in good agreement based on the measured data. Therefore, we consider the model to be validated and deem it useful for further evaluations and investigations.

In order to evaluate and analyse the thermal comfort features of the foyer, the developed model was used to conduct simulations throughout the heating period. The supply air temperature of the foyer was generally set at 20 °C during the heating season. However, the new French standards [2] recommend that the room temperature set-point should be 19 °C. In this regard, two cases with set-point room temperatures of 19 °C and 20 °C were studied.

Table 6 shows the frequency of the PMV index and energy consumption of both room temperature set-points of 19 °C and 20 °C for the entire heating period. The PMV index values at the two set-points varied at −1.5 to +3.0 and −0.7 to +3.0, respectively. The results indicate that 79.5% and 67.8% of the PMV indices at set-points of 19 °C and 20 °C, respectively, fell outside the acceptable comfort range of [-0.5, +0.5]; therefore, the recommended 10% PPD was not satisfied.

At a set-point of 20 °C the thermal comfort was better maintained with 4.7% of the PMV indices outside the range of [-0.7, +0.7] compared with 64.5% at a set-point of 19 °C. This resulted in 15% PPD for 4.7% of the occupied time, which is slightly above the recommended 3% to satisfy the moderate expectation level.

The energy consumption results show that at a set-point of 19 °C, the studied room consumed less heating energy compared with that at 20 °C. These results indicate good agreement with the obvious fact that energy saving competes with thermal comfort.

In this case study, in which the external walls were fully glazed, the results showed that occupants' thermal sensations of both hot and cold are expected. This relates to the fact that regular changes in the outdoor climate results in changes in ventilation and transmission heat loss. When the outdoor temperature and solar radiation reach maximum values, the external surface temperature of the glass façade increases, resulting in an increase in the internal wall surface temperature. This result is attributed to the thermal storage effect, which allows for an increased mean radiant temperature. On the contrary, low outdoor temperatures with low solar radiation could lead to a decrease in the mean radiant temperature. These frequent changes in mean radiant temperature affect both the thermal comfort and energy consumption.

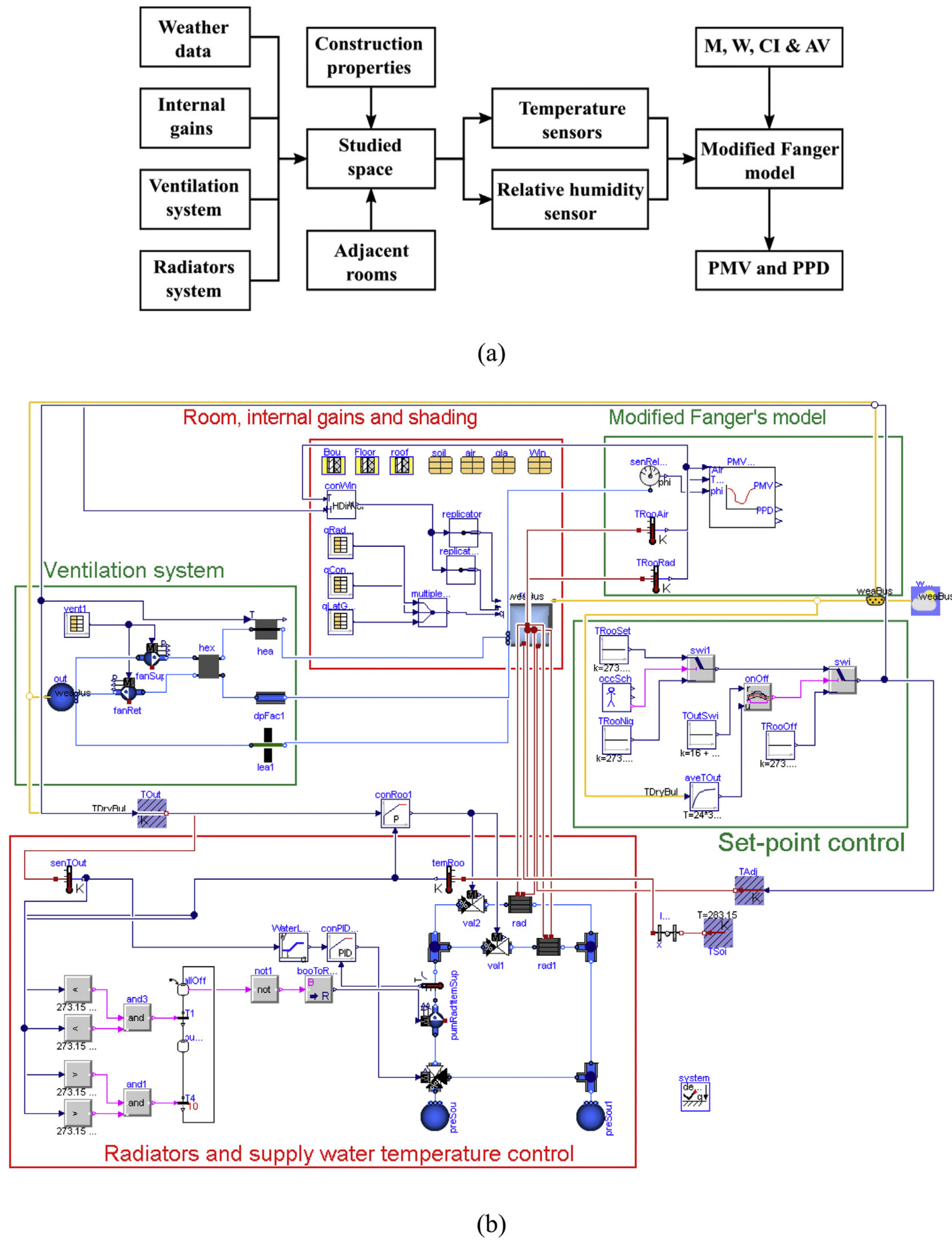


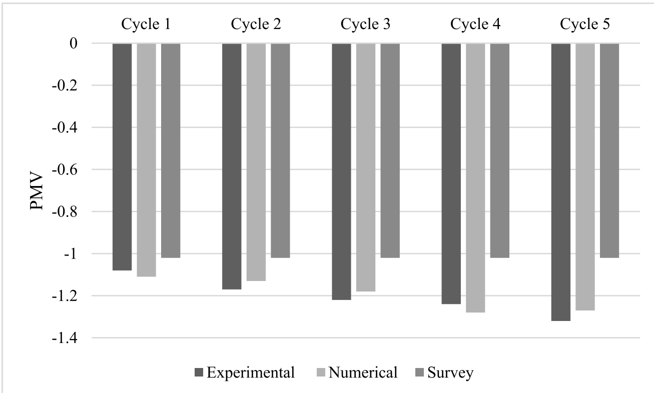
Fig. 17. Modelica® model of the foyer: (a) graphical diagram of sub-models; (b) Dymola® model.

6. Conclusion

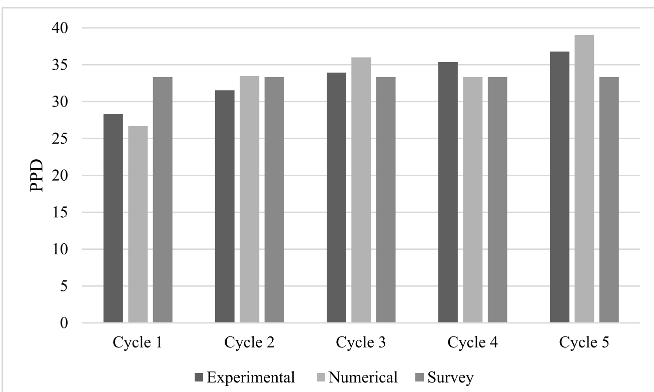
An energy audit coupled with IEQ assessment is a long-term and rigorous analysis which requires an examination of the mechanical and architectural drawings, investigation of the building, and interviews of the building users. The set of information collected by the BMS including the utility analysis, surface dimensions, or HVAC system evaluation should be conducted. Although the EPF building was chosen as a designed low energy use building, its energy consumption in fact exceeded the French standard by a factor of 1.33.

The first step of this work consisted of determining the different amounts of energy consumption; thus, the utility analysis was conducted to include three years of data collection from 2015 to 2017. Reflected in an annual bill of more than of 19,000 €, electricity was the main consumer and accounted for 52% of the entire bill in 2015. The second highest that year, the heating share, amounted to 14,600 € and showed a decreasing trend over the years.

The second step was to assess the IAQ in the building in winter because in summer, students are on vacation, and administrative and facilities staff members are in lower attendance. A case study of three



(a)



(b)

Fig. 18. Average values of (a) PMV and (b) the corresponding PPD for the various cycles.

Table 6
Frequency (hours) of the PMV index and heating energy consumption during the heating period.

PMV index	Set-point room temperature	
	19 °C	20 °C
−1.5 to −0.7	1442	0
−0.7 to −0.5	306	1427
−0.5 to −0.2	187	441
−0.2 to +0.2	199	214
+0.2 to +0.5	98	105
+0.5 to +0.7	49	68
+0.7 to +3.0	85	111
Energy consumption (kWh)	2710	3034

teaching rooms was considered because they are equipped with both CO_2 and ambient temperature sensors, which enables correlation between the thermal feeling and the IEQ in such rooms regarding the EN 15251 standard. The results showed that the air quality was satisfactory regarding the CO_2 rate.

The foyer was considered for investigation and analysis of the occupants' thermal comfort by means of experimental and numerical studies in addition to survey. The predicted PMV and PPD were compared with the calculated indices using the measured data. The obtained values of PMV from our developed model averaged −1.2, whereas the obtained average values of PPD from the Modelica® model averaged 33.69%. These results confirm the students' complaints during winter season.

Our validated model can be used as a fast and simple way to predict the energy consumption in a comfort-controlled room. In future work, we aim to investigate the sensitivity of heating energy consumption and energy-saving potential to outdoor climatic conditions and other environmental parameters in a thermal comfort-controlled, highly glazed room. Our developed model will be used to conduct a comparative building simulation study between PMV-based thermal comfort control and conventional thermostatic control as well as a sensitivity study based on the Design of Experiments (DoE) technique.

This study offers an overview of the post-occupancy evaluation of a newly constructed academic building and can serve as a case study for other buildings located in the Western European climate.

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References

[1] R. Gupta, M. Gregg, Empirical evaluation of the energy and environmental performance of a sustainably-designed but under-utilised institutional building in the UK, Ener. Build. 128 (2016) 68–80 https://doi.org/10.1016/j.enbuild.2016.06.081.
[2] Statistical Pocketbook 2018 of the European commission, (2018) WWW Document https://ec.europa.eu/transport/facts-fundings/statistics/pocketbook-2018_en , Accessed date: 23 August 2018.
[3] EU, Directive 2010/31/EU of the European Parliament and the Council of 19 May 2010 on the Energy Performance of Buildings (Recast), Off. J. Eur. Union, 2010, pp. 13–35.
[4] A. Martinez-Molina, P. Boarin, I. Tort-Ausina, J.-L. Vivanos, Post-occupancy evaluation of a historic primary school in Spain: comparing PMV, TSV and PD for teachers' and pupils' thermal comfort, Build. Environ. 117 (2017) 248–259 https://doi.org/10.1016/j.buildenv.2017.03.010.
[5] E. Burman, D. Mumovic, J. Kimpian, Towards measurement and verification of energy performance under the framework of the European directive for energy performance of buildings, Energy 77 (2014) 153–163 https://doi.org/10.1016/j.energy.2014.05.102.
[6] M.B. Luther, P. Horan, O.O. Tokede, A case study in performance measurements for the retrofitting of a library, Ener. Build. 169 (2018) 473–483 https://doi.org/10.1016/j.enbuild.2017.11.057.
[7] Agence de l'Environnement, et al., la Maîtrise de l'Energie (ADEME). Chiffres-clés de 2016, (2017) French report.
[8] Y. Allab, M. Pellegrino, X. Guo, E. Nefzaoui, A. Kindinis, Energy and comfort assessment in educational building: case study in a French university campus, Ener. Build. 143 (2016) 202–219 2017 https://doi.org/10.1016/j.enbuild.2016.11.028.
[9] Arrêté du 26 octobre 2010 relatif aux caractéristiques thermiques et aux exigences de performance énergétique des bâtiments nouveaux et des parties nouvelles de bâtiments, WWW Document https://www.legifrance.gouv.fr/jo_pdf.do?numJO=0&dateJO=20101027&numTexte=7&pageDebut=19260&pageFin=19285, (2010) , Accessed date: 30 August 2018(French report).
[10] A. Lebert, S. Lasvaux, F. Grannec, S. Nibel, F. Achim, N. Schiopu, Evaluation de la performance environnementale des bâtiments, définition d'ordres de grandeur, traitement statistique, WWW Document http://www.hqegbc.org/wp-content/uploads/2015/09/2013-10-HQEPerf_Annexes_Partie1.pdf, (2013) , Accessed date: 30 August 2018(French report).
[11] A. Asif, M. Zeeshan, M. Jahanzaib, Indoor temperature, relative humidity and CO_2 levels assessment in academic buildings with different heating, ventilation and air-conditioning systems, Build. Environ. 133 (2018) 83–90 https://doi.org/10.1016/j.buildenv.2018.01.042.
[12] Z.S. Zomorodian, M. Tahsildoost, M. Hafezi, Thermal comfort in educational buildings: a review article, Renew. Sustain. Energy Rev. 59 (2016) 895–906 https://doi.org/10.1016/j.rser.2016.01.033.
[13] S. Bengerth, M. Ohadi, C.A. Jenkins, Energy analysis of LEED silver certified dining Hall on an academic campus— A Revisit Three Years after its Initial Certification (GIA 14–15), 2017 ASHRAE Winter Conference, LV-17-012, (LV, Nevada).
[14] N. Alborz, U. Berardi, A post occupancy evaluation framework for LEED certified U.S. higher education residence halls, Procedia Eng. 118 (2015) 19–27 https://doi.org/10.1016/j.proeng.2015.08.399.
[15] A. Thewes, S. Maas, F. Scholzen, D. Waldmann, A. Zürbes, Field study on the energy consumption of school buildings in Luxembourg, Energy Build. 68 (2014) 460–470 https://doi.org/10.1016/j.enbuild.2013.10.002.
[16] I. Pegg, A. Cripps, M. Kolokotroni, Post-occupancy performance of five lowenergy schools in the UK, ASHRAE Trans. 113 (2007) 3–13 2007.
[17] C. Van Dronkelaar, M. Dowson, C. Spataru, D. Mumovic, A review of the regulatory energy performance gap and its underlying causes in non-domestic buildings, Fron. In Mech. Eng. 1 (2016) 17 https://doi.org/10.3389/fmech.2015.00017.
[18] M.W. Ahmad, M. Moursheda, D. Mundowb, M. Sisinni, Y. Rezgui, A Building energy metering and environmental monitoring – a state-of-the-art review and directions

for future research, Ener. Build. 120 (2016) 85–102 https://doi.org/10.1016/j.enbuild.2016.03.059.
[19] I. Sarbu, C. Pacurar, Experimental and numerical research to assess indoor environment quality and schoolwork performance in university classrooms, Build. Environ. 93 (2015) 141–154 https://doi.org/10.1016/j.buildenv.2015.06.022.
[20] P. Ricciadi, C. Buratti, Environmental quality of university classrooms: subjective and objective evaluation of the thermal, acoustic, and lighting comfort conditions, Build. Environ. 127 (2018) 23–36 https://doi.org/10.1016/j.buildenv.2017.10.030.
[21] S. Kumar, M.K. Singh, A. Mathur, J. Mathur, S. Mathur, Evaluation of comfort preferences and insights into behavioral adaptation of students in naturally ventilated classrooms in a tropical country, India, Build. Environ. 143 (2018) 532–547 https://doi.org/10.1016/j.buildenv.2018.07.035.
[22] L.V. de Abreu-Harbich*, V.L.A. Chaves, M.C.G.O. Brandstetter, Evaluation of strategies that improve the thermal comfort and energy saving of a classroom of an institutional building in a tropical climate, Build. Environ. 135 (2018) 257–268 https://doi.org/10.1016/j.buildenv.2018.03.017.
[23] S. Vilcekova, L. Meciarova, E.K. Burdova, J. Katunska, D. Kosicanova, S. Doroudiani, Indoor environmental quality of classrooms and occupants' comfort in a special education school in Slovak Republic, Build. Environ. 120 (2017) 29–40 https://doi.org/10.1016/j.buildenv.2017.05.001.
[24] U. Satish, M.J. Mendell, K. Shekhar, T. Hotchi, D. Sullivan, S. Streufert, et al., IsCO2 an indoor pollutant? Direct effects of low-to-moderate CO2concentrations on human decision-making performance, Environ. Health Perspect. 120 (2012) 1671–1677 https://doi.org/10.1289/ehp.1104789.
[25] S. Zuhaib, R. Manton, C. Griffinc, M. Hajdukiewicz, M.M. Keane, J. Goggins, An Indoor Environmental Quality (IEQ) assessment of a partially-retrofitted university building, Build. Environ. 139 (2018) 69–85 https://doi.org/10.1016/j.buildenv.2018.05.001.
[26] Weather Channel. InfoClimat, (2018) WWW Document https://www.infoclimat.fr/observations-meteo/temps-reel/troyes-barberey/07168.html , Accessed date: 3 February 2018.
[27] Y. Al Horr, M. Arif, A. Kaushik, A. Mazroei, E. Elsarrag, S. Mishrae, Occupant productivity and indoor environment quality: a case of GSAS, Int. J. S. Built. Environ. 6 (2017) 476–490 https://doi.org/10.1016/j.ijsbe.2017.11.001.
[28] CEN, EN-15251, Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics, (2007) (Brussels).
[29] P.O. Fanger, Thermal Comfort Analysis and Applications in Environmental Engineering, Danish Technical Press, Copenhagen, Denmark, 1970.
[30] ISO, ISO 7730: ergonomics of the thermal environment analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criterin, Management 3 (2005) 605–615.
[31] S.A. Zaki, S.A. Damiati, H.B. Rijal, A. Hagishima, A. Abd Razak, Adaptive thermal comfort in university classrooms in Malaysia and Japan, Build. Env. 122 (2017) 294–306 https://doi.org/10.1016/j.buildenv.2017.06.016.
[32] W. Michael, W. Zuo, T.S. Nouidui, Modeling of heat transfer in rooms in the Modelica buildings library, 12th IBPSA Building Simulation Conference, 2011, pp. 1096–1103.
[33] W. Michael, W. Zuo, T.S. Nouidui, Recent developments of the modelica buildings library for building heating, ventilation and air-conditioning systems, 8th Modelica Conference, vol. 10.
[34] W. Michael, W. Zuo, T.S. Nouidui, X. Pang. Modelica buildings library, J. Build. Perf. Sim. 7 (4) 253–270.
[35] A.A.W. Hawila, A. merabtine, M. Chamkhi, R. Bennacer, N. Troussier, An analysis of the impact of PMV-based thermal comfort control during heating period: a case study of highly glazed room, J. of Build. Eng. 20 (2018) 353–366 https://doi.org/10.1016/j.jobe.2018.08.010.