Thermal, lighting and energy performances of buildings constructed with polycarbonate panels. Case study of a classroom in Madrid.

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Abstract

Transparent plastic envelopes are increasingly used in building construction. This study is focused on the thermal and optical performance of a building envelope of structural multiwall polycarbonate sheets to determine the suitability of this solution. To do so, the extension of a scholar building, with walls and roof entirely made up of polycarbonate panels, has been monitored throughout a two-week period. The experimental results have been compared with those obtained with two energy simulation programs. It is observed that, due to the small thermal inertia of the solution, there is no time lag between indoor and outdoor temperatures and the temperature decrement is usually kept within a 5K range. The experimental tests also show that the building consumption for heating and lighting is, respectively, 66% and 89% lower than the predictions obtained with the simulations. It is concluded that the polycarbonate enclosure presents a good thermal, solar and optical behavior.

Keywords

Energy consumption in buildings, energy efficiency, thermal behavior, building envelopes, Polycarbonate panels.

1. Introduction

Modern architecture is characterized by the loss of materiality and its aspiration to lightness and transparency (Pallasmaa & Fuentes, 2010). By 1922, in its glass skyscraper projects (Stankard, 2002), Mies van der Rohe already anticipated such search for lightness and transparency when he proposed a whole glass façade in a high-rise building.

A well-known built precedent of this search can be found in the Crystal Palace, erected in London to house the Great Exhibition of 1851 (Auerbach, 2017). This building was designed by Joseph Paxton, a greenhouse builder (Benévolo, 1974) who brought the aesthetics of those modest industrial constructions to the dignity of a highly representative building. This use of glass has been nowadays fully extended by means of the curtain wall systems, currently adopted by all office buildings.

Environmental concerns have been an integral part of his design from the very beginning (Schoenefeldt, 2008), due to the obvious difficulty to simultaneously achieve transparency and thermal comfort in glass covered buildings.

From the mid-nineteenth century on, technical advances in the glass industry enabled the manufacture of larger pieces, with better mechanical attributes at more competitive prices, allowing the massive incorporation of glass in the construction sector (Boutet & Jacobo, 2005).

Non-residential buildings have large window surfaces in order to provide physical and visual connection to the outside. The glazing systems also allow the solar radiation getting into the buildings, affecting the heating demand and the indoor thermal comfort as well

(Buratti, Moretti, Belloni, & Cotana, 2013). The thermal and solar transmittance, the visible light transparency, the size and the orientation of transparent elements deeply influence energy use in buildings (Oral, Yener, & Bayazit, 2004).

A great design effort is being made to assure low thermal transmittance of the glazing and frame elements. However, these improvements imply a significant rise in the building fenestration (Jelle, et al., 2012).

To achieve transparent envelopes in highly glazed buildings, various technologies are being investigated, such as: multi-layer glazing, double-vacuum glazing, double glazing filled with inert gas or transparent insulation materials like silica aerogel, photovoltaic glazing, airflow window, water-flow window, reflective glazing, angular selective transmittance coatings, chromic technologies, low emissivity coatings and spectrally selective coatings (Ye, Meng, Long, & Xu, 2013).

On the other hand, from the middle of the 20th century the use of plastic in construction begins to be available (García & Díaz, 2005). In a pioneering effort to translate these new materials to architectural language, Peter Cook proposed in 1964 the Plug-in City project, in which plastic capsules were inserted in a mega-structure to constitute a modular and expandable city (Agudo-Martínez, 2013).

Once again, in the search for transparency, the aesthetics of the greenhouse is used when dealing with a new construction material. Thus, in 2005, Lacaton and Vassal built a 14 social housing building in Mulhouse in which spaciousness is achieved by incorporating polycarbonate greenhouses, conceived as "winter gardens", attached to the houses (Ruault & Mimbrero, 2005). Undoubtedly, the use of plastic not only offers lightness and luminosity at a reduced cost, but also opens up an infinite and fascinating range of aesthetic and constructive possibilities (Quinton, 2010).

Plastic-based transparent insulating innovative systems could also be used in order to obtain both transparency to visible light and thermal insulation. Nevertheless, they are generally too expensive. Moreover, cheaper plastic materials such as polycarbonate sheets and panels (Smith, 2004) are the best options to be considered. It is mainly due to the fact that the thermal conductivity of polycarbonate is 9% better than polyethylene and 5% better than PVC (Rasheed, Lee, & Lee, 2017).

Polycarbonate (PC) multiwall panels stand out among other plastic products for building applications because of their low weight, durability and high fire, weather, and UV resistance. They are also unbreakable. One of their best characteristics is the high impact resistance, which can be more than 200 times greater than tempered glass (Moretti, E, Zinzi, M., Carnielo, E., & Merli, F., 2017). They also provide a wide range of applications for fenestration systems, continuous windows, shed roofs and walls by employing products with different geometric structure characteristics, colours and thicknesses (Moretti, Zinzi, Merli, & Buratti, 2018).

PC multiwall panels have a good thermal and optical performance. With lower costs and easier installation, they are the most widespread solution in place of standard window systems (Alonso, Bedoya, Lauret, & Alonso, 2013). They have the additional advantage of providing diffused light which avoids glare problems and improves visual comfort (Moretti, Zinzi, & Belloni, Polycarbonate panels for buildings: Experimental investigation of thermal and optical performance, 2014). All these aspects are of the utmost importance for the sake of the users' health and energy conservation (Oral, Yener, & Bayazit, 2004).

In short, a dichotomy is raised between letting natural light into the buildings and at the same time being protected from harsh weather in the form of rain, wind, sun and ambient temperature (Jelle, B. P., 2013). Building fenestration is a key element to provide different and sometimes contradictory, requirements: heat flow control, protection from solar radiation and adequate level of natural light (Cellai, Carletti, Sciurpi, & Secchi, 2014).

Thus, to reduce the building's energy consumption, it is important to understand the thermal and optical performance of the glazing materials (Al-Mahdouri, Baneshi, Gonome, Okajima, & Maruyama, 2013). In terms of the visible light transmission, polycarbonate performs similarly to plain glass. It reaches its maximum level of transmission for visible light, is impervious to ultraviolet radiation, permeable to the near part of the infrared spectrum and opaque to long infrared radiation (Pizarro, 2002). This implies that its contribution to greenhouse effect is similar to that of glass.

The main objective of this paper is to assess the behaviour of polycarbonate as an envelope of a university classroom in terms of indoor temperature, relative humidity, illuminance and energy consumption. Since the classroom is used during the months of September to December and from February to May, special emphasis is placed on winter conditions.

It is a material with little thermal inertia so it can be affected by variations in outside temperature and humidity. In addition, due to its transparency, the reduction of indoor lighting needs and thermal gains due to solar radiation are expected.

Given these characteristics of the material used in the envelope, it is intended to evaluate for a university classroom with sporadic use mainly in winter its suitability in terms of energy consumption that is needed to maintain adequate indoor temperature, relative humidity, illuminance conditions while it is being using.

2. Methodology

2.1. Case study

As a case study to analyse the performance of polycarbonate panels, the Atlantic Copper classroom of the Technical School of Mining and Energy Engineers in Madrid has been chosen. It was designed by the architectural firm g+f Architects and was built in 2013. It has a rectangular shape plan with a floor area of 89 m^2, and a useful floor space of 82 m^2. The polycarbonate thermal envelope is composed by a pitched roof, two long vertical walls oriented east and west and a third wall facing north. The fourth side of the rectangle connects the class with the building from which it has the access.

The classroom is located in the second floor of the building. As figure 1 show, it is surrounded on either east and west sides by two near buildings that exceed in 10 meters the height of the classroom. It significantly reduces its access to solar radiation during great part of the day.

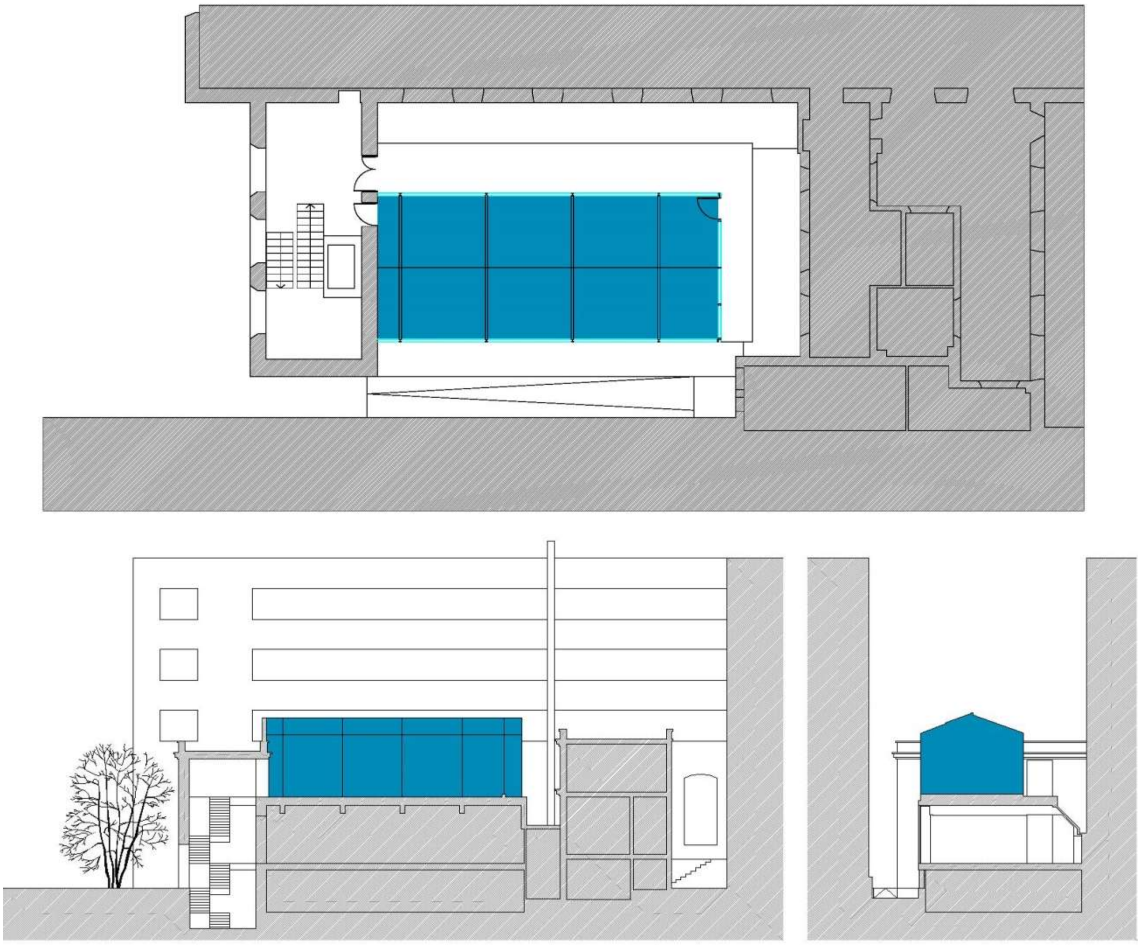

Figure 1. Atlantic Copper classroom. a) Floor plan; b) East and North elevations.

As it has been said, the entire envelope is solved with polycarbonate. The walls are formed by a sandwich of two structural multiwall polycarbonate sheets, 10 mm thick each, and a 100 mm air chamber. The tilted surfaces of the roof are translucent structural multiwall polycarbonate sheets 55 mm thick.

As long as the walls are naturally sheltered by nearby buildings, the roof is the only element to be protected from excessive solar gains through the transparent and translucent surfaces. This is solved by means of a retractable polyester thermal screen, which is kept open when the weather conditions are favourable, and closes in case solar protection is needed. It moves, operated by an electric motor, on the horizontal plane limited by the lower side of the structural triangular trusses that support the roof. Lighting fixtures and HVAC ducts are placed in the triangular space between the panels of the roof and the thermal screen.

Finally, in order to adequately ventilate the room and to expel the warm air accumulated in the upper part of the space, one of the panels of the roof is hinged at the ridge of the roof so it can be folded open to the outside, allowing the flow of hot air, if necessary.

The position and configuration of all the aforementioned elements of the envelope are shown in figure 2.

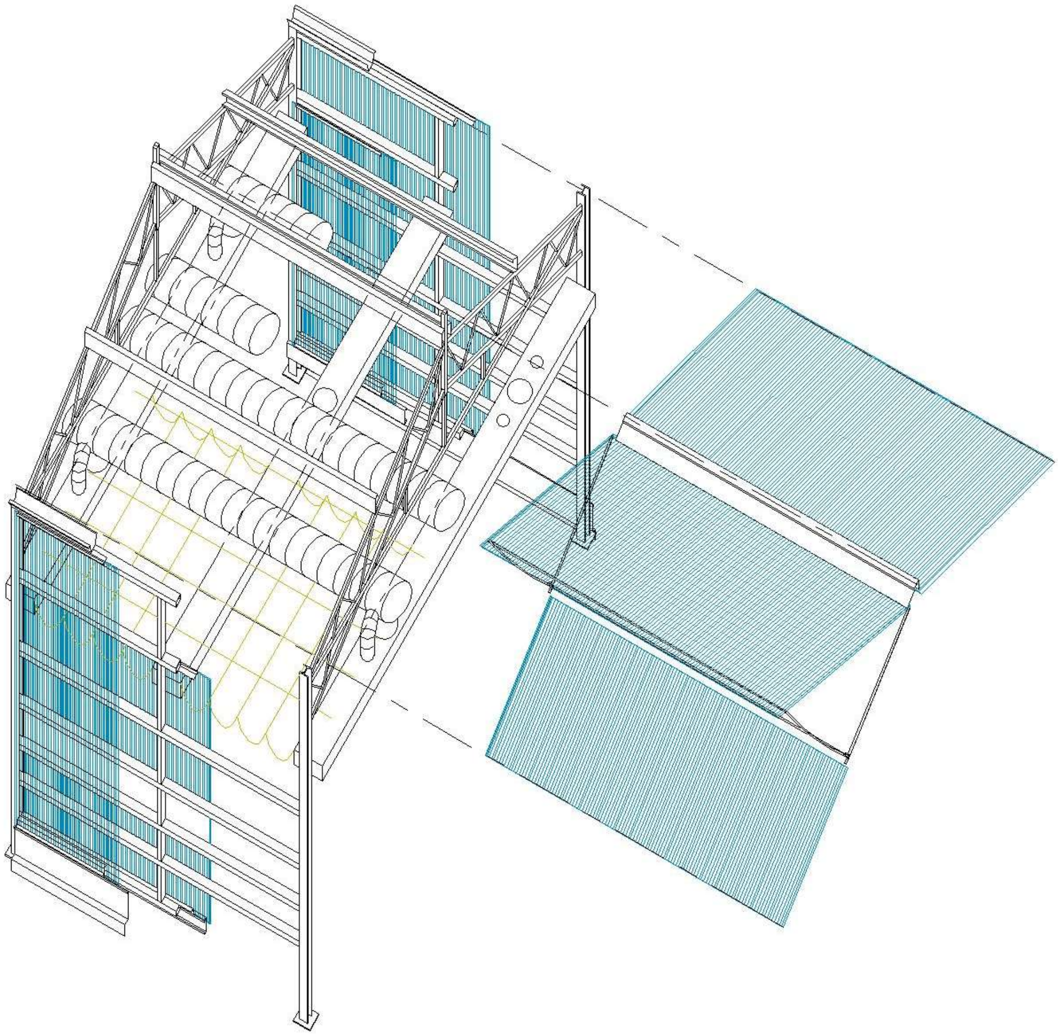

Figure 2. Atlantic Copper classroom. Axonometric.

In terms of energy flows, glazing can be characterized by two parameters: Firstly, the total solar energy transmittance, g, which denotes the percentage of the incoming solar energy that is eventually converted into heat in the indoor space. Secondly, the thermal transmittance, U, that represents how much heat is transferred through the glazing per square meter and Kelvin temperature difference between the interior and exterior ambient (Manz & Menti, 2012). U-values are used to describe the thermal performance of construction elements, and subsequently, the overall energy performance of buildings (Rezvani & Bribián, 2019).

Table 1 shows how the elements that constitute the thermal envelope are characterized in terms of the aforementioned parameters, g and U. All data are supplied by manufacturers.

Table 1. Building envelope elements characterization.

Building envelope	**Thermal transmittance U (W/m^2K)**	**Solar energy transmittance g**
Clear structural multiwall PC sheet 10 mm thick	2.48	0.65

Translucent structural multiwall PC sheet 55 mm thick	0.90	0.30
Polyester thermal screen	N.D.	0.69

The two structural multiwall PC sheet types used are Lexan Thermoclear LT2UV105R175 clear 10 mm thick and LT2UV55S Opal Solar 55 mm thick. The Svensson TEMPA 6562 D FB thermal screen is composed of 55% polyester and 45% aluminium in strips, as is shown in figure 3.

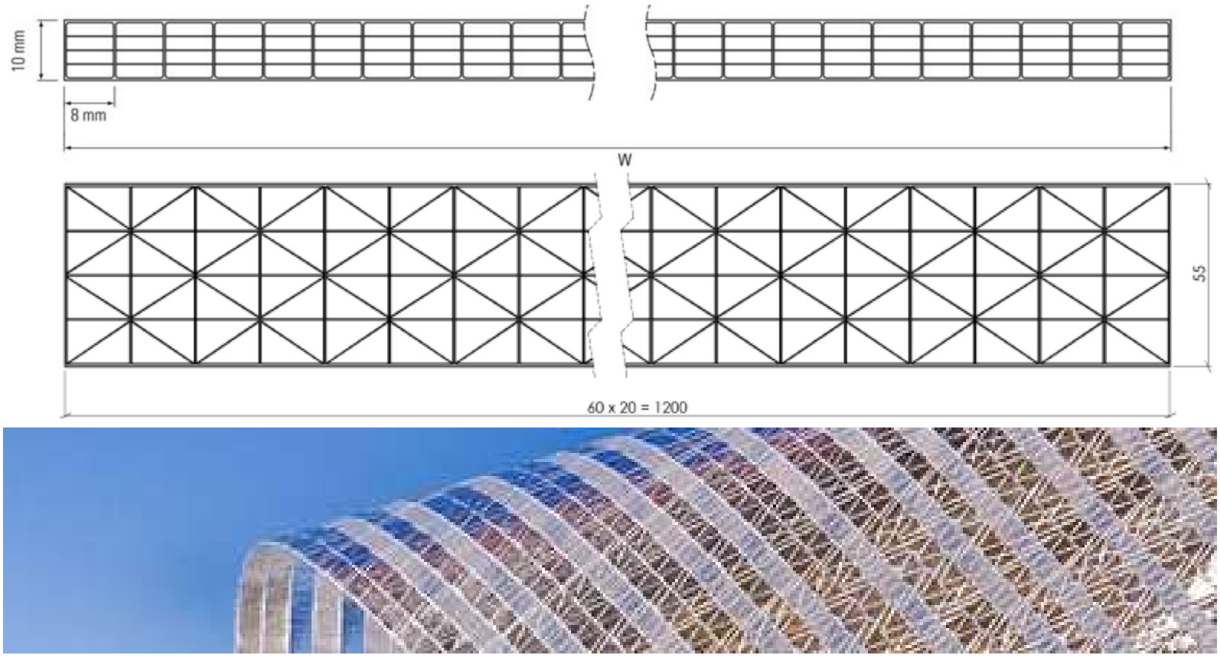

Figure 3. a) Cross sections of multiwall PC sheets; b) Picture of ther-mal screen (Lexan* Thermoclear*, 2019), (Lexan* Thermoclear*, 2019), (Svensson, 2019).

The Atlantic Copper classroom seeks to generate a feeling of lightness and luminosity by means of the use of PC in its entire envelope. The low cost of the material and its ease of assembly has made possible to feel the sensation of connection with the outside at a moderate price. Using glass instead would have been economically unfeasible. The indoor ambient thus generated brings us back to the aesthetics of the greenhouse, as can be observed in figure 4.

Figure 4. Atlantic Copper classroom. Interior view.

The HVAC for the classroom is provided by a Carrier 50PZ (40PZ / 38PZ) – 045 air to air heat pump, whose technical characteristics (Carrier, 2011) are shown in table 2.

Table 2. Heat pump characteristics

	Cooling	**Heating**
Capacity (kW)	43.60	50.18
Energy input required (kW)	21.6	20.8
Coefficient of performance (COP)	-	2.41
Energy efficiency ratio (EER)	2.02	-
Energy rating	G	F

The classroom lighting is provided by a set of 12 fluorescent tubes of 58 W and 16 fluorescent tubes of 18 W. It means a total installed specific power of 12 W/m^2.

2.2. Data collection

A two-week data collection has been carried out, from November 26th to December 6th, 2018.

On one hand, the Information and Communication Technolo-gies (ICT) Unit of the Technical School of Mining and Energy Engineers has provided ambient temperature data, which were measured in the roof of the building every 5 minutes. Affordable and easily available measurement instruments like Bosch BME280 sensors (Bosch, 2019) have been used. The information has been collected with a Raspberry Pi controller (Raspberry, 2019).

On the other hand, the Technical School of Computer Science Engineering has been in charge of measuring the classroom temperature, relative humidity and illuminance every 10 minutes. To do so, a Wireless Sensors Network has been used. Some advantages of this type of data collection system are the low cost and energy consumption, and their simple deployment and interoperability. In this case, the system is composed of a set of fleck sensors developed by Humanes (Humanes, 2018) that use Arduino UNO boards (Arduino, 2019) with ATmega328P microprocessor. Due to the multiple input and output pins it is very fast and easy to put them in operation. They use Zigbee technology (Zigbee, 2019) for the wireless communication system.

The sensor in charge of collecting temperature and humidity data is the DHT22. This sensor is capable of collecting temperatures between -40 and 80ºC and relative humidity between 0 and 100%. In addition, the sensor error margins are ±0.5ºC and ±1% humidity.

Six fleck sensors have been deployed in the classroom. Three of them in the eastern wall and the rest in the opposite wall, at 20 cm, 75 cm and 160 cm heights. Figure 5 shows one of these sensors and how they are arranged in the western wall.

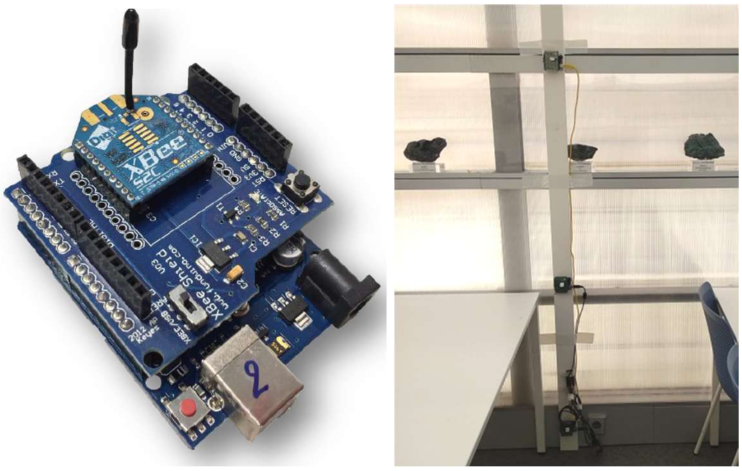

Figure 5. a) Fleck sensor (Raspberry, 2019); b) Sensors positions at different heights.

In addition, thermographic images have been taken with a Testo 870 camera, and CO2 concentration levels have been monitored with a Testo 535 meter.

2.3. Simulation

Prior to simulate the energy performance of the classroom, a calculation of the roof and external walls transmittances is needed. It has been made according to the European (CEN) Thermal Transmittance Calculation Method (EN 16012, 2015), based on the values supplied by manufacturers. The results are shown in table 3.

Table 3. Building envelope thermal characteristics.

Building envelope	Thermal transmittance U (W/m^2K)	Solar energy transmittance g
Walls	0.85	0.42
Roof	0.75	0.21

With these values, simulations of the classroom with two different programs have been carried out. The software used are: Lider-Calener Spanish official unified tool for the demand assessment and energy rating of buildings (HULC) (Ministerio de Fomento, 2017) and 4.6 version of Carrier's Hourly Analysis Program (HAP) (Carrier, 2019). HULC is appropriate for standard energy performance assessments (energy certification), and HAP is appropriate for hourly energy estimations.

The operational variables shown in table 4 have been considered.

Table 4. Variables used in simulation programs.

Variable	**HULC**	**HAP**
Schedule	Monday – Friday: 7:00 – 14:00 Weekend: No operation	Monday – Friday: 7:00 – 14:00 Weekend: No operation
Occupation (number of persons)	50	54
Infiltration (air changes per hour)	0,6	0,5

2.4. Fit of the input data in the simulation

Once the classroom monitoring data are obtained, the HAP program schedule is modified by entering the actual classroom utilization data. A fitted monitoring is carried out with these data. As the HULC software does not offer the possibility of modifying these parameters, the corresponding fitted simulation has not been performed in this case.

Despite calibration is the process of improving the agreement of a code calculation or set of code calculations with respect to a chosen set of benchmarks through the adjustment of parameters implemented in the code (Trucano, Swiler, Igusa, Oberkampf, & Pilch, 2006), it is not possible to modify the climatic data of the simulation programs because these values have not been monitored for a year.

3. Results

The first week (November 26 th to 30th) is a school week and the room is used during the class schedule with the HVAC system running. The following week the room is unoccupied, since it is a holyday week, and the HVAC system is turned off.

In figure 6, it can be observed both indoor and outdoor air temperature evolution during the two-week period.

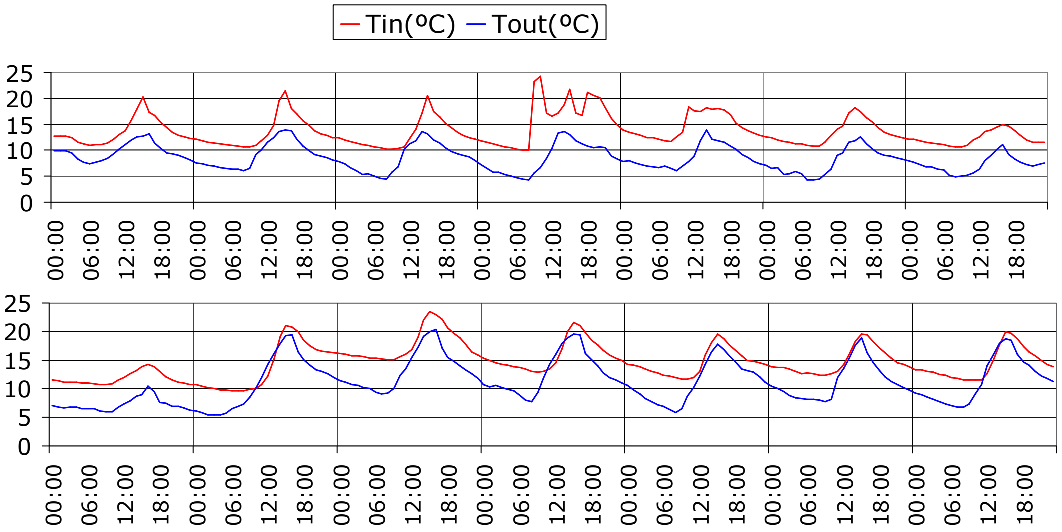

Figure 6. Indoor and outdoor air temperature evolution during school week (above) and holiday week (below).

Additionally, figure 7 shows the room relative humidity evolution for both periods.

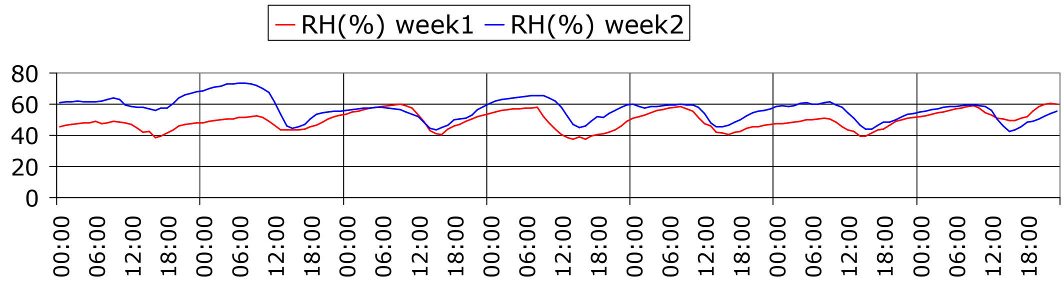

Figure 7. Room relative humidity comparison between school week (1) and holiday week (2).

Finally, in figure 8, the room illuminance evolution during both weeks is also compared.

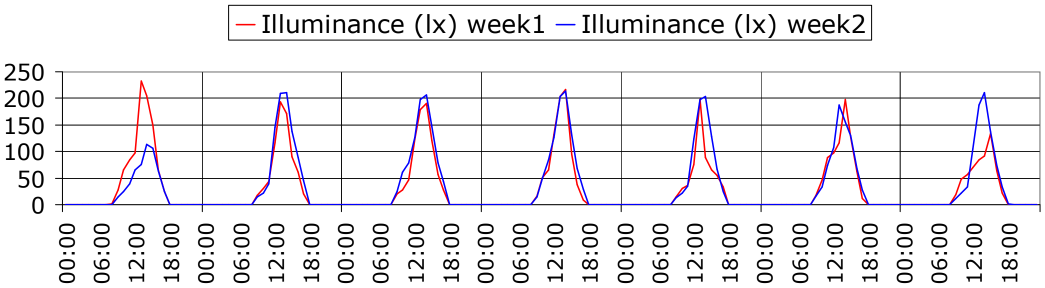

Figure 8. Illuminance measured during school week (1) and holiday week (2).

The thermographic image of figure 9 shows the range of surface temperatures maintained in the inner side of the polycarbonate wall during the experiment. The outdoor temperature is 17ºC and the HVAC is not in operation.

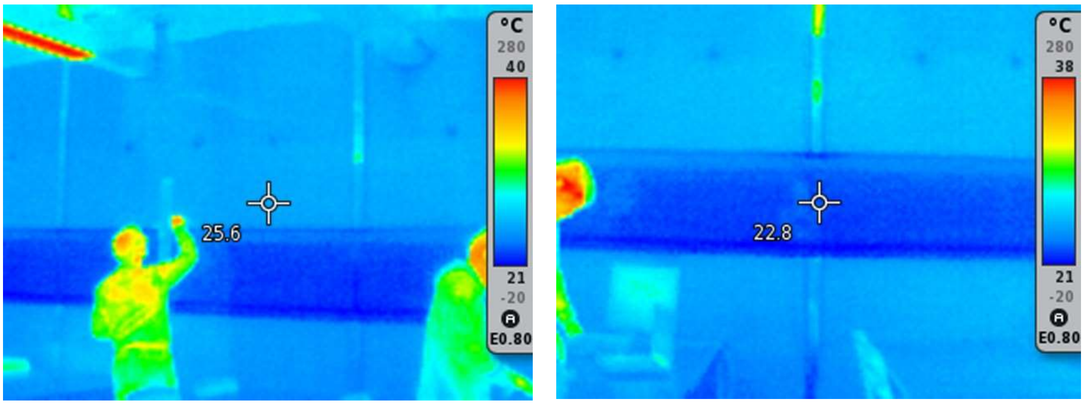

Figure 9. Surface temperature of the interior side of the polycarbonate wall obtained with a TESTO 870 camera.

The CO2 concentration measured in the classroom at the end of a lecture is 1,032 ppm. This value descends to 985 ppm during lunchtime, when the classroom is used as a dining room and the door remains open.

HULC and HAP simulations results of non-renewable primary energy consumed in the all year round operation of the classroom can be observed in table 5.

Table 5. Non-renewable primary energy consumption (kWh/m^2 year)

	HULC	**Energy rating**	**HAP**
Heating	1,015.08	B	1,082.01
Cooling	180.78	E	178.88
Lighting	36.97	C	43.45
Hot water	0	A	0
TOTAL	1,232.83	B	1,304.34

4. Discussion of the results

From the temperature data measured during the holiday week, when the HVAC system does not work, it can be observed that there is no noticeable delay from the time the outside surface temperature changes to the time when the interior surface responds to such change. The absence of delay in the phase of oscillation of ambient temperature is due to the small thermal mass of the polycarbonate enclosure. This feature is beneficial for energy consumption purposes, as lectures are taught at the time of the day when ambient temperature is higher and, therefore, so is the classroom temperature. Under such conditions, the energy need for heating the space to reach comfort conditions is reduced.

For the same week, the figure 10 shows how the amplitude of the interior temperature oscillation (in red) decreases.

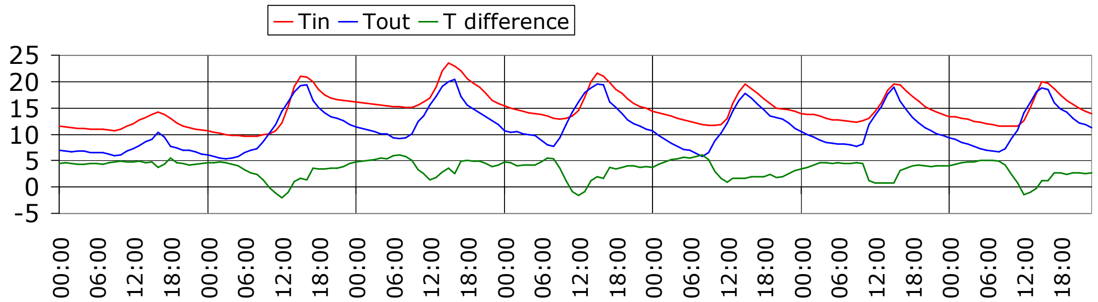

Figure 10. Amplitude attenuation of the temperature oscillation due to the polycarbonate envelope. Measured data during the holiday week.

During the night, from 17:50 to 8:20, temperature difference between indoor and outdoor ambient is almost constant, about 5ºC. On the other hand, in daytime both temperatures increase, and its difference is reduced, having its minimum at noon, within the range of ±1ºC. When outdoor temperature begins to ramp up early in the morning, indoor temperature follows this tendency, but at a lower rate of growth. During this period of temperature rise, it occasionally occurs that outside temperature becomes even higher than classroom temperature. This has happened three times during the week. Nevertheless, when outdoor temperature reaches its maximum, around 15:00, temperature difference is restored to the aforementioned nocturnal values, close to 5ºC.

The effect of attenuation of the interior temperature swing during the night is also beneficial, for it provides, even with little thermal, mass a significant thermal protection of 5ºC when outdoor temperatures are the lowest.

If the phase delay and amplitude attenuation of the temperature oscillation are analysed as a whole, it is observed that the indoor air temperature rises at the same pace that the outdoor temperature. However, there comes a time when it increases much faster, due to the heat captured within the space enclosed by the polycarbonate. Just like glass, polycarbonate is transparent to short wavelength radiation coming from the sun. Once solar rays fall upon the floor, it heats up and emits long wave radiation that is blocked by the polycarbonate, resulting in an overheating of the room by greenhouse effect, as it would have been the case with a glass enclosure. Both temperatures simultaneously reach their maximum values when solar radiation ceases due to the shading effect of nearby buildings.

This greenhouse effect works in favour of the energy balance of the building at the time of the year when it has been monitored. On the contrary, the effect must be dealt with under summer conditions by means of an adequate management of natural ventilation through the roof openings.

Differences between indoor and outdoor temperatures evolution along the two studied weeks are shown in figure 11.

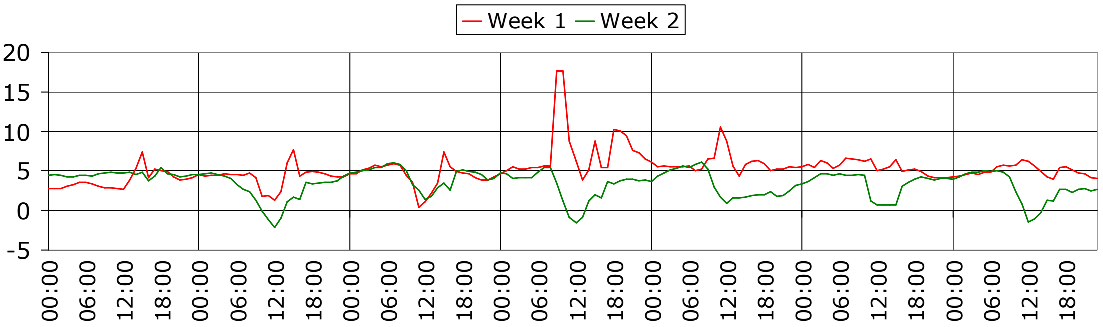

Figure 11. Outdoor-indoor temperature difference evolution for week 1 (with HVAC system on) and week 2 (with no HVAC).

Attention must be paid to the moments of the day when a discrepancy exists between outdoor-indoor temperature differences for both weeks. It reveals that HVAC system has been running for more than two hours on weekdays.

For these specific moments, the data measured in the classroom show that the very first hour of the HVAC system operation, its temperature rises from 15.2ºC to 20.2ºC, but the next hour the rate of increase slightly slows down, for it only reaches 22.0ºC. Once the air conditioning system is turned off temperature drops to 17.5ºC in one hour.

The HVAC system is used 10 hours a week. For the whole year, this means that it runs 300 hours, only a 3% of the annual hours. For such a limited use, a building envelope of small thermal inertia but relatively high amplitude attenuation of the temperature oscillation is a good solution, since no energy is used to heat the wall and an adequate temperature is maintained only while the classroom is being used.

With the obtained data, the annual energy consumption of the air conditioning system is shown in table 6.

Table 6. Energy consumption of the HVAC system throughout the year.

	Energy input required (kW)	Hours / week	Weeks	Energy consumption (kWh)	Energy consumption (kWh/m^2)	% Energy consumption calculated / Energy consumption simulated (average results shown in table 5)
Heating	20.8	10	20	4,160	50.7	5%
Cooling	21.6	10	10	2,160	26.3	15%
Total					77.1	6%

Simulation considers the HVAC system is running 7 hours a weekday for 56 weeks. That is, 1,960 hours, a 22% of the hours in a year.

The classroom is used only a 15% of the time that is set by default in the software used for simulation. Energy consumption in cooling mode responds to such reduction of the time of operation. However, the calculated heating consumption is 66% lower than the result obtained with the simulation. This improvement of the energetic performance of the classroom under real conditions of use, compared to the simulation, is due to the fact that it is mainly used during the periods of time when ambient temperature is higher, taking advantage of the limited thermal inertia of the polycarbonate envelope. The simulation sets by default a HVAC system run time schedule that starts at 7:00, when increasing the indoor temperature to 20ºC would mean a high energy consumption.

Given the significant divergence between the monitoring and the simulation results, the schedule of the HAP simulation has been modified, using instead the hours of system functioning detected in the monitoring process. Thus, a further simulation has been performed. The results obtained with the new simulation are this time much closer to those of the monitoring, as it is shown in table 7.

Table 7. Comparison between the results of the monitoring and the simulation.

	Energy consumption of monitoring (kWh)	Energy consumption of simulation (kWh)	% Energy consumption of simulation / Energy consumption of monitoring
Heating	4,160	4,000	96,2%
Cooling	2,160	2,250	104,2%

The relative humidity is always kept within the range of 40% to 60%, which are considered the usual limits of the comfort zone. Only once, during the holyday week, a value of 75% is reached, without exceeding the 80% established by Givoni (Givoni, 1969) as the maximum upper limit of the comfort zone.

As for the optical performance of the envelope, similar values of illuminance have been registered for both weeks. Only during the cloudy periods, one Monday, when the room was unoccupied, as well as on the second week's Sunday, lower values of illuminance have been measured, which means that artificial light is needed. On average, 18% of the days the sky is covered in Madrid (Agencia Estatal de Meteorología, 2010), which implies that luminaries must be lit during a 18% of the 300 hours of the annual classroom use. This means 54 hour a year of artificial light.

With this assumption, table 8 shows the economic study of the savings in the lighting system when the existing fluorescent tubes are replaced by LED lamps.

Table 8. Economic analysis of the substitution of fluorescent tubes by led lamps.

Lamp type	**Power (W)**	**Units**	**Hours use / year**	**Energy consumption (kWh)**	**Cost of the consumed energy (€)**	**New lamps investment (€)**
Fluorescent tube	58	12	54	37.6	6.77	
Fluorescent tube	18	16	54	15.6	2.81	
TOTAL				53.2	9.58	
LED tube	24	12	54	15.5	2.79	108
LED tube	8	16	54	6.9	1.24	80
TOTAL LED				22.4	4.03	188
Savings				30.8	5.55	
Simple payback period (years)						33.9

The need for artificial light only during cloudy days implies that the energy consumption of the lighting system very small in buildings with polycarbonate walls and roofs. This means that the otherwise energetically efficient measure of replacing the existing fluorescent lamps with LED lamps has a high payback period in this case. However, in the event that the lamps were left unintentionally lit during a weekend, the hour of operation of the lighting system would practically double, so that the payback period would be reduced by half. So, when the service life of an existing fluorescent lamp is close to its end, it is advisable to replace it with more energy efficient devices equipment like LED tubes.

The simulations carried out give as result an energy consumption of the lighting system of 3,300 kWh per year. As the classroom is used only 15% of the schedule set by default in the simulation, the annual energy consumption of the technical system is reduced to 495 kWh. Due to the transparency of the polycarbonate envelope, the actual energy consumption of the lighting system is the 11% of the consumption calculated by the simulation once its operation schedule has been adjusted to the real use of the classroom. This means an energy consumption of 0.65 kWh/(m^2·year). With such performance, the building can be properly included, concerning its lighting system, in the group of nearly zero energy buildings. Furthermore, this is achieved without the necessity to use LED lamps or electronic devices that regulate the luminous flux of the lamps depending on the level of illuminance provided by natural light, which would make the investment more expensive. In addition, key to this achievement are the great optical properties of the polycarbonate concerning the use of natural light.

5. Conclusions

The study carried out has served to characterize the thermal, solar and optical performance of a building refurbishment made of structural multiwall polycarbonate panels.

Regarding its thermal performance, it should be noted that the polycarbonate envelope, due to its small thermal inertia, has no delay effect in the phase of oscillation of ambient temperature. This attribute is beneficial for the classroom it encloses, since the space is mainly used during the time of the day when outdoor temperature is higher, so that the energy needed to heat the indoor ambient is reduced.

It is also observed that, even with so little thermal mass, an effective temperature attenuation of 5ºC is achieved when outdoor temperature is at its lowest. This effect turns out to be also beneficial for the classroom air conditioning requirements.

It is also of great significance the speed of response of the HVAC system to reach comfort conditions. As the envelope has almost no thermal mass, it is not necessary to devote any amount of energy at all to heat up the construction materials of walls and roof.

Regarding the radiative heat exchange performance, the polycarbonate envelope allows the solar radiation to enter the room. As a consequence, indoor temperature increases faster than ambient temperature does, providing a free heating to the space on sunny but cold winter days. On the other hand, the building has the appropriate solar protections to avoid overheating under summer conditions. Two nearby buildings that exceed 10 metres in height the studied building, at 3 and 5 metres of distance, respectively, shelter East and West elevations. The roof has a retractable thermal screen that is unfolded in summer to protect the room from solar rays and is rolled up in winter to collect the energy coming from the sun.

Finally, as for the optical performance of the envelope material, it has been confirmed that, thanks to its transparency, artificial light is only needed on cloudy days.

So, the suitability of this solution is proven because the studied building performs adequately from thermal, solar and optical points of view.

The measured data show a much better performance of the polycarbonate used in the thermal envelope than that obtained by means of the two thermal simulations, once their schedules have been adjusted to the real operation of the building. The classroom actually consumes a 66% less energy in heating mode and a 89% less energy in the lighting system than the expected according to the simulations.

The authors are not able to affirm that these conclusions can be extrapolated to climates and building operation patterns different to those exposed of the paper. It would be necessary to carry out further studies on the subject, that include comprehensive (thermal, lighting, and energetic) analysis of the performance of polycarbonate building envelopes to confirm that the use of such construction material is appropriate in other circumstances than the studied in this paper.

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