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Effects of the type of facade on the energy performance of office buildings representative of the city of Barcelona

C. Planas *, E. Cuerva, P. Alavedra

E.T.S Enginyeria Industrial de Barcelona, Dep. Enginyeria de Projectes i de la Construcció, Universitat Politècnica de Catalunya (UPC), Av. Diagonal, 647 Planta-6, Barcelona 08028 Spain

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ABSTRACT

The aim of this article is to analyze the energy efficiency issues of eight office buildings built in Barcelona. Using computer simulations to compare energy demand and level of indoor natural lighting, it is demonstrated that there are considerable differences in demand – in some cases more than double – depending on the type of facade, and these differences are not directly related to the economic cost of the construction solutions used. In all cases, the cooling demand represents more than 80% of the total climate control demand, and solar radiation is the parameter with the greatest effect. The overall solar factor of the facade stands out as a key variable to control to both reduce the overall energy needs of a building and separate the cooling demand from the orientation of the building. The level of natural lighting is a differentiating element only in cases that had similar thermal energy performance.

1. Introduction

The building envelope is the physical interface between the indoor and outdoor environments of a building, and it is responsible for much of the energy balance that occurs in the building. As a result, the type of construction used in the facade is a key factor in determining the energy performance of a building and therefore its level of sustainability. For example, the extensive use of glass (very common in office buildings of large European and North American cities) directly affects the energy needs of the building and its level of internal thermal comfort ([1;2]). This condition is critical in climates such as the Mediterranean climate that have high solar radiation with moderate temperature winters and warm summers.

Supplying natural light is another key factor in choosing a specific type of facade. The balance between supplying light and reducing energy demand through properly controlling the solar gains is one of the main issues addressed in the scientific literature ([3,4;5]). These studies have concluded that since the energy demand of a space is affected by the internal loads caused by both artificial lighting and the external load of solar radiation, energy demand must be analyzed by accounting for the interaction between natural lighting and the air conditioning system. However, another study concludes that an even broader approach is necessary, in which the air conditioning, ventilation, lighting and acoustics need to be studied together [6].

In addition, numerous studies have been conducted to optimize the thermal design of facades of specific buildings located in different climates (Sweden [7], Brussels [1], Turkey [8] and Malaysia [9]). One of the findings is that it is very important to adapt a design to the climate conditions to ensure reduced energy demand and appropriate internal thermal comfort. This point is particularly relevant in the case of office buildings with glass facades that have greater sensitivity to climate conditions because of increased access of solar radiation compared to other types of facades. Therefore, detailed energy simulations are recommended to thoroughly analyze these cases ([7,10;11]).

The main aim of this article is to analyze the energy efficiency issues of actual buildings constructed by an important architectural firm in Barcelona by using simulation tools. The buildings were selected to analyze the most diverse types of facades possible, of which the materials and construction details data were available, as well as the associated construction costs, to perform comparisons. The comparative analysis allowed for considering the

* Corresponding author.
E-mail addresses: carla.planas@upc.edu (C. Planas), eva.cuerva@upc.edu (E. Cuerva), pere.alavedra@upc.edu (P. Alavedra).

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most appropriate types of construction for each use and location to establish design guidelines to achieve gradual improvement in energy efficiency and to serve as a support tool for future decision making in the planning, design and rehabilitation of facades.

Below are the results of the analysis of the facades of eight buildings representative of the province of Barcelona. For each study module, the energy demand for cooling and heating is examined, as well as the level of indoor natural lighting using the daylight factor. The effects of the four main orientations (north, south, east and west) were considered to analyze the suitability of each type of facade in each specific orientation.

2. Description of the facades studied

This study includes eight facades of administrative use (office) buildings, as shown in Fig. 1. Both the actual pictures of the buildings and the thermal simulation models used for the analysis are shown.

The characteristics of each facade were obtained from the Tribuna de la Construcción journal [12] and data provided by the architectural firm that designed the buildings. The following parameters were used to perform the analysis:

- Area of the openings compared to the total surface area of the façade (%) [1]
- Mass per unit area of the opaque portion of the façade (kg/m^2)
- Time constant *h* (indicative of the thermal inertia of the opaque facade) [2]
- Heat transfer coefficient of the opaque portion *Uo* (W/m^{2}K)
- Heat transfer coefficient of the glass *Uv* (W/m^{2}K)
- Heat transfer coefficient of the frame *Um* (W/m^{2}K)
- Heat transfer coefficient of the opening *Uh* (W/m^{2}K)
- Overall heat transfer coefficient of the facade *Ug* (W/m^{2}K)
- Solar factor (FS) of the glass *FS* (%)
- Overall solar factor of the facade *FSg* (%)
- Solar shields used

To obtain overall energy factors to facilitate comparisons between the different cases, an overall heat transfer factor (*Ug*) and overall solar factor (*FSg*) of the entire facade were calculated. For the calculation of *Ug*, the *U* of the opaque portion of the facade and the *U* of the openings (glass and frame) were considered and weighted according to their respective surface areas. For the calculation of *FSg*, the solar factor of the glass, the glass percentage of the opening, the surface area of the openings in the facade and the presence or lack of obstacles (setbacks, overhangs, etc.) were used. Thus, the *FSg* represents the ratio of solar radiation at a normal incidence angle that enters the building through the opening to the radiation that would enter if the opening had a perfectly clear glass without obstacles for 100% of the facade.

Table 1 shows the description and values of the influence parameters of each facade analyzed:

Fig. 1. Facades of the studied buildings. Real pictures and thermal models.

3. Methodology

The methodology for the study consists of performing a thermal energy and lighting analysis of the different facades by modeling them in *Tas Engineering* software, whose potential and capabilities are clear in numerous studies and is a favorite among specialists ([13;14]). *Tas Engineering* has been used, for example, to analyze the energy performance of office buildings in relation to their shape, proportion of glazed area, insulation and degree of ventilation [1]. It has also been used for analyzing the sensitivity of factors that may affect the overheating of different types of residential buildings ([15;16]) or for evaluating and optimizing the energy performance of existing buildings through simulations calibrated with experimental data [17].

[1] Is included the surface of the glass and the surface of the frame.

[2] Time (h) required by a construction solution to restore thermal balance after a sudden temperature change in any of its surfaces.

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Table 1
Parameters of the thermal energy and lighting analysis of the facades analyzed.

FAÇADE	Description	Year of construction or rehabilitation	Area of Openings (%)	Mass per unit area (kg/m^2)	Time constant (h)	U of opaque portion (W/m^{2}K)	U of glass (W/m^{2}K)	U of frame (W/m^{2}K)	U of opening (W/m^{2}K)	U of overall facade (W/m^{2}K)	FS of glass (%)	FS of overall facade (%)
Case A	Glass facade composed of double pane glass with a solar protection system made up of long, one meter deep balconies and slidable sunshades composed of 50% open area and 50% Corten steel sheets. The doors accessible from the facade are made of solid pine and thermally insulated with shaped polyurethane foam board	2008	64,1%	67.42	1.8	0.82	1.7	2.2	1.77	1.33	40.0%	14.6%
Case B	The facade of the building comprises a double glass curtain wall and extruded aluminum profiles without a thermal bridge break. It is protected by eaves made of translucent colored polyvinyl butyral laminated glass supported by stainless steel straps and anchorages	2002	87.3%	27.00	0.0	3.11	2.8	5.7	2.90	2.96	72.0%	52.9%
Case C	The facade of the buildings is based on the systematic repetition of identical window openings. It is made with mass-colored concrete with type II mineral wool thermal insulation. The glass is double pane glass with a solar control and low emissivity. The framework is made of extruded aluminum without a thermal bridge break and with a natural anodized finish	2009	37.9%	604.00	7.4	0.42	1.4	5.7	1.88	1.15	35.0%	8.3%
Case D	The facade has glazed elements with lintels alternating with opaque panels. The opaque portion is composed of perforated brick with sprayed polyurethane foam (type II) thermal insulation and mass-colored Glass Reinforced Concrete (*GRC*) cladding. The glazing is made of double pane glass with reinforced thermal and acoustic insulation, and the framework is a fixed frame profile aluminum frame with a thermal bridge break	2008	25.9%	239.75	23.1	0.32	2.7	4.0	2.80	1.00	64.0%	13.1%
Case E	The building has a double facade: the framework, located on the inner side, is anchored from floor to ceiling, allowing the cantilevered slab to be used for attaching the second skin to the framework edge. The glass is double pane glass with low emissivity and solar control through colorless polyvinyl butyral, while the framework is made of extruded aluminum without a thermal bridge break. The facade is protected by an outer stainless steel mesh, which ensures a shading coefficient of 50%, and a 0.8 m perimeter eave	2006	81.7%	27.00	0.0	0.86	1.7	5.7	2.36	2.09	52.0%	17.0%
Case F	The facade is made of hollow brick thermally insulated with shaped polyurethane foam (type II) and covered with thermally hardened resin boards. The windows have double pane glass and the framework is formed by galvanized and thermolacquered steel profiles with a thermal bridge break	2009	60.8%	172.25	4.4	0.52	1.6	3.0	1.82	1.61	38.0%	16.0%
Case G	The building has a reinforced concrete facade with type I mineral wool thermal insulation and corrugated aluminum sheet cladding. The windows have low emission double pane glazed glass and a framework of extruded aluminum with a thermal bridge break. The facade is protected by partially screen-printed laminated glass louvers with different inclination angles (20–76°)	2005	33.6%	965.15	19.7	0.36	1.5	4.0	1.77	0.88	62.0%	14.0%
Case H	The building has a facade composed of a double pane glass curtain wall with a low emissivity treatment and solar control (using colorless polyvinyl butyral). The framework is made of galvanized steel and powder coated without a thermal bridge break. Additionally, the facade has a perimeter overhang of 1.2 m	2007	97.9%	134.25	0.0	0.56	1.6	4.2	1.81	1.70	40.0%	31.0%

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3.1. Modeling phases

To determine the energy demand and daylight factor associated with the modeled indoor space, in the first phase, it is necessary to create geometric models that reproduce the architectural features of each facade. In the second phase, the rest of the parameters necessary to perform the simulation of the system are defined: the construction solutions are generated; the profiles of occupancy, lighting, electrical equipment and infiltrations are assigned to each of the defined zones; the temperature and humidity environmental conditions to maintain are assigned; and, finally, a database is developed using hourly climate values for the selected location, which defines the conditions outside the building including temperature, humidity, solar radiation, wind speed and wind direction.

To simulate the daylight factor, the *Split-Flux* method proposed by the *Building Research Establishment* (BRE) was used [18], which is an effective and recognized technique for calculating the daylight factor. The method is based on the calculation of the three components of natural light that are independent of each other and reach every point inside a building: the sky component, externally reflected component and internally reflected component; the sum of these components is the daylight factor (expressed as a percentage). The values of this factor are calculated using a lighting distribution that corresponds to a standardized overcast sky (*CIE Standard General Sky*). The results are for the worst possible case and because the sky model only varies with altitude, the results do not change for different times of day or for different days, and they do not change with the orientation of the building. Because this method is a simplified method, this lighting analysis has been used mainly to discriminate between cases where facades have similar thermal energy performance. Finally, the thermal energy performance is addressed in more detail by calculating the solar gain of the spaces analyzed; the calculation takes into account the influence of factors such as solar shields, orientation and time of day.

3.2. Definition of the models

A model was created for each facade studied using the construction and geometric parameters provided by the architectural firm that designed the buildings. To be able to compare the different models, it was necessary in some cases to modify only the shape and dimensions the simulated facade module. In addition, because the intent was to only assess the effect of each facade on the energy demand of the interior space, a model with three floors and six rooms per floor was created. Only the area of the intermediate floor that is completely surrounded by conditioned spaces is analyzed, i.e., the analysis module. This eliminates variables such as energy gains and losses through floors in contact with the ground and roofs in contact with the external environment and focuses the study on the impact of the facade on energy efficiency.

In addition, an exhaustive review of the existing literature in the field of energy simulations of office buildings was performed to determine if the dimensions chosen for the analysis module were adequate. In some of the most important references in this field ([2;19]), the model used, which was proposed by the International Energy Agency for medium size offices [20], has dimensions very similar to those of the analysis module, although it has been necessary to make minor changes to adapt the modules to the facades of this study. The analysis module has a space that has a depth of 4 m, a height of 3.5 m between slabs (free height of 2.8 m) and a facade length that varies between 3.6 and 4 m, depending on the module application in each of the cases analyzed. The priority of the developed model was simplicity to obtain results that were easily attributable to the elements analyzed and not to the particular configuration of the building.

Finally, analysis of the four main orientations (north, south, east and west) was considered for the studied modules to verify the suitability of each facade type for each possible orientation.

3.3. Indoor environmental parameters

The operational conditions and internal stresses of the area studied depend on the specific use of the building. In this case, the characteristic values of a conventional administrative building, with high internal load, were used. Thus, numerous national regulations, such as the Regulation on Thermal Installations in Buildings (RITE) [21] and the Technical Building Code (CTE) [22], as well as international standards such as ASHRAE [23] were reviewed to define the internal loads. In cases where the regulations diverged, the average value of the actual internal loads of the buildings in question was applied.

Regarding the flow of outside air for ventilation, the requirements of indoor air quality established in RITE [21] for office buildings were used. With regard to infiltrations, because these depend on many factors such as wind speed, which affects the overpressure or vacuum created in different facades, urban environment, building geometry, size and position and air permeability of the slits and orifices where air enters, it was convenient to establish an average value proposed by ASHRAE [23] for non-residential buildings.

The values of the indoor parameters applied in the model are:

- Internal loads:

Occupancy density	10 m^2/pers
Sensitive Load Occupation	70 W/pers
Latent Load Occupation	45 W/pers
Electrical power installed in lighting	15 W/m^2
Electrical power installed in electrical equipment	10 W/m^2
Ventilation air	12, 5 l/(s·pers)
Infiltrations	0, 5 rph

- Indoor environmental conditions: the temperature set point for cooling is 25 °C, and for heating, it is 21 °C, with 40–60% relative humidity.
- Hours of occupancy and air conditioning operation: Monday through Friday from 8 am to 8 pm.

The ventilation air is supplied to the inside in a controlled manner using a mechanical system that ensures indoor air quality requirements during the hours of occupancy. When this air supply is activated, it is assumed that the flow of air blown out compensates infiltrations, and therefore, during the hours of occupancy and operation of the air conditioning system, infiltrations are considered to be zero.

3.4. Outdoor environmental parameters

Because the buildings are at the same location and same altitude, the climatic basis used for all the simulations corresponds to a typical year for the city of Barcelona, which was obtained from

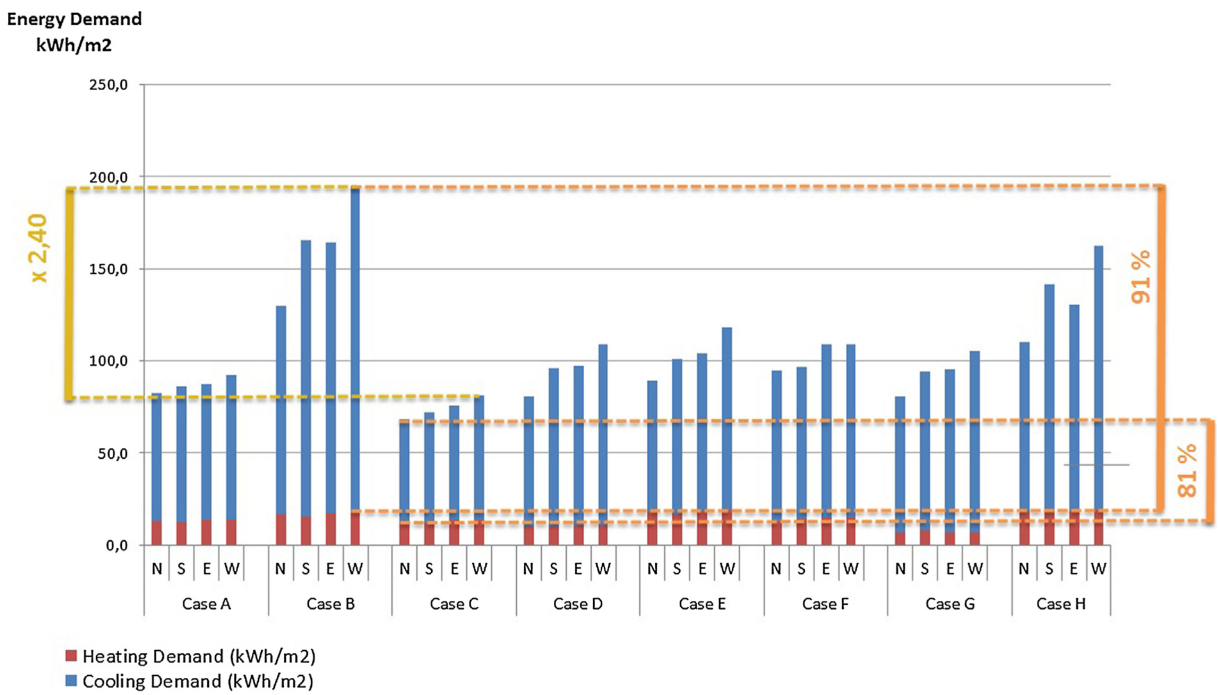

Fig. 2. Energy demand in kWh/m² for air conditioning of the buildings analyzed.

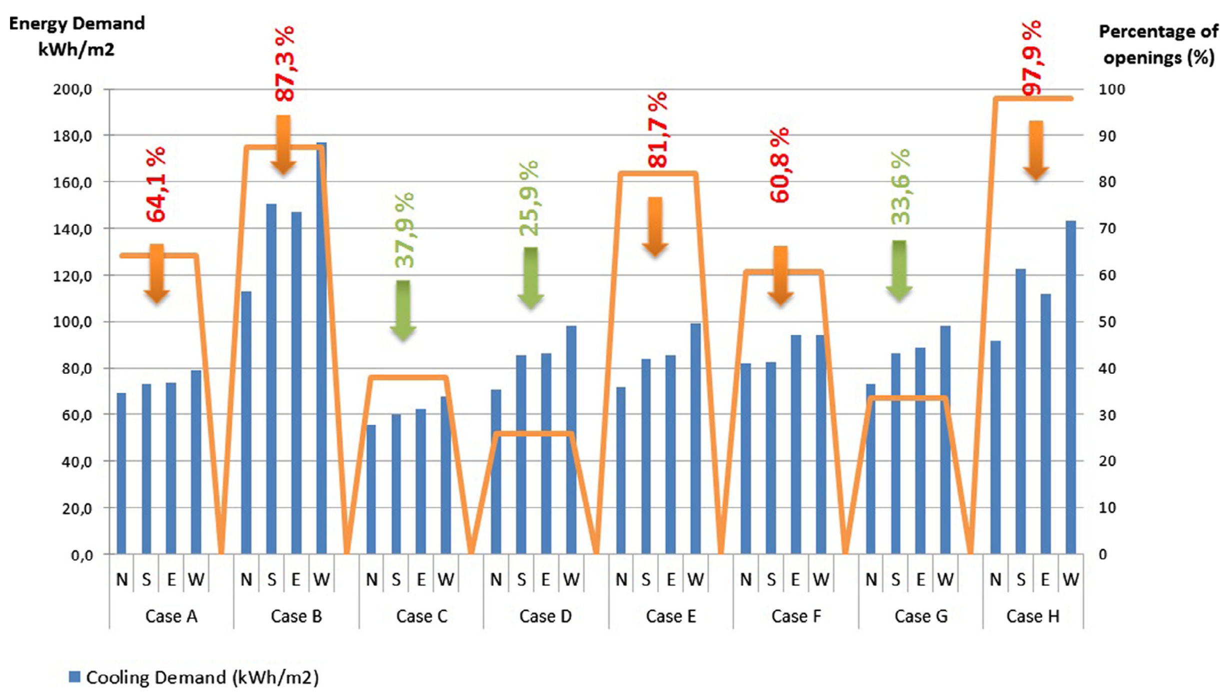

Fig. 3. Cooling energy demand in kWh/m² for the buildings analyzed. Comparison is based on the percentage of openings (axis on the right).

the METEONORM software (*Global Meteorological Database for Solar Energy and Applied Meteorology)*.

4. Results and discussion

Below are the results obtained for the buildings studied in regards to cooling demand (in blue[3] in Figs. 2, 3, 4 and 6) and heating demand (in red in Figs. 2, 5 and 6), as well as daylight factor (Fig. 7) and solar gain (Fig. 8) for the different buildings. A comparison between the different facade types was done. The effect of each of basic parameters of the facades on the thermal energy and lighting performance of the simulated models was examined separately.

4.1. General analysis of the air conditioning demand of the buildings analyzed

The first thing that can be seen is that for the same use (office) and orientation of the building, the type of facade used can make a significant difference in the energy demand for air conditioning

[3] For interpretation of color in Figs. 2.3.4 and 6, the reader is referred to the web version of this article.

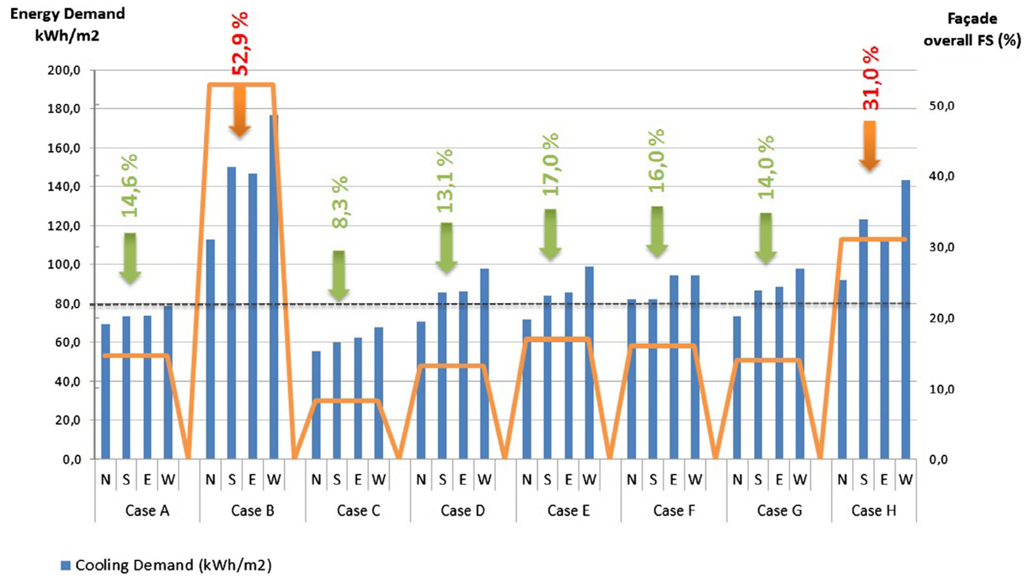

Fig. 4. Cooling energy demand in kWh/m^2 for the buildings analyzed. Comparison is based on to the overall solar factor of the facade (axis on the right).

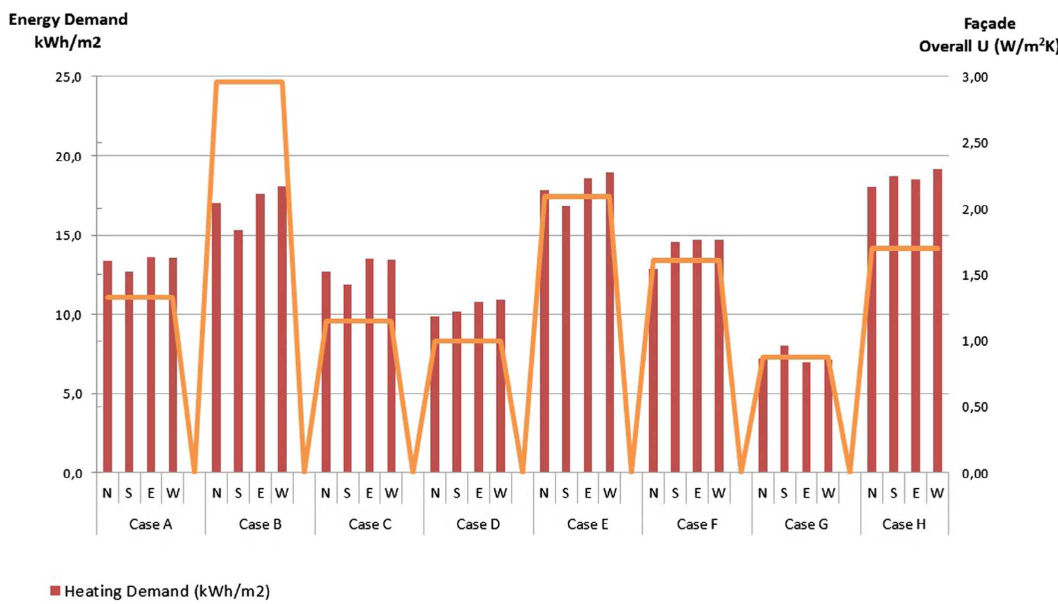

Fig. 5. Heating energy demand in kWh/m^2 of the buildings analyzed. Comparison is based on the thermal transmittance of the facade (axis on the right).

of the building. Depending on the case, this difference can be more than twice as high. For example, for Case B, the demand of the west facade is 2.4 times higher than the west facade of Case C; this difference is directly attributable to the type of construction used (Fig. 2).

Additionally, it can be seen in all the analyzed cases that the cooling demand dominates (Fig. 2), representing between 81% and 91% of the total climate control demand. This result is consistent with those obtained in several previous studies ([1,2,6,24]), which indicate that in buildings used for retail and, in particular, for offices located in Mediterranean climate areas, the energy demand for cooling prevails. This result is mainly because of the presence of a large number of equipment that generates heat and the high typical occupancy of these types of buildings. These factors result in some very high internal loads that are constant throughout the year, which combined with high incident solar radiation, result in a significant need to dissipate heat toward the outside of the building.

4.2. Facade parameters that affect cooling demand

The simulations indicate that the cooling demand of the building depends directly on the percentage of openings of the facade and, consequently, on its level of solar control, as Fig. 3 shows, in which the percentage of openings of each facade is indicated, and Fig. 4, in which the overall solar factors are indicated.

There are cases (for example Case A or Case E) where the percentage of openings and *FSg* are substantially different because solar shielding elements, such as overhangs or louvers, in the facade reduce this factor, and consequently, the cooling demand decreases to a value smaller than expected based on the percentage of openings of the facade. The conclusion is the determining parameter that affects the level of cooling demand of the building is the *FSg* of the facade; therefore, there can be facades with a high percentage of openings that do not have increased cooling demand.

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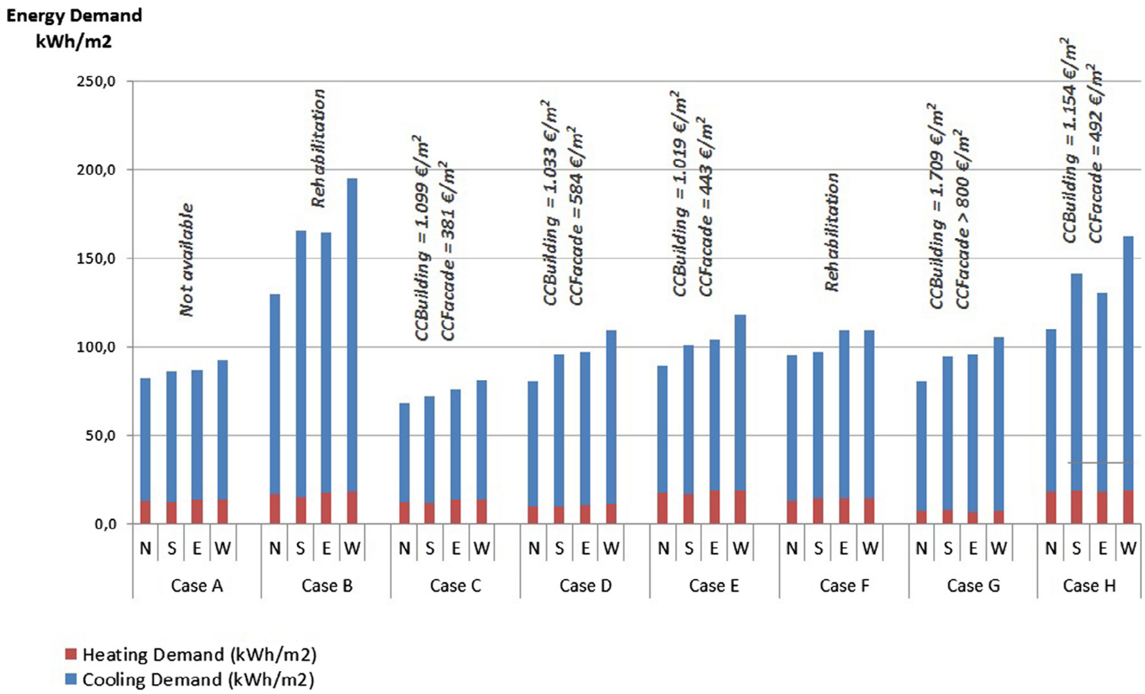

Fig. 6. Air conditioning energy demand in kWh/m^{2}for the buildings analyzed. Comparison is based on the orientation of the facade and construction costs (CC).

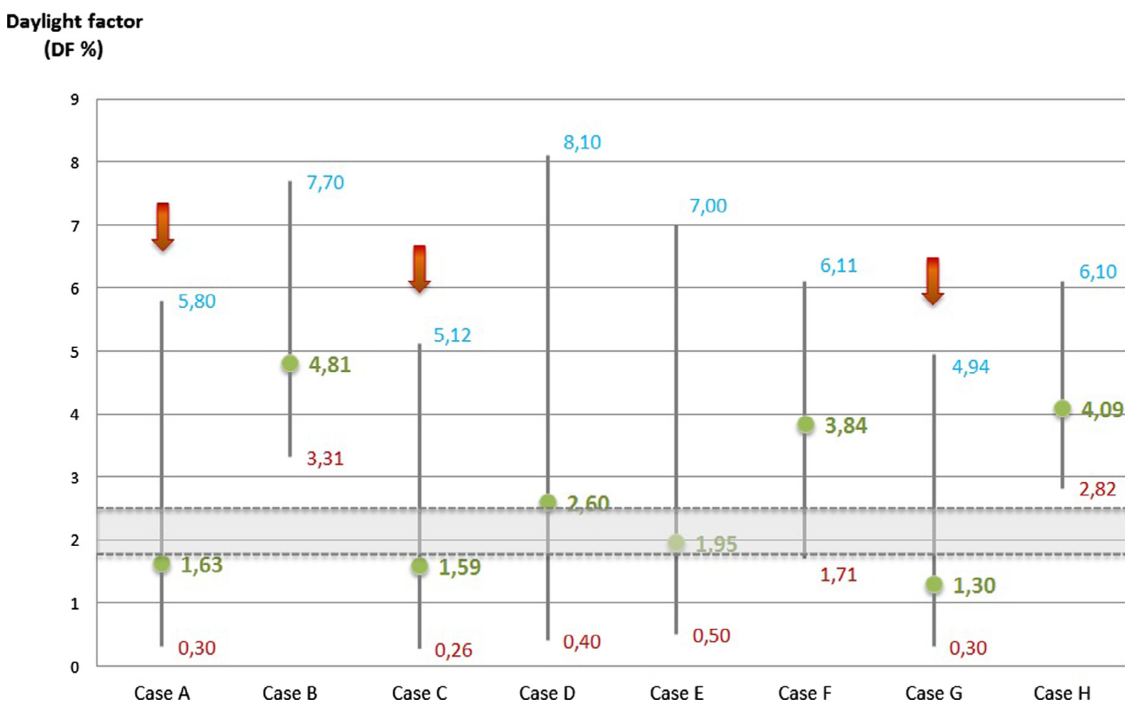

Fig. 7. Level of natural lighting inside the buildings analyzed: average (green), maximum (blue) and minimum (red) Daylight Factors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In addition, the simulations also indicate that, in general, a larger *FSg* results in a greater difference between the four orientations, especially for cooling demand. For example, in Case C, which has the facade with the lowest *FSg* (8.3%), the cooling demand varies relatively little with the orientation of the model (the maximum difference is 12.3 kWh/m^2, 18% variation). In contrast, in cases with high *FSg*, such as Case B and Case H, these differences are far more evident. In case B, the facade with the highest *FSg* (52.9%), the cooling demands for the north orientation is approximately 60% of the west orientation, which represents an 82.1 kWh/m^2 difference.

4.3. Facade parameters that affect heating demand

The results indicate that the heating demand of the building depends largely on the degree of thermal insulation *U* (W/m^{2}K) of the facade (Fig. 5), although other factors may also have a large impact, such as the level of direct solar gain, which is directly

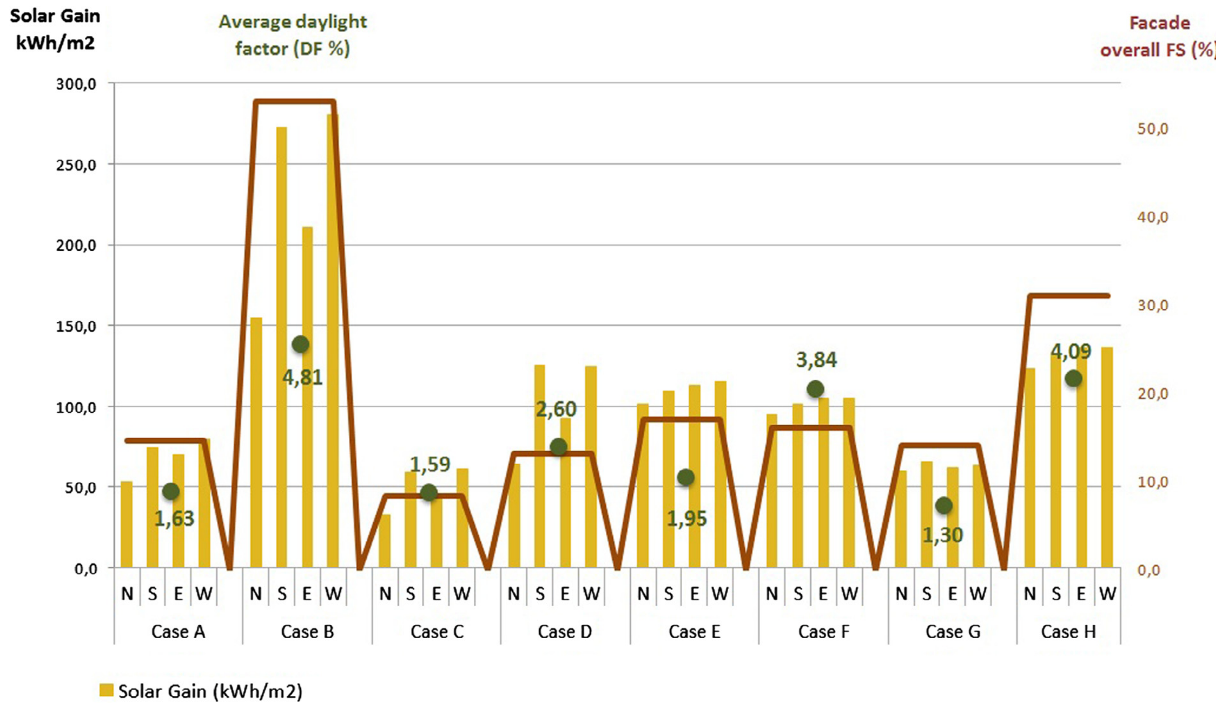

Fig. 8. Solar gain in kWh/m^2 inside the buildings analyzed. Comparison is based on the FSg of the facade (axis on the right) and the average daylight factor (green dots).

related to the percentage of openings of the facade, or the thermal inertia of the walls. Therefore, in the analysis of the parameters that affect heating demand, it is necessary to take into account all the factors that cause heat gains and losses.

Greater thermal insulation and inertia result in fewer losses, and therefore, leads to lower heating demand. Case D and Case G are examples of this because these cases have a high level of overall facade insulation (*Ug* is 1.00 and 0.88 W/m^{2}K, respectively) and have greater thermal inertia (time constant *h* is 23.1 and 19.7, respectively) because the opaque portion of the facade, which represents a significant percentage of the overall facade since, in both cases, the facades do not having many openings, is composed of heavy materials (mainly concrete).

In addition, the great importance of solar radiation in providing thermal gains and offsetting some of the energy losses that occur through the facade is established by the observation that a greater *FSg* usually results in higher solar gains and worse overall insulation level. When the effect of this parameter on heating demand is analyzed, it is noted that solar gains are more important than the overall insulation level. Thus, for example, in Case A and Case F, the *FSg* is 14.6% and 16.0% with a *Ug* of 1.33 and 1.61 W/m^{2}K, respectively. These cases have an average heating demand that is similar to Case C with an *FSg* that is almost half, at 8.3%, and *Ug* of 1.15 W/m^{2}K. Although the latter case has a lower level of heat insulation (almost 30% lower), the solar gain of the other two cases is almost twice as high (101.4 kWh/m^2 for Case F compared to 49.6 kWh/m^2 for Case C); therefore, the effects of both parameters offset each other, and the heating demand is equal.

4.4. Effect of facade orientation on air conditioning demand

According to the results obtained, it is not possible to affirm, in general, that there are facade solutions that work particularly well for each particular orientation. However, it is important to note that there are certain problematic situations in which it is important to take greater precautions when selecting the type of façade.

Fig. 6 shows that the west orientation is the most problematic orientation in all the cases analyzed because that orientation has the greatest cooling demand. This phenomenon is because the west facade receives a large amount of radiation. The radiation begins at solar noon, which is very difficult to control because it falls perpendicular to the surface of the facade, which increases the cooling demand with respect to the less exposed orientations, such as the north orientation. Furthermore, during the afternoon hours, both the exterior and indoor temperatures of the building usually increase considerably, which results in favorable conditions for increased cooling demand.

It is proven that the most critical cases correspond to the buildings that have facades with higher *FSg* values (Case B and Case H). In these cases, the difference in energy demands between the critical (west) and most favorable orientation (north) is 42% and 32%, respectively. These differences are not seen in buildings that have facades that use solar control glass combined with solar shields and have a lower *FSg*, like in Case A and Case C. Therefore, solar control glass and solar shields are appropriate strategies to reduce and equalize the cooling demands in the different orientations of a building.

4.5. Effect of the construction costs of the facade on air conditioning demand.

One of the objectives of the analysis was to determine whether the construction costs of the facade had any influence on the air conditioning demand of the building to justify selecting a more expensive construction method based on the energy benefits. However, as shown in Fig. 6, the results show that the facades with lower demand are not necessarily the most expensive. For example, Case C has a lower energy demand (74.3 kWh/m^2 average), and its facade is one of the most economical. Of the cases analyzed, Case G is the building with the highest construction cost (greater than 800 €/m^2), and its energy demand is 93.9 kWh/m^2 on average. This represents a 26.4% increase in the demand of the building compared to the building with the lowest construction cost (which has a cost of 381 €/m^2).

It is remarkable that the construction costs of the building alone do not directly affect the energy demand of the building. For exam-

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ple, Case D and Case G have similar energy demands, while the construction costs of their facades vary by almost 50%.

4.6. Facade parameters that affect the level of indoor natural lighting

The results of the lighting study are summarized in Fig. 7, which shows the average (indicated in green), maximum (indicated in blue) and minimum (indicated in red, all in %) values of the daylight factor for each facade. According to BREEAM [25], the average daylight factor in all buildings should be higher than 1.7% to obtain an adequate level of natural light, while the factor should be greater than 2.55% for those buildings to have optimal levels of natural light. The range of these values is represented in Fig. 7 by the horizontal gray band. In regards to the minimum daylight factor, it should be higher than 0.68% to ensure that the users of the building have enough access to natural light.

It can be seen that certain facades, like Case A, Case C and Case G, do not have the recommended average daylight factor value. In relation to the minimum daylight factor, only the facades of Case B, Case F and Case H exceed it.

By comparing the values of the average daylight factor with the percentage of openings values and the *FSg* of each facade, it is observed that as the surface area of the openings in the facade increased, the daylight factor increased. Thus, the two facades with the highest percentage of openings and greatest *FSg* (Case B and Case H) are the ones with higher average daylight factors and higher minimum daylight factors, as well as highest cooling demands. The facades that do not reach the minimum daylight factor have shielding systems or passive solar protection systems that do not achieve optimal levels of natural lighting, although they minimize the cooling demand and achieve a level of protection capable of reducing and equalizing the demands of the different orientations. Within the facades with intermediate air conditioning demand (Cases D–G), all cases except Case G reach the recommended average daylight factor. Consequently, the decisive parameter for selecting a type of facade could be the lighting level achieved. For example, Cases D and G have almost identical air conditioning demands, but Case D has the most favorable lighting behavior, so it should be the preferred facade.

Because the results of the lighting study hinder a joint analysis of the building from an energy and natural lighting point of view, this aspect has been addressed in more detail through the calculation of the solar gain of the spaces analyzed; this variable takes into account the influence of factors such as solar shields, orientation and time of day. Fig. 8 shows the solar gain of the interior space (in KWh/m^2) for each facade calculated as the sum of the solar gains obtained through all the walls that delimit the area of study.

The facades that have a lower *FSg*, because of either incorporating exterior solar shields (Case A and Case G) or having a low percentage of openings in the facade and low solar factor glass (Case C), are the facades that have less solar gain through the walls (mainly through the facade of analysis). For example, Case C (with the lowest *FSg*) has an average solar gain of 49.6 kWh/m^2, an average daylight factor of 1.59% (lower than the recommended 1.7%) and a cooling demand of 61.4 kWh/m^2, which is the lowest of all the cases. In comparison, Case F (whose *FSg* is twice as high) has an average solar gain of 101.4 kWh/m^2, an average daylight factor of 3.84% and a cooling demand of 102.5 kWh/m^2. Regarding Case B (with the highest *FSg*), the average solar gain is 229.5 kWh/m^2, the average daylight factor is 4.81%, and the cooling demand is the highest, 146.8 kWh/m^2.

The comparison of these values reveals the close relationship between energy and lighting aspects, which in turn are both strongly related to the exterior solar shielding elements, the surface of the openings and their thermal energy characteristics.

5. Conclusions

The results of the energy performance study of office buildings representative of the city of Barcelona demonstrate that there are considerable differences between the energy performance results for different types of facade analyzed and that these differences are not directly related to the economic cost of the solutions used.

In regards to the effect of the facade on cooling demand, the results affirmed that the decisive parameter that affects cooling demand is the incident solar radiation. This confirms that solar shielding is a fundamental factor in buildings with high internal load. For that reason, in climates with high solar radiation and relatively high temperatures, such as the Mediterranean climate, the design of facades with a low overall solar factor is crucial to properly control the air conditioning demand. This is accomplished by using exterior shielding elements and high quality glass that improve thermal comfort without increasing cooling energy needs, which is the main energy consuming element of the building.

Additionally, based on the results, the heating demand depends on a combination of different parameters: the thermal insulation and inertia of the walls and the modified solar factor of the facade, among others. The influence of each of these factors depends on the climate of the area; thus, in mild climates with high solar incidence, like the cases analyzed, the solar gains help to offset most of the energy losses through the facade. It was even demonstrated that facades with worse insulation can have a lower heating demand than facades with better insulation.

In regards to the orientation of the building, it cannot be asserted, in general, that there are facade solutions that work particularly well for each particular orientation. However, it can be asserted that the west orientation stands out as the most problematic for cooling demand, while the north orientation is the most favorable because of its lower demands. In cases in which it is desirable to reduce and equalize the cooling demands for different orientations of the building, it is necessary to design the facade with the lowest possible *FSg*.

Lastly, with regard to the effect of the facade on the indoor natural lighting, the results show that in climates such as the Mediterranean climate, the requirements of natural lighting of the buildings with high internal load clearly go against the need to control the cooling demand. For facades that have similar thermal energy performance, the level of natural lighting reached inside the building can be used as a discriminating element in the selection of the most appropriate type of construction. However, the balance between contributing natural light and reducing demand by adequately controlling solar gains is one of the main issues to resolve in each particular case. The use of selective glass, which provides a medium-high visible light transmission while at the same time reduces the amount of thermal radiation absorbed by the glass and transmitted to the interior of the building, is a solution that when combined with exterior shielding elements, offers good overall results. Additionally, the use of active facades, which have systems to adapt to changing external environmental conditions, could be one of the best answers to this problem.

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Carla Planas. Ingeniera Industrial (2005) por la Universitat Politècnica de Catalunya (UPC). Estudiante de Doctorado en Sostenibilidad (esperado 2019). Profesora del Departamento de Ingeniería de Proyectos y de la Construcción de la UPC desde 2009. Especializada en herramientas de simulación aplicadas a los edificios, en eficiencia energética y en certificaciones ambientales (LEED, BREEAM y VERDE). Fundadora de la empresa 3EA energía. Autora/coautora de varios artículos, comunicados, Abstracts o Ponencias en Revistas Técnicas e indexadas (JCR y SJR) y Congresos de reconocido prestigio. Participante en dos proyectos de investigación nacionales (2013 y 2017) sobre Sostenibilidad agrourbana mediante invernaderos en cubierta.

Eva Cuerva. Ingeniera Industrial (2007) e Ingeniera en Organización Industrial (2015) por la Universitat Politècnica de Catalunya (UPC). Doctora en Ingeniería de la Construcción por la UPC (2013). Profesora del Departamento de Ingeniería de Proyectos y de la Construcción de la UPC desde 2009. Especialista en el análisis del comportamiento termoenergético de la envolvente edificatoria del edificio, especialmente de fachadas ventiladas. Autora/coautora de 9 artículos indexados (JCR y SJR) en revistas de reconocido prestigio, así como de numerosas ponencias en congresos nacionales e internacionales. Participante en dos proyectos de investigación nacionales (2013 y 2017) sobre Sostenibilidad agrourbana mediante invernaderos en cubierta.

Pere Alavedra. doctor ingeniero industrial por la universitat politècnica de catalunya (upc) en 1979. ingeniero industrial por la escuela técnica superior de ingeniería industrial de barcelona en 1972. Profesor del departamento de ingeniería de proyectos y de la construcción de la upc desde 1991. rector universitat internacional de catalunya: 2010-2015. presidente de la comisión de comunicación de las universidades españolas (crue): 2014-2015. Miembro del Comité editorial de la Revista Dyna. Revisor de la Revista: building research & information. Autor/coautor de artículos indexados (JCR y SJR) y en revistas de reconocido prestigio, así como de numerosas ponencias en congresos nacionales e internacionales.

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