Transient simulation of the influence of wind conditions on the airtightness of windows. A case study for a tertiary building.

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Abstract:

Achieving a reasonable level of airtightness is important for the energy efficiency of living spaces and the comfort of occupants. The benefits of improved insulation levels and more energy efficient heating systems are lost if warm air can leak out of a building and cold air can leak in. Poor airtightness can be responsible for up to 40% of heat loss from buildings. Airtight buildings require airtight windows. Airtightness of windows is often evaluated in lab conditions in the context of initial type testing. Testing methods can be found in several international standards, leading to airtightness classifications of windows for building codes. The level of airtightness achieved is measured as air permeability, as the quantity of air that leaks into or out of the window per hour. Airtightness of windows is typically expressed per meter opening joint or per square meter. Nevertheless, airtightness of window is highly sensitive with respect to wind conditions, mostly speed and direction. Increased attention to energy efficiency and airtightness of buildings has led to more research on the performance of windows, and can be estimated by appropriate simulation. This work presents a case study of the influence of wind speed and direction on the thermal load of a tertiary building due to leakage through windows. Transient simulation by means of Transient System Simulation (TRNSYS) package is presented. Results are analyzed as a function of standardized window type. Besides, relative influence of the internal layers of the façade on the thermal load of the building is studied. Three alternative cases of high thermal inertia are compared with the existing one with low thermal inertia.

Keywords:

Airtightness, Energy Efficiency, Thermal Inertia, TRNSYS.

1. Introduction.

The thermal transmittance of building enclosures and windows is the main factor taken into account in Spain when studying the energy efficiency in new buildings. The solar factor of windows is also important in warm climate areas.

The permeability of windows is another important factor, but it is not always correctly assessed. Frequently the lowest level allowed by building codes is adopted. Spanish building codes are not strict enough for cold climate areas.

The effect of the thermal inertia of building enclosures on the energy demand is also frequently not evaluated because it is not compulsory by Spanish building codes.

The purpose of this work is making an energy simulation of a tertiary building located in the city of Burgos, in the North of Spain. It has a continental climate similar to Central European climates. It has 42° 20' 28'' North latitude and a 861 m altitude over the sea level. The influence of the permeability of the existing windows on the energy demand, in contrast with the less airtight windows allowed, will be evaluated. At the same time, the effect on the energy demand of changing the façade layer located between the isolation and the inside lining for materials with more thermal inertia will be assessed.

2. Materials and method.

2.1. Literature review.

First of all, a literature review about the Spanish codes in relation with saving energy in buildings has been done. Transposed from [1], there are some compulsory documents in [2]:

- Energy demand limits in heating and cooling in buildings and different calculation methods are explained in [3]. Particular limits for different parts of the buildings, like the permeability of windows, are also explained. The steps for making an energy simulation are totally described.
- Wind loads on the buildings, including assessment methods for the pressure on small area parts like windows, are explained in [4].

International codes referred in [3-4] have been reviewed founding similar explanations and assessment methods, because Spanish codes are transposed from international ones. Not Spanish researchers can find that information in these documents:

- Codes about the permeability of windows, in [5-7].
- Codes about the thermal inertia in buildings, in [8-9].

Other documents reviewed are [10-11] in relation with airtightness of windows and [12] with thermal inertia.

2.2. Building energy simulation

A floor of a hospital has been simulated. It is the lower floor of a five storey building used for hospitalization of patients. Fig. 1 is a picture of the simulation made with Transient System Simulation (TRNSYS).

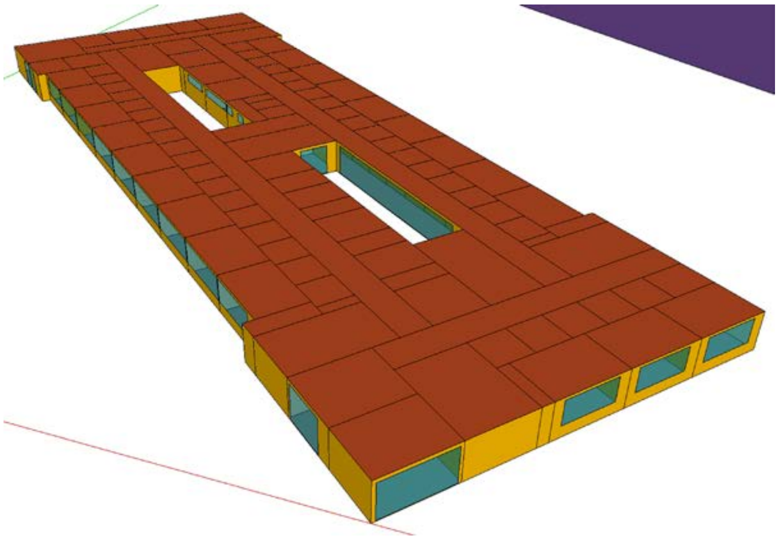

Fig. 1. Energy simulation made with TRNSYS.

2.2.1. Building geometry

The building has a rectangular form. It is 72.85 m long and 26.36 m wide (outside measurement). The floor is 2.70 m high (inside measurement). It does not rest on the ground. It is elevated with pillars over another three storey building. The plan is turned. The long façade is turned 40º with West-East direction and the short façade is turned 50º with the same direction, as it is shown in Fig. 2.

This work is focused in the study of the behaviour of four rooms representative of each of the four façades. They are drawn in Fig. 2, and their characteristics are in Table 1.

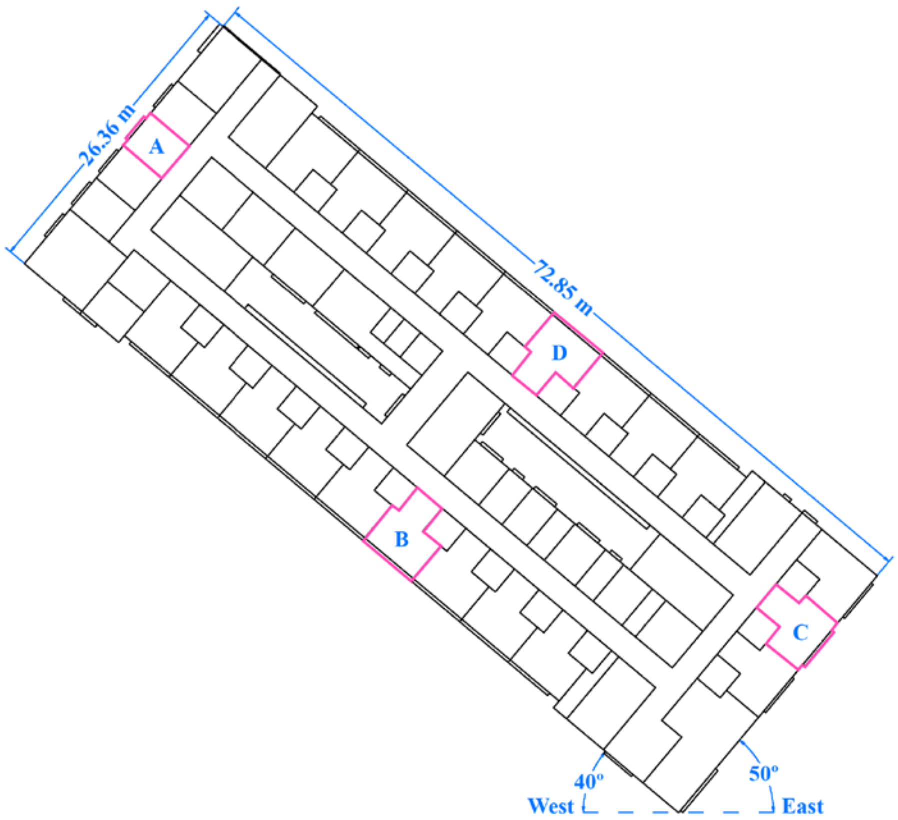

Fig. 2. Building geometry and studied rooms.

Table 1. Rooms

Façade orientation	Room	*A*, m²	*V*, m³
Northwest	A	15.55	41.99
Southwest	B	26.52	71.60
Southeast	C	25.50	68.85
Northeast	D	26.52	71.60

2.2.2. Building constructive features

Building enclosures and interior partitions have been generated by layers with TRNSYS, ordered from inside to outside. The constructive features of the materials of each layer are detailed in Tables 2 to 5.

Table 2. Exterior floor composition

Material	*t*, m	λ, W/m×K	C_p, J/kg×K	δ, Kg/m³	R_n, m²×K/W
Terrazzo	0.020	1.300	1,000.000	1,700.000	---
Cement mortar	0.080	0.700	1,000.000	1,350.000	---
EPS isolation	0.080	0.029	1,000.000	30.000	---
Reinforced concrete	0.300	2.500	1,000.000	2,600.000	---

Table 3. Façade composition

Material	*t*, m	λ, W/m×K	C_p, J/kg×K	δ, Kg/m³	R_n, m²×K/W
Plasterboard	0.013	0.250	1,000.000	825.000	---
Textile lining	0.010	0.060	1,300.000	200.000	---
MW isolation	0.060	0.031	1,000.000	40.000	---
Steel	0.008	50.000	450.000	7,800.000	---
MW isolation	0.020	0.041	1,000.000	40.000	---
Vertical and slightly ventilated air chamber	0.100	---	---	---	0.095
Slate	0.040	2.200	1,000.000	2.400	---

Table 4. Interior partitions composition

Material	t, m	λ, W/m×K	C_p, J/kg×K	δ, Kg/m^3	R_n, m^2×K/W
Plasterboard	0.013	0.250	1,000.000	825.000	---
Plasterboard	0.013	0.250	1,000.000	825.000	---
MW isolation	0.060	0.050	1,000.000	40.000	---
Plasterboard	0.013	0.250	1,000.000	825.000	---
Plasterboard	0.013	0.250	1,000.000	825.000	---

Table 5. Interior ceiling composition

Material	t, m	λ, W/m×K	C_p, J/kg×K	δ, Kg/m^3	R_n, m^2×K/W
Plasterboard	0.013	0.250	1,000.000	825.000	---
Horizontal and not ventilated air chamber	1.000	---	---	---	1.800
Reinforced concrete	0.300	2.500	1,000.000	2,600.000	---
Cement mortar	0.080	0.700	1,000.000	1,350.000	---
Terrazzo	0.020	1.300	1,000.000	1,700.000	---

Inside and outside convective heat transfer coefficients of building enclosures are detailed in Table 6, according with [3].

Table 6. Convective heat transfer coefficients of building enclosures

Position	Heat flow direction	R_{so}, m^2×K/W	R_{si}, m^2×K/W
Vertical (façade)	Horizontal	0.040	0.130
Horizontal (ceiling)	Vertical and ascending	0.040	0.100
Horizontal (floor)	Vertical and descending	0.040	0.170

Solar absorptance values according to the building enclosures colours are detailed in Table 7, according with [3].

Table 7. Solar absorptance values

Building enclosure	Surface	Colour	Tone	α
Floor	Interior	Grey	Medium	0.65
Floor	External	Grey	Medium	0.65
Ceiling	Interior	White	Medium	0.30
Façade	External	Green	Dark	0.88
Façade	Interior	White	Medium	0.30
Interior partition	Interior	White	Medium	0.30

All the existing linear thermal bridges in the simulated floor have been identified and generated with TRNSYS. The linear thermal transmittance values are detailed in Table 8, according with [3].

Table 8. Linear thermal bridges

Linear thermal bridges	ψ, W/m×K
Interior floor – façade	0.42
Exterior floor – façade	0.43
Projection corner	0.15
Entering corner	0.01
Window edge	0.24
Pillar – façade	0.84

Windows are built with a double glazing with interior air chamber (4/15/4 mm) and an aluminium frame with thermal bridge breakage. Their features are shown in Table 9.

Table 9. Windows features

Material	U, W/m^2×K	g	α	A_{fr}/A_w, %	R_{so}, m^2×K/W	R_{si}, m^2×K/W	Q_{100}, m^3/h×m^2
Glazing	1.430	0.605	---	---	---	---	---
Frame	2.900	---	0.650	---	---	---	---
Glazing + frame	---	---	---	23.000	0.040	0.130	< 3.000

2.2.3. Building operational conditions

The simulated floor is occupied every day of the week because it is used for hospitalization of patients, who receive medical care and visits from their relatives and friends in their rooms. There are not large internal gains owing to the occupation, the lighting or the equipment. A use profile based on the "not residential conditions with low intensity during 24 hour use profile", from [3], has been generated for TRNSYS. It has been harmonized for all days of the week. Lighting internal gains have been calculated based on the use of compact fluorescent lamps with an energy performance of 80 lm/W. The average horizontal illuminance is 100 lux. The values are detailed in Tables 10 to 12.

Table 10. Set point temperatures

Days of the week	Schedule	System	*T*, ºC
Working days, Saturdays, Sundays and Holidays	0h00 – 24h00	Cooling (high)	25.00
		Heating (low)	20.00

Table 11. Mechanical ventilation

Days of the week	Schedule	ren/h
Working days, Saturdays, Sundays and Holidays	0h00 – 24h00	0.80

Table 12. Internal gains

Days of the week	Schedule	Owing to	W/m^2
Working days, Saturdays, Sundays and Holidays	0h00 – 24h00	Sensible occupation	2.00
		Latent occupation	1.26
		Lighting	1.25
		Equipment	1.50

HVAC systems description is not an aim of this work.

2.3. Assessment of the wind load effect on the windows

The wind load on each of the four windows of each of the four rooms has been calculated according with [4]. Windows and façades areas are detailed in Table 13.

Table 13. Windows and façades areas

Façade orientation	Room	A_w, m^2	A_f, m^2	A_w/A_f, %
Northwest	A	4.11	9.71	42.33
Southwest	B	9.18	14.58	62.96
Southeast	C	6.43	14.20	45.28
Northeast	D	9.18	14.58	62.96

Wind static pressure (1) supported by each window owing to the wind load is a perpendicular strength to the surface exposed points. It is the result of the multiplication of the wind dynamic pressure by the wind exposure coefficient and by the wind coefficient.

$$q_e = q_b \times c_{ew} \times c_{pe}, \qquad (1)$$

- Wind dynamic pressure has been calculated according with (2). It is the result of multiplying one half of the air density by the basic wind speed squared.

  $$q_b = 0.5 \times \delta_a \times v^2, \qquad (2)$$

  The Ideal Gas Law (3) has been taken into account in order to assess the air density. The hourly values of the dry bulb temperature of the year 1995 are available from the Spanish National Meteorological Agency.

  $$P \times V = n \times R \times T, \qquad (3)$$

Supposing that the average atmospheric pressure for the city of Burgos is 910 mbar, the hourly values of the air density can be calculated according with (4).

δ_a = 1,293×(910/1013)×[273/(T+273)], (4)

The hourly basic wind speed values of the year 1995 are also available from the Spanish National Meteorological Agency.

Finally, a file with 8760 hourly values of the wind dynamic pressure has been generated.

- The wind exposure coefficient is function of the geometrical center high of each of the windows. It is 12.45 m for all of them.

  It also depends on the terrain roughness of the building location. In this case, an urban, industrial or forest category has been considered.

  Using these inputs, tabulated values for heights of 12.00 m and 15.00 m are available in [4]. These values are 1.90 y 2.10 respectively.

  The wind exposure coefficient value has been calculated by linear interpolation, and it is 1.93. It is valid for the four windows during the 8760 hours of the year.

- The wind coefficient depends on the share and the orientation of the windows in relation with the wind. It also depends on the windows location on each of the façades. Tabulated values for vertical walls taking into account the windows locations are available in [4] according with Fig. 3.

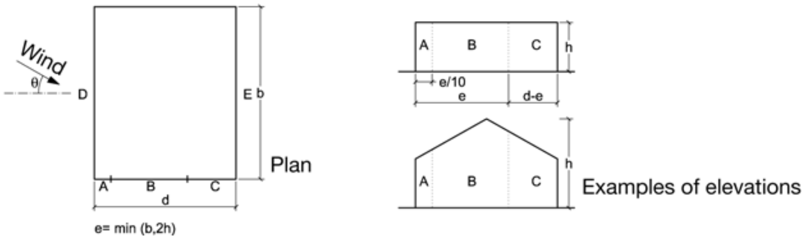

Fig. 3. Possible window positions in the façades [4].

The hourly wind direction values for the year 1995 are also available from the Spanish National Meteorological Agency. The impact angle values vary from 129º to 190º with a clockwise measurement, and supposing that the North orientation angle is 0º. Taking into account the orientation façades in Fig. 2, only the Northwest and the Northeast ones support a wind load forming an angle of $-45º < \theta < 45º$, as it is shown in Fig. 4.

The maximum height of the building is 29.20 m. The length of the façades perpendicular to the wind direction (± 45º) is 26.36 m and 72.85 m for the Northwest and the Northeast orientations respectively. The four assessed windows are located in the middle of their façades.

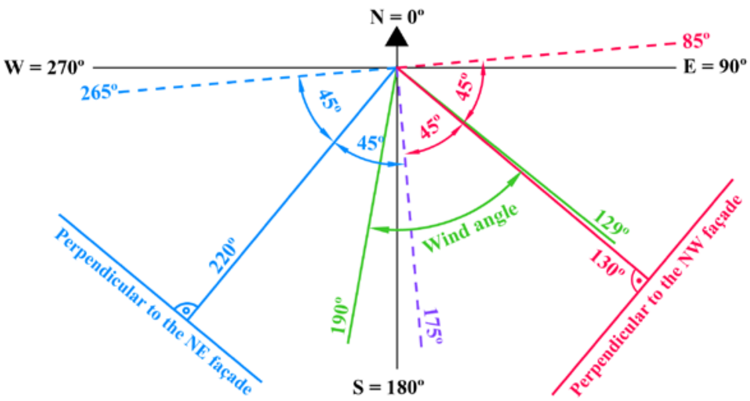

Fig. 4. Wind load angles on the façades.

Therefore, the wind coefficient assessment has been divided in two study cases taking into account which façade supports the wind load, according with [4] as it is shown in (5).

$c_{pe,A} = c_{pe,1}+[(c_{pe,10}-c_{pe,1})\times\log_{10}A_w]$, (5)

The obtained results are detailed in Table 14. They have been linked with the hourly wind direction values. Finally, 8760 hourly values have been generated for each of the windows. A negative value means suction, and a positive value means pressure.

Table 14. Wind coefficients

Room	Orientation	$c_{pe,A}$	Orientation	$c_{pe,A}$
A	Northwest	0.88	Northeast	−0.92
B		−0.81		−0.33
C		−0.51		0.86
D		0.81		0.73

2.4. Air infiltration loss on windows

The approved laboratory "Ensatec" has provided the permeability test for the existing windows obtaining "Class 4" according with [6-7]. At the same time, this laboratory has provided another test of a similar window which obtains only "Class 2", which is the maximum permeability allowed for the climatic zone of the city of Burgos according with [3]. The results of these tests are detailed in Tables 15 to 16.

Table 15. Original air permeability for existing windows "Class 4"

Pressure levels, Pa	Pressure, $m^3/h\times m^2$	Suction, $m^3/h\times m^2$
50	1.67	1.59
100	2.29	2.24
150	3.05	2.99
200	3.71	3.67
250	4.43	4.39
300	5.19	5.10
450	6.73	6.68
600	7.54	7.48

Tabla 16. Original air permeability for windows "Class 2"

Pressure levels, Pa	Pressure, $m^3/h\times m^2$	Suction, $m^3/h\times m^2$
50	15.80	17.80
100	25.12	26.58
150	34.32	34.77
200	39.11	39.03
250	45.07	43.52
300	50.72	46.69
450	64.94	52.72
600	64.97	58.30

The observed data have been fitted to a mathematical model using a spreadsheet. This model is a third grade polynomial (6-9). It is a good approximation to the observed data drawn in a scatter plot as it is shown in Fig. 5.

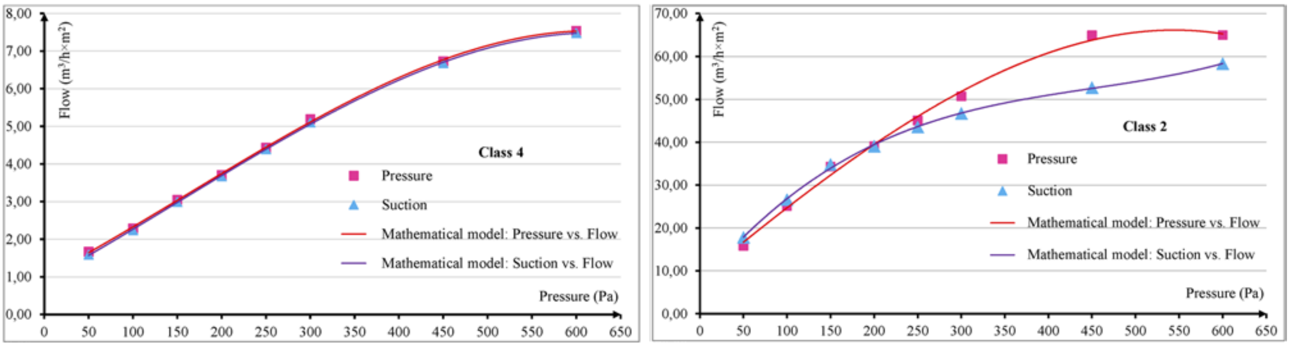

Fig. 5. Scatter plot and mathematical model.

Mathematical model: Pressure vs. Flow. Original air permeability in Class 4 windows test.

$y = -2.316E-08x^3+1.142E-05x^2+1.237E-02x+9.999E-01,$ (6)

Mathematical model: Suction vs. Flow. Original air permeability in Class 4 windows test.

$y = -2.183E-08x^3+1.003E-05x^2+1.278E-02x+9.107E-01,$ (7)

Mathematical model: Pressure vs. Flow. Original air permeability in Class 2 windows test.

$y = -1.505E-07x^3-3.096E-05x^2+1.675E-01x+8.400E+00,$ (8)

Mathematical model: Suction vs. Flow. Original air permeability in Class 2 windows test.

$y = 3.529E-07x^3-4.756E-04x^2+2.442E-01x+6.805E+00,$ (9)

The 8760 hourly values of the wind static pressure have been entered in these equations. The same number of hourly values of the infiltration flow for each of the window has been obtained. The hourly values of the number of air renovations per hour have been calculated multiplying the infiltration flow by the area of each of the windows and dividing by the volume of each of the rooms.

Three study cases have been simulated with TRNSYS in order to assess the effect of the windows air permeability in the energy demand of the four rooms:

- Class 4 windows.
- Class 2 windows.
- Zero air permeability.

2.5. Thermal inertia in the façade

The effect of changing the thermal inertia of the initial façade composition, which is detailed in Table 3, on the energy demand, has been assessed. Three study cases have been proposed based on changing the second layer from inside. The textile lining has been exchanged for three different materials with greater thickness, specific heat and density, as is shown in Table 17.

Table 17. Proposed materials for the second layer of the façade

Material	t, m	λ, W/m×K	C_p, J/kg×K	δ, Kg/m^3
Hollow brick	0.115	0.667	1,000.000	1,140.000
Solid brick	0.115	0.991	1,000.000	2,170.000
Concrete block	0.100	0.632	1,000.000	1,210.000

New magnitudes related with thermal inertia have been calculated both for the initial façade and for the three alternative façades proposed. Thermal inertia is the degree of slowness with which the temperature of a body approaches that of its surroundings and which is dependent upon its absorptivity, its specific heat, its thermal conductivity, its dimensions, and other factors.

The first magnitude is the thermal mass (10), which is the amount of heat that a body is able to incorporate and store.

$m_t = \delta \times c_{pe} \times t,$ (10)

The second magnitude is the thermal time constant (11), which shows the reaction time of a body when external temperature changes.

$CTT = [R_{so}+(0.5\times R_1)]\times m_{t1}+[R_{so}+R_1+(0.5\times R_2)]\times m_{t2}+...+[R_{so}+R_1+R_2+...+(0.5\times R_n)]\times m_{tn},$ (11)

The third magnitude is the useful thermal mass (12), which shows the thermal mass of the construction materials located between the isolation layer and the internal space.

$m_{tu} = CTT/R_T,$ (12)

The last magnitude is the useful thermal mass percentage (13), which is a relation between the useful thermal mass and the total thermal mass of the façade.

$$\% \, m_{tu} = m_{tu} / m_t, \qquad (13)$$

The total results of these calculations for the four models of façade studied are detailed in Table 18.

Table 18. Thermal inertia of the façades

Façade	R_T, m²×K/W	m_t, J/m²×K	*CTT*, s	m_{tu}, J/m²×K	% m_{tu}, %
Initial	2.931	140,000.605	63,775.714	21,756.657	15.47
Initial + hollow brick	2.937	269,105.000	406,793.301	138,503.259	51.47
Initial + solid brick	2.881	387,555.000	715,281.685	248,301.582	64.07
Initial + concrete block	2.923	259,005.000	378,827.423	129,607.556	50.04

Four energy simulations of the studied floor of the building, with the four different proposed façades, have been developed with TRNSYS in order to assess the effect on the energy demand of the four studied rooms.

3. Results and discussion

The results of the energy simulations of the different suggestions related with the windows air permeability and with the thermal inertia of the façades of the hospitalization floor, performed with TRNSYS in order to assess the effect on the energy demand, are detailed in Tables 19 to 20. All the data have been standardized to square meter in order to be able to compare the results of the four studied rooms, which have different areas. These results are also shown in graphs in Figs 6 to 7.

Table 19. Results of the energy simulations related with the windows air permeability

Case study	Heating demands, (kWh/m²×year)				Cooling demands, (kWh/m²×year)			
⇓ Rooms ⇒	A	B	C	D	A	B	C	D
Class 4 windows	127.33	99.48	108.60	138.18	9.64	53.88	27.42	6.39
Class 2 windows	206.19	196.38	180.03	242.26	7.66	42.07	20.39	4.15
Zero air permeability	118.40	88.75	100.63	126.34	10.05	55.82	28.65	6.89
Case study	Difference between the case study and the zero air permeability case, (%)							
Class 4 windows	7.54	−4.08	12.09	−3.48	7.92	−4.29	9.37	−7.26
Class 2 windows	74.15	−23.78	121.27	−24.63	78.90	−28.83	91.75	−39.77

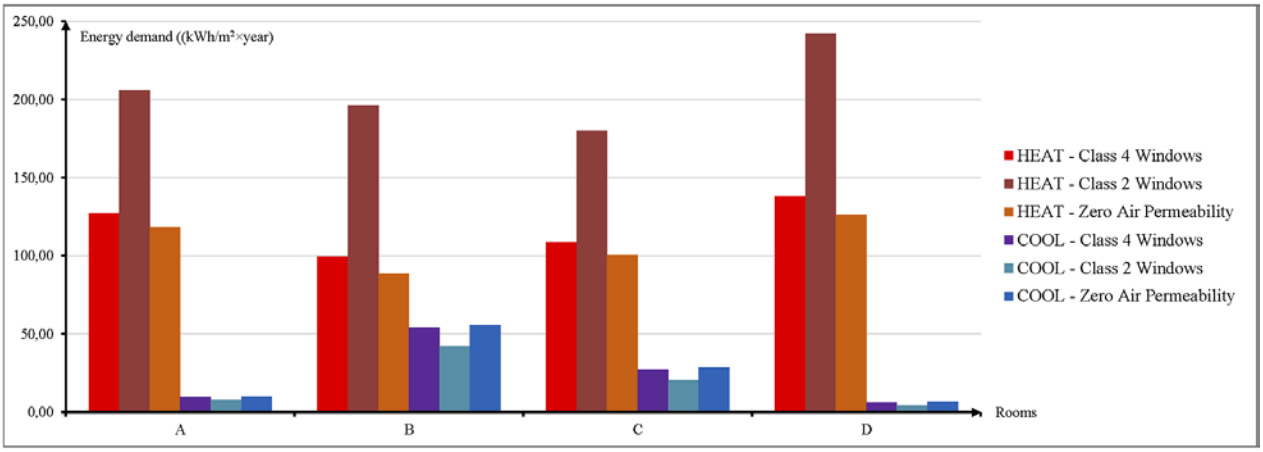

Fig. 6. Results of the energy simulations related with the windows air permeability.

Table 20. Results of the energy simulations related with the façades thermal inertia

Case study ⇓ Rooms ⇒	Heating demands, (kWh/m²×year) A	B	C	D	Cooling demands, (kWh/m²×year) A	B	C	D
Façade	127.33	99.48	108.60	138.18	9.64	53.88	27.42	6.39
Façade + hollow brick	126.34	96.32	105.49	137.49	8.63	50.06	24.21	5.90
Façade + solid brick	126.34	95.59	104.85	137.43	8.46	49.23	23.58	5.78
Façade + concrete block	126.40	96.37	105.56	137.53	8.62	50.07	24.21	5.90
Case study	Difference between the case study and the façade case, (%)							
Façade + hollow brick	−0.78	−10.48	−3.18	−7.09	−2.86	−11.71	−0.50	−7.67
Façade + solid brick	−0.78	−12.24	−3.91	−8.63	−3.45	−14.00	−0.54	−9.55
Façade + concrete block	−0.73	−10.58	−3.13	−7.07	−2.80	−11.71	−0.47	−7.67

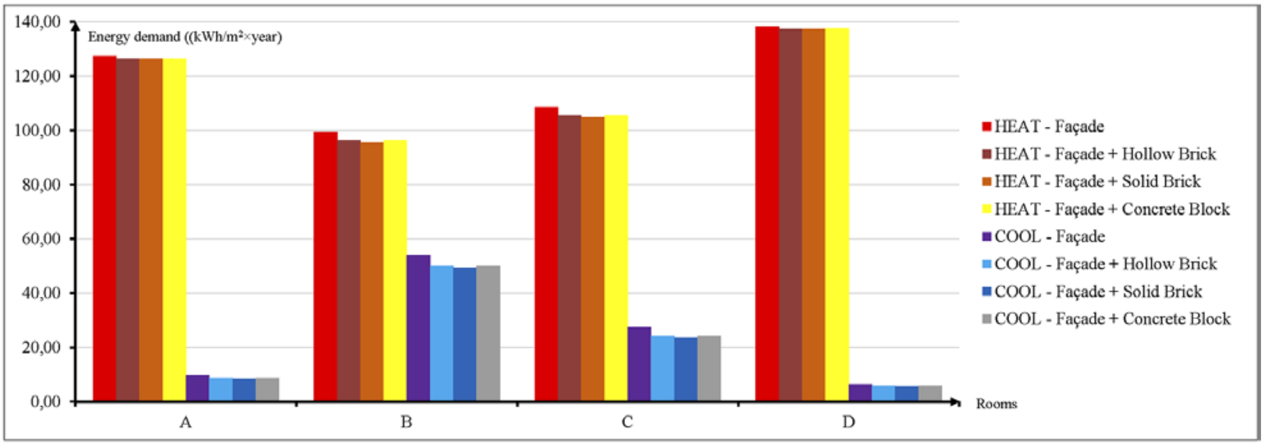

Fig.7. Results of the energy simulations related with the façades thermal inertia.

Annual energy heating demand is greater than annual energy cooling demand in all of the energy simulations performed. It is owing to the location of the city of Burgos in the coldest climate zone of Spain, with severe Winters and moderated Summers.

Owing to the rooms' façades orientations, the descending order for the annual energy heating demands of the rooms is as it follows: D > A > C > B, in all of the simulations performed with one exception, which is the data related with the Class 2 windows air permeability. In this case, the descending order is: D > A > B > C. The descending order for the annual energy cooling demands of the rooms is the opposite in all of the simulations: B > C > A > D.

The frames and the glazing of the two kinds of windows have the same features, but the different air permeability has a great effect on the energy demand, especially on the heating demand. The air permeability of the windows should be an essential factor in the design of the buildings. Only Class 4 windows, according with [6-7], should be allowed in the climate zone where the city of Burgos is located.

The three alternative proposed façades with solid construction materials located between the thermal isolation and the internal space have greater thermal inertia than the original façade. But the four of them have similar thermal resistance. There is an insignificant difference between the energy demands when the results for heating and cooling of each of the four rooms are compared. It is owing to the great percentage of the façades areas occupied by the windows, where there is not an increase of thermal inertia. But the most important reason is the fact that it is more important to increase the thermal inertia in areas exposed to direct solar radiation, like floors, and not in the isolated façades. Floors have a horizontal position and a greater area. These features give to floors a better energy storage capacity than the façades, and the ability of transmitting that energy to the air that has a convective movement inside the room.

4. Conclusions

An energy simulation of a tertiary building located in Burgos has been performed with TRNSYS, assessing different proposals. The air permeability of windows has a great effect, especially on the heating energy demand, so it should be an essential factor in the design of the buildings. On the other hand, increasing thermal inertia in façades has an insignificant influence on the energy demand, so it is better to increase it in areas exposed to the direct solar radiation, like floors.

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Nomenclature

Letter symbol and subscripts

A	area, m^2
A_f	area of a façade, m^2
A_{fr}	area of a frame, m^2
A_w	area of a window, m^2
CTT	thermal time constant, s
C_p	specific heat, J/kg×K
c_{ew}	wind exposure coefficient, dimensionless
c_{pe}	wind coefficient, dimensionless
$c_{pe,A}$	wind coefficient in relation with exposed area, dimensionless
$c_{pe,1}$	wind coefficient for an exposed area of 1 m^2, dimensionless
$c_{pe,10}$	wind coefficient for an exposed area of 10 m^2, dimensionless
g	solar factor, dimensionless
m_t	thermal mass, J/ m^2×K
m_{tu}	useful thermal mass, J/ m^2×K
n	amount of gas, mol
P	pressure, Pa
Q_{100}	permeability under a lab pressure of 100 Pa, m^3/h×m^2
q_b	wind dynamic pressure, Pa
q_e	wind static pressure, Pa
R	ideal gas constant, J/K×mol
R_n	thermal resistance of a layer, m^2×K/W
R_{si}	inside convective heat transfer coefficient, m^2×K/W
R_{so}	outside convective heat transfer coefficient, m^2×K/W
R_T	thermal resistance of a building enclosure, m^2×K/W
T	temperature, ºC
t	thickness, m
U	thermal transmittance, W/m^2×K
V	volume, m^3
v	basic wind speed, m/s

Greek symbols

α solar absorptance, dimensionless

δ density, kg/m^3

δ_a air density, kg/m^3

θ wind angle, °

λ thermal conductivity, W/m×K

ψ linear thermal transmittance, W/m×K

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