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THERMAL MASS NUMERICAL STUDY – ANALYSIS OF SOME FACTORS INVOLVED AND THEIR IMPORTANCE

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ABSTRACT

This study aims to show, from a theoretical point of view, the influence of various factors on dynamic thermal behaviour of buildings. This type of analysis requires the consideration of many factors that vary with the type of building construction, type of occupation and climatic conditions. With the increasing concern with energy consumption, it is important to understand how these factors interact with each other. From all the factors involved, thermal mass is the main focus of this study. It is a very important aspect for south European climate conditions, due to the fact that it can reduce peak cooling and peak heating loads and indoor air temperature variations during the day, but its efficiency depends on the combination with all the other factors.

In this context, numerical simulations of generic simplified building envelopes with different thermal mass were performed to evaluate the influence of several factors considered independently and combined. These factors were the geographic location, the envelope thermal insulation, the glazing orientation, the type of occupation and the ventilation of indoor air.

The software Energy Plus was the tool used in numerical simulations. The model was a simplified building construction, a closed box, where the walls, the roof and the ground floor had the same composition. This model was used to simulate three different envelopes: heavyweight elements with exterior insulation, heavyweight elements with interior insulation and a lightweight elements thermal insulated. All those three different envelopes had the same thermal resistance.

In the parametric simulations the next aspects have been considered: local weather, thermal resistance, thermal mass, glazing orientation, occupation and ventilation. Concerning the factors considered in the simulations, the weathers from two Portuguese districts were chosen in order to compare the thermal behaviour in two different climates. To study the relation between thermal resistance and thermal mass, the insulation layer was increased in similar rate for each envelope. In order to evaluate the importance of glazing in thermal behaviour, windows were applied in North and South walls. To determine the importance of occupation, the permanent presence of 5 people within the indoor space was considered. The last studied factor was the implementation of two different ventilation rates of indoor air.

The results obtained were the indoor temperatures for each of the described factors, which were translated in 3 parameters: average temperature, temperature damping and thermal lag. These parameters were calculated for the coldest and hottest months, which in Portugal coincide with January and August, respectively, and allowed to determine thermal mass influence in indoor temperature and its relative weight when combined with the other factors considered.

Keywords: thermal mass, building envelope, numerical simulations, dynamic modelling, indoor air temperature

INTRODUCTION

a) General concepts

Thermal comfort and energy consumption have become increasingly important, and it reflects the emergence of more demanding standards and regulations. However, thermal inertia is taken into account with very simplistic methods in a lot of these documents.

In building design, thermal mass is a property of the mass of a building which enables it to store heat, providing "inertia" against temperature fluctuations. The best way to study this property is to simulate the thermal performance of buildings in dynamic regime.

Dynamic analyzes are complex and require many parameters which vary both with the climate as with the type of occupation. These parameters can be grouped as internal conditions, external conditions and properties of the envelope elements between the two environments, Fig.1.

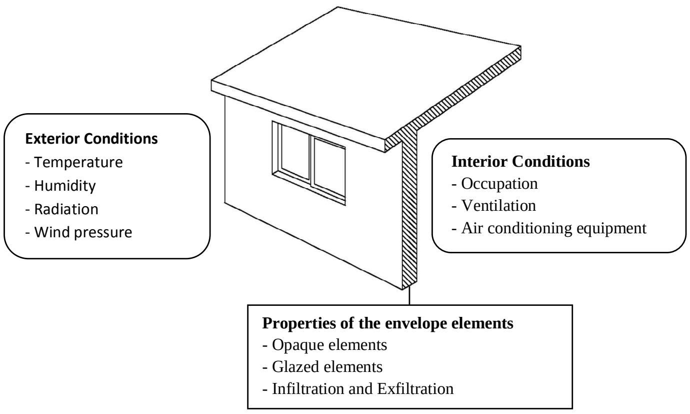


Fig.1 Synthesis of the factors involved in an energy calculation

The exterior conditions are essentially the local weather. These values are measured by seasons and are available from institutional data bases, and may be arranged as:

- annual design conditions (annual heating and humidification; annual cooling and dehumidification and extreme annual conditions);
- monthly and hourly design conditions (temperatures, degree-days and degree-hours, relative humidity, wind direction and speed, monthly/hourly dry-bulb and wet-bulb and mean coincident temperatures, solar irradiance and radiation, amongst others).

The indoor conditions depend on and are conditioned by the type of occupation. These conditions are characterized by:

- the gains from building occupancy;
- the gains and losses from ventilation;
- the gains from air conditioning equipment.

Regarding the gains from building occupancy, this condition is due to human occupation and activities carried out in the interior spaces (thermoregulation of the human body, the gains from lighting and other equipment's).

The gains and losses from ventilation is associated to the intentional introduction of outside air into the building through natural or mechanical ventilation. The introduction of outside air into the buildings is responsible for a lot of the heat loss (winter) or heat gain (summer) in the interior spaces, and for this reason it is important to limit these exchanges without impairing the quality of indoor air. Losses due to air exchanges can represent 20 to 50% of the thermal load of the building (ASHRAE, 2009). Natural ventilation is the flow of air through the building elements such as windows, doors and open grids due to pressure differences between spaces, temperature differentials or caused by wind gusts. Mechanical ventilation (or forced) is the intentional movement of air in the building using fans of introduction and extraction of air.

Regarding the gains from air conditioning equipment, this aspect is associated to the need to incorporate heating, cooling or HVAC (Heating, Ventilation and Air Conditioning) equipment, to ensure a comfortable and constant indoor environment throughout the year, since in most cases the building alone is not capable of ensuring the comfort requirements. In an dynamic energy analysis the consideration of air-conditioning systems is indispensable.

Regarding the properties of the envelope and the interior elements, the main properties of the of the envelope that are important to characterize are the infiltrations and exfiltrations and the properties of the construction elements that allows calculating the thermal flow

The infiltrations are leaks that occur from the external environment to the interior, while exfiltrations make the opposite direction, from inside to outside. These air leaks are due to unintentional nature and occur throughout cracks or openings in constructive elements, and are mainly caused air movements imposed by wind pressure, Fig.2.

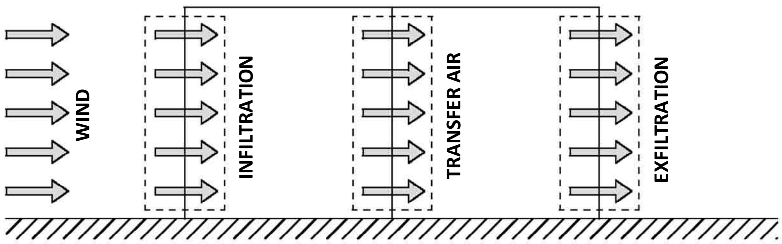


Fig.2 Two-space building with infiltration and exfiltration (adapted from ASHRAE, 2009)

Despite infiltrations and exfiltrations being unavoidable, they are increasingly less significant because most recent buildings are increasingly air tighter. However, it is for this reason that there is the need for inclusion of grids on facades, or even the incorporation of mechanical fans, to ensure the required renewal of indoor air and air quality.

Regarding the properties of the construction elements and calculation the thermal flow, in energy analysis it is necessary to characterize the properties of the building elements, opaque or glazed. Buildings are traditionally made of walls, floors and roof, and the gaps are doors, windows and skylights. To characterize these elements, it is necessary to know the core properties and the surface properties of the elements. The core properties of the elements define the resistance offered by the materials to heat transfer between spaces:

- ρ - material density, kg/m^3;
- k - thermal conductivity, W/(m.^{o}C);
- Cp - thermal capacity, J/(kg.^{o}C);
- α - thermal diffusivity = k/(ρCp), m^2/s.

The thermal conductivity quantifies the ability of a material to conduct thermal energy, the thermal capacity is the physical quantity that determines the relationship between the amount of heat supplied to the material and the temperature variation, and thermal diffusivity expresses how quickly the materials react to temperature changes.

The surface properties of the elements, such as absorptance coefficient, reflection coefficient and emissivity coefficient, are needed for the determination of thermal gain by solar radiation, which is decomposed into absorbed, reflected and transmitted energy (the transmission is zero for opaque elements), Fig.3.

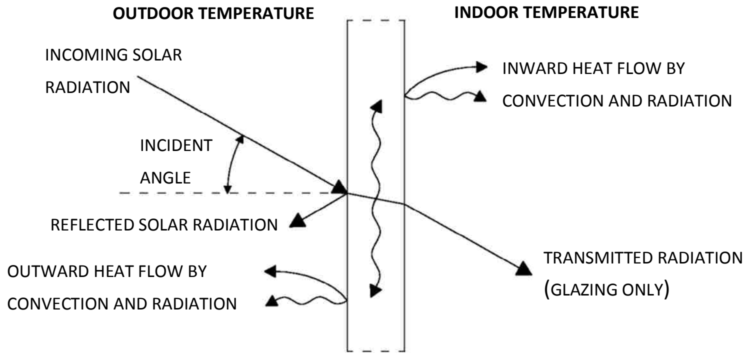


Fig.3 Instantaneous heat balance for sunlight (adapted from ASHRAE, 2009)

Moreover, on glazing elements it is necessary to take into account the presence or not of shading elements. These shading elements significantly reduce solar radiation, thus reducing the thermal gains through the glazing, Fig.4.

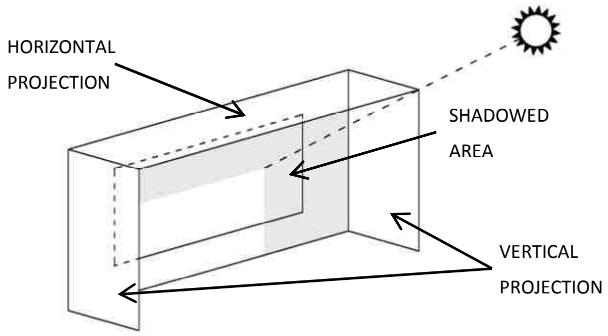


Fig.4 Vertical and horizontal projections and related profile angles for vertical surface containing fenestration (adapted from ASHRAE, 2009)

These properties allow the calculation of the heat flux. Considering a static heat flow, the calculation can be done by the following expressions:

Opaque elements: $$Q = UA_{op}(t_i - t_e) \quad (1)$$
Glazed elements: $$Q = UA_{pf}(t_i - t_e) + (SHGC)A_{pf}E_t \quad (2)$$

$Q =$ instantaneous energy flow, W/h
$U =$ overall coefficient of heat transfer, W/(h.m^2. ^{o}C)
$A_{po} =$ total projected area of opaque elements, m^2
$A_{pf} =$ total projected area of fenestration, m^2
$t_{in} =$ indoor air temperature, ^{o}C
$t_{out} =$ outdoor air temperature, ^{o}C
$SHGC =$ solar heat gain coefficient, dimensionless
$E_t =$ incident total irradiance, W/(h.m^2)

The expressions (1) and (2), while useful, do not express the influence of thermal mass. For a transient state of the phenomenon, the expression (3) determines the temperature (T), at a given position, (x), and time, (τ), for a constant heat flux in a semi-infinite element (flat element with finite thickness) (Holman, 1986):

Opaque elements: $$T = t - t_i = \frac{2q_0\sqrt{\alpha\tau/\pi}}{kA} exp\left(\frac{-x^2}{4\alpha\tau}\right) - \frac{q_0 x}{kA}\left(1 - erf\frac{x}{2\sqrt{\alpha\tau}}\right) \quad (3)$$

$t =$ temperatures, ^{o}C
$k =$ thermal conductivity, W/(m. ^{o}C)
$\alpha =$ thermal diffusivity, m^2/s
$x =$ position/thickness, m
$\tau =$ moment/time, s
$erf =$ error function (see in [3])
$\frac{q_0}{A} =$ constant heat flow through the element, W/m^2

However, this last expression does not take into account the variation of heat flux over time. The variation of conditions to which the building is subjected can lead to complex energy calculations. The heat fluxes vary over time, making it necessary the use of dynamic simulations. For these simulations are typically used hourly calculation tools, to study the response of buildings in extreme temperature conditions. For these calculations the most efficient way is the use of computer programs, such as Energy plus software. Nevertheless, some calculation methods for energy use for space heating and cooling are defined standards, such as ISO 13790 (ISO 13790, 2008).

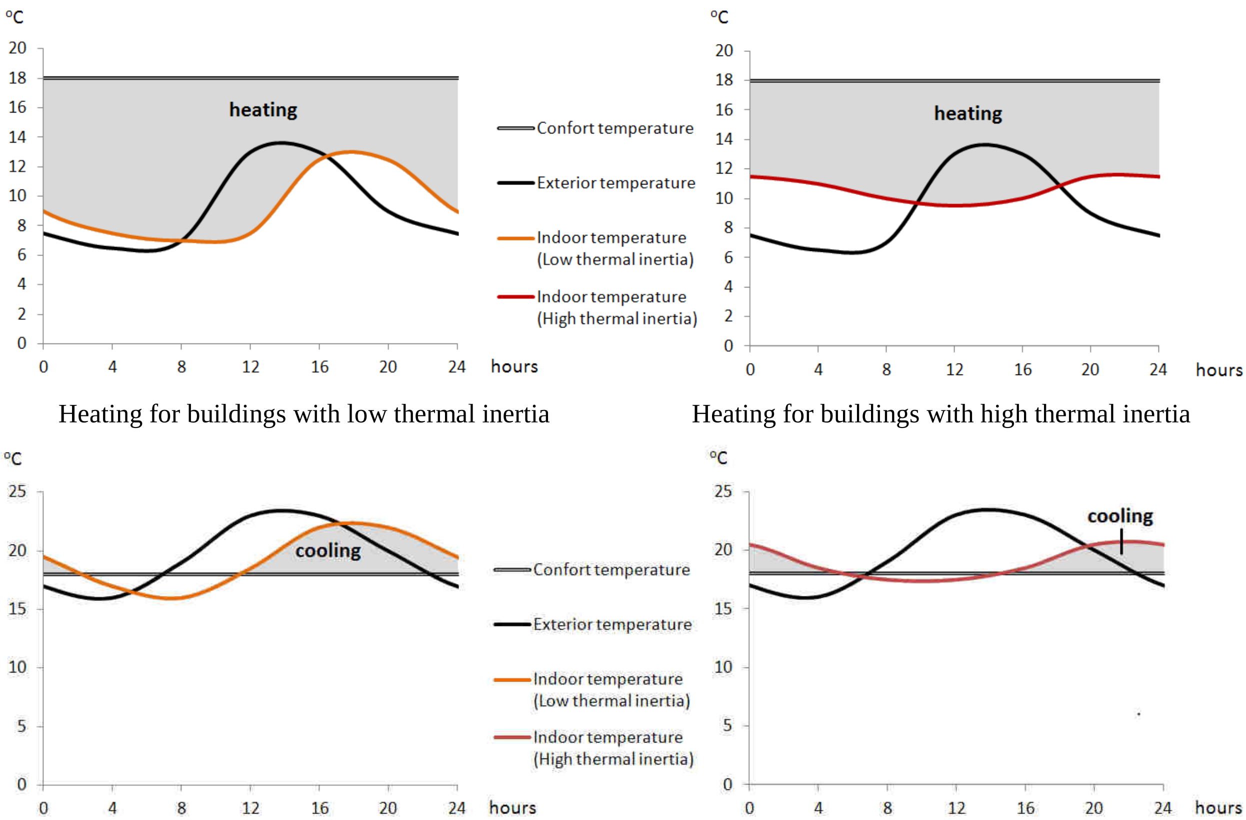
b) Role of thermal inertia in buildings

One aspect that impacts the comfort of the indoor environment is the capacity of building elements, such as walls and slabs, for damping temperature variations of outdoor air, in particular damping the maximum and minimum temperature points. This effect is commonly referred to thermal inertia.

The thermal inertia increases with increasing mass of the walls, which means, in other words, increasing the thermal capacity of the wall (thermal mass). Therefore, in addition to a low thermal conductivity, it should also be ensured a high heat capacity, which it can be obtained with a heavier construction. A strong thermal inertia can bring benefits in energy consumption of a building, especially for buildings with continuous habitation on temperate climates.

In addition to the damping effect, there is also the time lag effect that allows building elements to provide heat in the colder hours of the day and absorb heat in the hotter hours. Recommendations for this time lag range from 6 to 12 hours (Tubi, 1999; Alves e Sousa, 2003), depending on the geographical location, building orientation and weather season.

Figure 5 illustrates the expected behavior of two buildings with different thermal inertia in the coldest and hottest months of the year in Portugal. It can be seen that the need for heating a high thermal inertia is lower in the heating season (winter), while cooling requirements e are reduced in the cooling season (summer) and can also be lessened with a high thermal inertia.



Heating for buildings with low thermal inertia | Heating for buildings with high thermal inertia

Cooling for buildings with low thermal inertia | Cooling for buildings with high thermal inertia

Fig.5 Heating and cooling to ensure comfort in the coldest month and in the hottest month of the year

In conclusion, the thermal inertia can bring benefits to energy consumption, but there are other factors that can completely change the referred behavior, in particular the percentage of glazing and the indoor air ventilation. The existence of large glazed areas can be beneficial in the heating season (winter), but causes overheating of the indoor environment, if these elements are not properly protected during the cooling season (summer).Ventilation can be beneficial in the cooling season (summer) for removing the heated indoor air, but the air exchanges in the heating season (winter) are responsible for a significant part of the heat loss of the indoor air.

NUMERICAL SIMULATIONS - PARAMETRIC STUDY

To better understand the influence of some of the factor described before, numerical simulations were performed with software developed by the US Department of Energy (Energy Plus). The factors simulated in this parametric study were:

a) influence of Local weathers;
b) influence of increasing the thermal insulation on the exterior envelope;
c) glazing/fenestration orientation;
d) occupation (Indoor gains);
e) indoor air ventilation;
f) combination of factors.

The assumptions made on each one factors are explained afterwards in the discussion of results. To simplify the study, a single compartment was modelled in which the walls and roof were in contact with the outside environment and the floor with the ground, Fig.6.

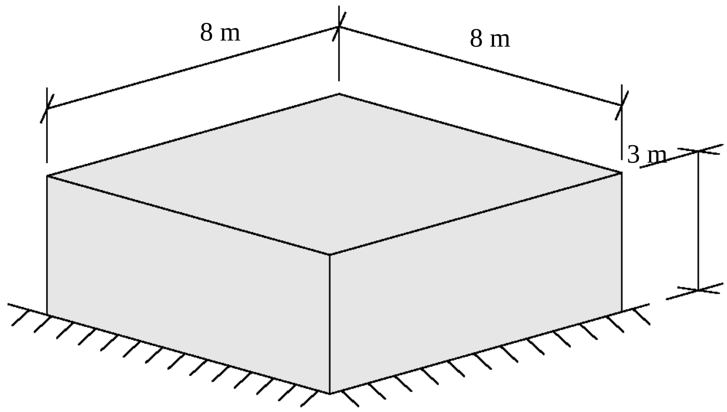


Fig.6 Representation and dimensions of the simulated compartment

The constructive solutions considered for building elements (floor, walls and roof) in the numerical simulations were:

- HeavyConst_ExtIns - Concrete structural element with external thermal insulation;
- HeavyConst_IntIns - Concrete structural element with internal thermal insulation;
- LightConst - Element composed exclusively of thermal insulating material with interior and exterior coatings.

For these three solutions it was ensured that the heat transfer coefficient and the coating solutions were all the same. In Table 1 are shown the properties used for the building elements. The performed simulations are synthesized in Table 2.

Tab.1 Thermal properties used for the constructive solutions

Constructive solutions / Layers		Thickness (cm)	ρ (kg/m²)	c_p (1) (J/kg.K)	λ (W/m.K)	U (W/m².K)
HeavyConst_ExtIns	Rendering (exterior)	2,5	1858	837	0,6918	
	Thermal insulation (Wool)	3,4	91	837	0,0432	
	Concrete	20,3	2243	837	1,7296	
	Gypsum plaster (interior)	1,3	785	830	0,1600	
HeavyConst_IntIns	Rendering (exterior)	2,5	1858	837	0,6918	
	Concrete	20,3	2243	837	1,7296	0,98
	Thermal insulation (Wool)	3,4	91	837	0,0432	
	Gypsum plaster (interior)	1,3	785	830	0,1600	
LightConst	Rendering (exterior)	2,5	1858	837	0,6918	
	Thermal insulation (Wool)	3,9	91	837	0,0432	
	Gypsum plaster (interior)	1,3	785	830	0,1600	

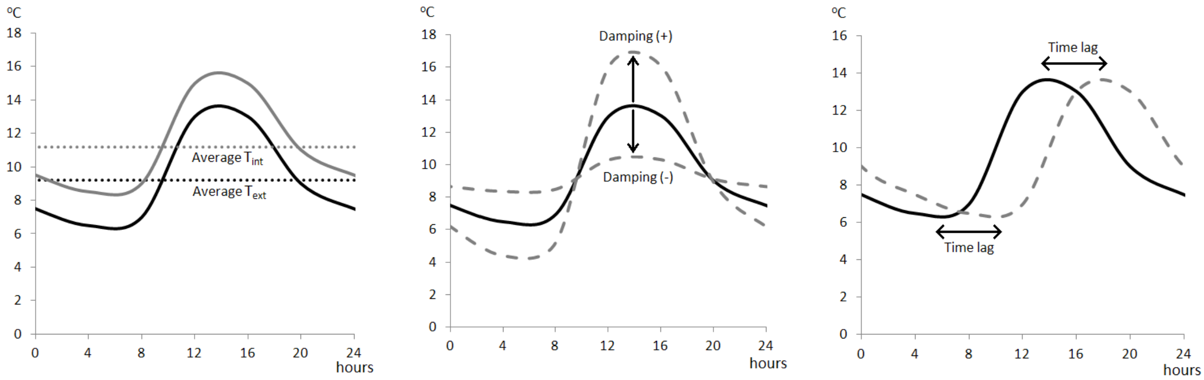
(1) For current building materials, except metals, plastics and wood, specific heat values have little variations (between 800 and 1000 J/kg.K).

Tab.2 Combinations simulated with Energy Plus software

Cases	**Weather**			**Season**		**Increased insulation**	**Fenestration**		**Occupation**	**Ventilation (air changes per hour)**	
	Porto	Bragança	Évora	Heating (January)	Cooling (August)		North	South	5 occup.	0,4 ach	0,6 ach
1.1 – Porto, winter (reference)	✓			✓							
1.2 – Porto, summer (reference)	✓				✓						
1.3 – Bragança, winter		✓		✓							
1.4 – Bragança, summer		✓			✓						
1.5 – Évora, winter			✓	✓							
1.6 – Évora, summer			✓		✓						
2.1 – Increased insulation, winter	✓			✓		✓					
2.2 – Increased insulation, summer	✓				✓	✓					
3.1 – North fenestration, winter	✓			✓			✓				
3.2 – South fenestration, summer	✓				✓		✓				
3.3 – North fenestration, winter	✓			✓				✓			
3.4 – South fenestration, summer	✓				✓			✓			
4.1 – Occupation, winter	✓			✓					✓		
4.2 – Occupation, summer	✓				✓				✓		
5.1 – Ventilation-0,4 ach, winter	✓			✓						✓	
5.2 – Ventilation -0,4 ach, summer	✓				✓					✓	
5.3 – Ventilation -0,6 ach, winter	✓			✓							✓
5.4 – Ventilation -0,6 ach, summer	✓				✓						✓
6.1 – Combination (reference), winter	✓			✓			✓	✓	✓		✓
6.2 – Combination (reference), summer	✓				✓		✓	✓	✓		✓
6.1 – Combination (increased insulation), winter	✓			✓		✓	✓	✓	✓		✓
6.2 – Combination (increased insulation), summer	✓				✓	✓	✓	✓	✓		✓

For each combination referred in Table 2, the following parameters were calculated, Fig.7:

- AVERG - Monthly average indoor temperature (°C);
- DAMP - Average damping of peak temperatures (ºC);
- LAG - Time lag of the maximum and minimum peak temperatures (hours).



Average temperature | Temperature damping | Time lag

Fig.7 Schematic representation of the calculated parameters from simulations output

For comparison purposes with considered combinations, it was admitted that the first two cases, 1.1 and 1.2 (Porto winter and summer), were reference situations.

RESULTS AND DISSCUTION

a) Influence of local weathers

In order to compare the thermal behavior of the compartment in different weathers, it was chosen to study the cities of Porto (reference), Bragança and Évora. The weather files were obtained from the Energy Plus database (U.S. Department of energy, 2014). The results are presented in Table 3.

Tab.3 Results for the locations in Porto (1.1; 1.2), Bragança (1.3; 1.4) and Évora (1.5; 1.6).

	T$_{ext}$	**HeavyConst_ExtIns**			**HeavyConst_IntIns**			**LightConst**		
Cases	Averg (ºC)	Averg (ºC)	Damp (ºC)	Lag (hours)	Averg (ºC)	Damp (ºC)	Lag (hours)	Averg (ºC)	Damp (ºC)	Lag (hours)
Ref-1.1	9,4	13,2	-3,4	5 - 7	13,7	-2,4	5 - 8	13,3	3,0	1 - 2
Ref-1.2	19,4	25,2	-3,1	6 - 7	26,5	-1,1	7	25,1	7,7	2
1.3	4,3	10,2	-2,3	4 - 6	10,3	-1,5	4 - 6	10,0	2,9	0 - 1
1.4	21,0	26,9	-5,7	5 - 6	27,6	-3,6	6	26,5	5,9	1
1.5	8,8	14,2	-2,0	5 - 10	14,0	-1,0	6 - 7	13,7	3,8	2
1.6	22,9	27,8	-5,6	6	28,1	-3,3	7	27,8	5,6	1

From these results, the following aspects are highlighted:

- average temperatures do not differ significantly;
- heavy construction has a high damping (-2 to -6 ° C), although slightly smaller when the insulation is in the interior;
- the temperature peaks in the lightweight construction are aggravated, unlike the other solutions, causing overheating (from +3 to +8 ° C);
- the time lag is higher for heavy construction (4 to 8 hours) and extremely low or zero for lightweight construction (0 to 2 hours);
- average temperatures have slight differences due to more extreme temperatures in Bragança and Évora weather;

- comparing with Bragança and Évora weathers, damping for the Porto weather is slightly higher for the heating season (winter) and slightly lower for the cooling season (summer);
- the time lag for Bragança weather is generally lower.

b) Influence of increasing the thermal insulation on the exterior envelope

As mentioned before, it was assumed as reference that the three constructive solutions had the same heat transfer coefficient, U=0,98 W/m^{2}K. For the studied cases treated in this point, it was considered an insulation increment of 3,4 to 10,1 cm for the two heavy solutions, and for lightweight solution an insulation increment of 3,9 to 10,6 cm. This resulted in a new heat transfer coefficient, U= 0,39 W/m^{2}K (Cases 2.1 and 2.2). The results are presented in Table 4.

Tab.4 Results with increased thermal insulation (2.1; 2.2)

	T_{ext}	**HeavyConst_ExtIns**			**HeavyConst_IntIns**			**LightConst**		
Cases	Averg (ºC)	Averg (ºC)	Damp (ºC)	Lag (hours)	Averg (ºC)	Damp (ºC)	Lag (hours)	Averg (ºC)	Damp (ºC)	Lag (hours)
Ref-1.1	9,4	13,2	-3,4	5 - 7	13,7	-2,4	5 - 8	13,3	3,0	1 - 2
Ref-1.2	19,4	25,2	-3,1	6 - 7	26,5	-1,1	7	25,1	7,7	2
2.1	9,4	13,8	-3,5	6 - 11	13,6	-3,0	7 - 12	13,3	-0,3	3 - 4
2.2	19,4	25,2	-3,4	7 - 8	26,5	-2,4	9	25,3	2,3	4

From these results, the following aspects are highlighted:

- it appears that there are no noticeable changes in average temperature with increased thermal insulation, which may be justified by the lack of internal heat gains;
- damping presents no change for the heavy construction with exterior insulation, while a reduction of peak temperatures were found for lightweight construction (3 to 5 °C);
- time lag presents a clear increase in general (1 to 4 hours).

c) Influence of glazing/fenestration orientation

The existence of glazing elements/fenestrations were considered in the north and south walls (cases 3.1, 3.2, 3.3 and 3.4) with an area equal to 25% of the area of these walls. The simulations were performed separately for the north and south walls with glazed elements. The features considered these elements were: - glass thickness (3 mm); - thermal conductivity (2,5 W/m.K); emissivity (0,84); transmittance (0,85). The results are presented in Table 5.

Tab.5 Results for the incorporation of windows in the North (3.1 and 3.2) and South walls (3.3 and 3.4).

	T_{ext}	**HeavyConst_ExtIns**			**HeavyConst_IntIns**			**LightConst**		
Cases	Averg (ºC)	Averg (ºC)	Damp (ºC)	Lag (hours)	Averg (ºC)	Damp (ºC)	Lag (hours)	Averg (ºC)	Damp (ºC)	Lag (hours)
Ref-1.1	9,4	13,2	-3,4	5 - 7	13,7	-2,4	5 - 8	13,3	3,0	1 - 2
Ref-1.2	19,4	25,2	-3,1	6 - 7	26,5	-1,1	7	25,1	7,7	2
3.1	9,4	13,2	-3,4	1 - 6	13,6	-2,5	1 - 6	13,2	3,4	1 - 2
3.2	19,4	25,5	-3,1	2 - 4	26,6	-1,1	3 - 4	25,3	8,2	2
3.3	9,4	15,0	-2,8	1 - 0	15,3	0	1 - 0	14,8	5,9	1
3.4	19,4	26,8	-2,8	2 - 0	28,0	0,3	3 - 1	26,7	10,3	2 - 1

From these results, the following aspects are highlighted:

- no major changes in the average indoor temperatures, the damping or the lag, due to the fact that north walls in Portugal have a reduced sun exposure;
- an increase in the average indoor temperature was found when incorporating glazing elements on the south wall (1 to 2 °C);
- damping is differently affected by the existence of glazing elements on the south wall: it ranges from a slight increase in the peak temperatures for heavy construction with exterior insulation (0,3 to 0,6°C), to a large increase in the peak temperatures for lightweight construction (2,6 to 2,9°C);
- the results show that the heavy solution, either with interior or exterior insulation, is not able to damp the gains by solar radiation;
- time lag is lost when incorporating glazing elements in the south wall.

d) Influence of occupation (Indoor gains)

The influence of occupation in indoor environment was considered by a permanent occupation of 5 people, in which each person corresponded to 75W of heat gain. The results are presented in Table 6.

Tab.6 Results for indoor occupation (4.1 e 4.2).

Cases	T_{ext} Averg (ºC)	HeavyConst_ExtIns Averg (ºC)	Damp (ºC)	Lag (hours)	HeavyConst_IntIns Averg (ºC)	Damp (ºC)	Lag (hours)	LightConst Averg (ºC)	Damp (ºC)	Lag (hours)
Ref-1.1	9,4	13,2	-3,4	5 - 7	13,7	-2,4	5 - 8	13,3	3,0	1 - 2
Ref-1.2	19,4	25,2	-3,1	6 - 7	26,5	-1,1	7	25,1	7,7	2
4.1	9,4	15,9	-3,3	5 - 7	16,4	-2,3	5 - 7	15,8	3,0	1 - 2
4.2	19,4	27,2	-3,1	6 - 7	28,3	-1,4	7	26,8	6,7	2

From these results, the following aspects are highlighted:

- a general increase in average temperature was found (1.7 to 2.7 °C);
- damping and time lag did not report significant changes with indoor occupation.

e) Influence of indoor air ventilation

The ventilation rates simulated were 0.4 and 0.6 ach in a steady state. The results are presented in Table 7.

Tab.7 Results for indoor air ventilation of 0,4 ach (5.1 e 5.2) and 0,6 ach (5.3 e 5.4).

Cases	T_{ext} Averg (ºC)	HeavyConst_ExtIns Averg (ºC)	Damp (ºC)	Lag (hours)	HeavyConst_IntIns Averg (ºC)	Damp (ºC)	Lag (hours)	LightConst Averg (ºC)	Damp (ºC)	Lag (hours)
Ref-1.1	9,4	13,2	-3,4	5 - 7	13,7	-2,4	5 - 8	13,3	3,0	1 - 2
Ref-1.2	19,4	25,2	-3,1	6 - 7	26,5	-1,1	7	25,1	7,7	2
5.1	9,4	12,1	-2,9	1 - 0	12,4	-1,6	1	12,1	2,9	1
5.2	19,4	23,5	-2,8	2 - 1	24,3	-1,2	3	23,3	6,4	2 - 1
5.3	9,4	11,9	-2,8	1 - 0	12,2	-1,6	1	11,9	2,8	1
5.4	19,4	23,2	-2,7	1	24,0	-1,2	2	23,1	6,1	2 - 1

From these results, the following aspects are highlighted:

- influence of ventilation rate of 0.4 ach: - reduction in the average temperature (1,1 to 2,2 ° C); - slight increase in the peak temperatures for heavy construction with exterior insulation (0,3 to 0,5 °C); - slight reduction in the peak temperatures for lightweight construction (1,3 °C); - time lag was lost for heavy construction with exterior insulation, while no change was found for lightweight construction.
- influence of ventilation rate of 0.6 ach: - there is a slight reduction in average temperature and a slight increase in peak temperatures (0,1 to 0,3°C) when compared to ventilation rate of 0.4 ach.

f) Combination of factors

To better understand the influence of combining some of the factors analyzed, a simulations were performed for the constructive solutions listed in table 1 with increased insulation as referred in b). The combination of factors considered are listed in table 2 (cases 6.1, 6.2, 6.3 and 6.4). The results are presented in Table 8.

Tab.8 Results for combination of factors

	T_{ext}	**HeavyConst_ExtIns**			**HeavyConst_IntIns**			**LightConst**		
Cases	Averg (ºC)	Averg (ºC)	Damp (ºC)	Lag (hours)	Averg (ºC)	Damp (ºC)	Lag (hours)	Averg (ºC)	Damp (ºC)	Lag (hours)
Ref-1.1	9,4	13,2	-3,4	5 - 7	13,7	-2,4	5 - 8	13,3	3,0	1 - 2
Ref-1.2	19,4	25,2	-3,1	6 - 7	26,5	-1,1	7	25,1	7,7	2
6.1	9,4	15,2	-2,3	0	15,4	0,6	1 - 0	15,1	4,9	0 - 1
6.2	19,4	26,6	-2,2	1 - 0	27,3	0,7	2 - 0	26,3	8,0	1
6.3	9,4	16,7	-2,2	0	16,6	1,8	1	16,4	3,7	1
6.4	19,4	27,7	-2,3	1 - 0	28,2	2,0	2 - 1	27,7	5,6	2 - 1

The following aspects are highlighted for the cases 6.1 and 6.2:

- increase in the average indoor temperature (1 to 2°C);
- increase in peak temperatures in relation to the reference cases (cases 1.1 and 1.2), particularly the solution with interior insulation, in which the damping became zero;
- time lag became globally close to zero for all the constructive solutions.

The following aspects are highlighted for the cases 6.1 and 6.2:

- increase in the average indoor temperature higher than the previous cases (2 to 3 °C);
- damping for the heavy construction solution with exterior insulation has not changed significantly in relation to cases 6.1 and 6.2;
- the heavy construction solution with interior insulation had its peak temperature increased (1°C in relation to cases 6.1 and 6.2);
- the lightweight construction solution had, unlike the others, its peak temperature reduced (1°C in relation to cases 6.1 and 6.2);
- time lag did not changed significantly.

CONCLUSION

From the simulations made in this paper, the following aspects are concluded:

- comparing the constructive solutions, it was concluded that the heavy construction ensures a higher indoor temperature stabilization than lightweight construction;
- unlike heavy solutions, the lightweight construction promoted overheating of the interior space, despite of having the same heat transfer coefficient as the heavy solutions;
- the comparative analysis of Porto, Bragança and Évora weathers has shown small differences in temperatures for the three simulated solutions due to certain weathers being more extreme than others;
- the presence of glazing on the north wall had a negligible contribution for the interior heating in all constructive solutions and in both seasons;
- the presence of glazing on south walls promoted interior heating, with an increase in average daily temperature, reducing the temperature damping and eliminating any existing time lag;
- with the presence of glazing in the south walls, the solutions with interior insulation demonstrated not being able to damp temperature fluctuations in the same way as the solutions with exterior insulation;
- the occupation of interior spaces increased indoor temperature in all simulated cases, but the damping and the time lag were not affected;
- the ventilation reduced the indoor temperatures in all cases and eliminated any time lag promoted by the constructive solutions;
- increasing thermal insulation only had significance in indoor temperatures if any indoor thermal gains occur, such as solar radiation through glazing or heat gains due to occupation;
- higher thermal insulation increased the time lag of indoor temperatures for all the solutions and for both seasons;
- when factors were combined, heavy construction continued to be important in stabilizing the indoor temperature, with higher damping than lightweight construction.

In summary, it was concluded that heavyweight construction ensures higher stability to indoor temperatures, although the use of interior insulation reduces slightly that stability. Furthermore, heavyweight construction is much more stable than lightweight construction. Moreover, it was concluded that glazing orientation and ventilation are the most influential factors since all temperature stability given by the thermal mass can be lost when these factors are more prominent.

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