Márcia Cristina Pereira Tavares
Hélder José Perdigão Gonçalves
Jorge Novais Telles de Faria Corrêa Bastos

Thermoenergetic performance of residential buildings in temperate climate

Abstract

This study sought to link architectural and thermal aspects of buildings to contribute to the design practice by providing an information set related to issues of comfort and energy consumption, obtained through a methodological process involving an experimental component (involving summer and winter monitoring in residential buildings in Lisbon where over 60% of the main façade is glazed) and a numerical component (thermal simulations with the use of the EnergyPlus dynamic program, with modeling and calibration of representative geometric models of frequent typologies). This, therefore, allowed the observation of different parameters, enabling the establishment of performance comparisons between a broad spectrum of solutions (Matrix of current solutions) under a typical Mediterranean climate like that of the city of Lisbon. Thus, this study presents a set of results that demonstrates the potential for designing and constructing buildings with different (in particular large) areas of glazing in temperate climates.

Keywords

Thermal comfort. Thermal buildings. Thermal and energy performance. Passive solar systems. Glazing areas. Residential buildings.

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DESEMPEÑO TERMO-ENERGÉTICO DE EDIFICIOS RESIDENCIALES EN CLIMA TEMPLADO

DESEMPENHO TERMO-ENERGÉTICO DE EDIFÍCIOS RESIDENCIAIS EM CLIMA TEMPERADO

Resumen

Este estudio trata de vincular los aspectos de la Arquitectura y la Térmica de los edificios para contribuir a la práctica de diseño que proporcionan un conjunto de información relacionada a las cuestiones de comodidad y el consumo de energía. Obtenido en un proceso metodológico basado en un componente experimental (realización de monitoreo de verano e invierno en edificios residenciales en Lisboa con superficie acristalada superior al 60% de la fachada principal) y un componente numérico (simulaciones térmicas que utilizan el programa dinámico *EnergyPlus* en un proceso que involucró la modelación y calibración de modelos geométricos representativos de tipologías frecuentes). Esto permitió la observación de diferentes parámetros con la posibilidad de comparar el rendimiento en un amplio espectro de soluciones actuales (soluciones Matriz) bajo un clima típicamente mediterráneo, como el de la ciudad de Lisboa. De esta manera, se presenta un conjunto de resultados que demuestran la capacidad de diseñar y construir edificios de viviendas con diferentes áreas de vidrio, especialmente de grandes proporciones, en Clima Templado.

Palabras clave

Confort térmico. Térmica de edificios. Desempeño térmico y energético. Sistemas solares pasivos. Áreas de acristalados. Edificios residenciales.

Resumo

O presente estudo procura interligar aspectos da Arquitetura e da Térmica dos Edifícios visando contribuir para a prática de projeto disponibilizando um conjunto de informações relacionadas com as questões de conforto e consumo de energia, obtidas a partir de um processo metodológico fundamentado numa componente experimental (medições *in loco* de Verão e Inverno, sobretudo em unidades de edifícios residenciais em Lisboa com áreas de envidraçados superiores a 60% da fachada principal) e numa componente numérica (simulações térmicas recorrendo ao programa dinâmico *EnergyPlus*, num processo que envolveu modelação e calibração de modelos geométricos representativos de tipologias frequentes); o que permitiu a observação de diferentes parâmetros com possibilidade de comparar o desempenho entre um espectro alargado de soluções correntes (Matriz de soluções) sob um clima tipicamente mediterrâneo como o da cidade de Lisboa. Desta forma, sendo assim apresentado um conjunto de resultados que comprovam a possibilidade de se projetar e construir edifícios residenciais com diferentes áreas de envidraçados, principalmente com grandes proporções, em Clima Temperado.

Palavras-chave

Conforto térmico. Térmica dos edifícios. Desempenho térmico e energético. Sistemas solares passivos. Áreas de envidraçados. Edifícios residenciais.

1. Introduction

Buildings are an important economic sector in Portugal. Furthermore, they represent close to 30% of the final energy consumption of the country and are responsible for almost 55% of the electricity consumption (17% residential and 36% services), placing this sector in second place for greenhouse gases emissions. It is also important to consider that Portugal produces only a small fraction of the energy it consumes (about 20%). The trends show an increase in the annual average consumption which, tied to an increase in the search for better comfort and building quality, results in economic and socio-environmental concerns (DGGE, 2012).

More specifically in relation to the residential sector, it is worth highlighting that thermal comfort (heating and cooling) consumption represents almost one quarter (22%) of the total energy consumption of residential units (SOUSA *et al.*, 2012). Meanwhile, in the last decades Portugal was compelled to take action to limit the production of greenhouse gases. Measure of particular note are Decrees-Law 79-80/2006 (PORTUGAL, 2006) that established the residential buildings and services energy regulations that aimed to meet tighter building requirements for European Union countries and led, on average, to an increase of 25% in requirements in relation to previous levels, regulated by Directive n.° 2002/91/CE (Figure A.1.c Annex A).

Both thermal regulations were revised in 2013, in line with Directive n.° 2010/31/EU, as can be observed in the new certification that forms part of the residential, commercial and service building regulation (Decree-Law n.° 118/2013) and in respective ordinances (Port. n.° 349/2013). These documents establish that the Portuguese building stock should progressively move towards almost zero energy needs (buildings with high energy performance: low or zero carbon dioxide emissions and energy consumption), by applying an optimum cost methodology where buildings are evaluated and subject to envelope thermal quality requisites, expressed in thermal transmission coefficient terms and glazing solar factors. In the residential buildings case, the established reference U value for vertical opaque envelopes is now between 0.30 – 0.5 and for glazing between 2.2 – 2.90. The corresponding values for Climate Zone V1, which includes Lisbon, can be seen in Table 1 of Figure A.1.c.

The gradual tightening of building quality regulatory requirements (opaque and transparent elements) has been taking place at the same time as an increase in the interest in and application of glass in the Portuguese building stock, a result of production and manufacturing advances. The increase in the use of glass in architecture and construction can be seen more frequently in the services building stock in Lisbon (see Figure 1.a). By contrast, although residential buildings generally display more contained and controlled glazing, a clear increase of its use is noted, in particular in constructions built during recent decades (Figure 1.b) where glazed façades, similar to those found in service buildings, can be observed. (see Figure 1.b.2).

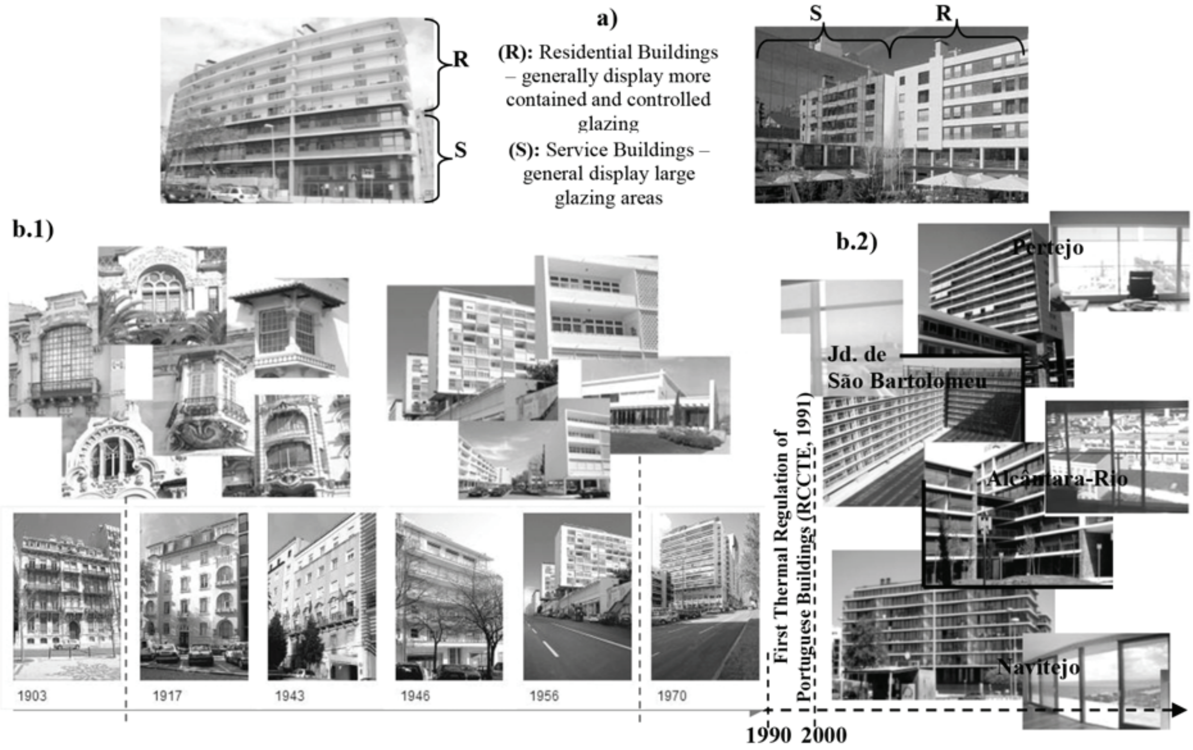


Figure 1: Example of mixed buildings (services and residential) in Lisbon. b) Residential building evolution and glazing areas (Lisbon, Portugal): 1) Valmor Award Buildings (SILVA et al, 2004); 2) Buildings with large glazing areas built in the last decades (exterior and interior views of the study object buildings).
Source: TAVARES, 2012.

In this context, it is important to consider that heat exchange between the inside and the outside of a building depends on the type of materials (opaque, non-opaque) employed and their relative size. However, heat exchange generally takes place through transparent elements (due to the amount of radiation directly transmitted towards the interior), that is, those building envelope elements better able to adapt to climate variations, providing greater radiation, ventilation and natural illumination control. In other words, this is the most dynamic, flexible, and interesting building envelope element (allowing for adjustments and adaptations to obtain the desired interior conditions), essential for the successful application of most passive solar heating systems (when under the correct solar orientation) when considering the city of Lisbon's climate.

Thus, large glazing areas in residential buildings are architectural solutions/ options that allow for a more homogeneous exterior aesthetic view, landscape contemplation, greater transparency and luminosity. However, they also have a direct impact on the interior temperature conditions and a satisfactory thermal and energetic performance will depend on design. The larger the dimensions of glazing area in a housing unit, the greater the potential for the unit to gain or lose heat (the overall heat transfer coefficient of glazing is greater than that of opaque envelopes).

Furthermore, the thermal behavior of a building also depends on factors such as the glazing solar control and protection devices, thermal inertia, building thermal insulation levels, and air exchange rates. Therefore, in order to assess the interior conditions of a building with large glazing areas, it is necessary to evaluate different case studies so as to uncover the relationship between variables that also make up the Passive Solar System.

1.1. Objective

The main aim of this study is to assess *whether there are solutions (and if so, which) that present interior air conditions within certain temperature thresholds that, at the same time, result in lower energy expenditures* in residential buildings with large glazing areas in a typically Mediterranean climate such as the city of Lisbon (used for the application of the proposed methodology).

In addition, the objectives of this study also include:

- Verifying the thermal and energetic behavior of large glazing areas, under the influence of various parameters;

- Observing a set of representative constructive solutions - typical of solutions widely used in the building stock - where the transparent envelope is the main element and, therefore, analyze the possible limits and constraints that may exist within a solutions map, whilst at the same time respecting the architect's freedom to design.

Thus, by considering building quality and interior comfort conditions this study aims to assist professional architects in their decision-making process during the initial phases of the project, contributing to a building design that maximizes performance and minimizes consumption.

1.2. Methodology

In order to conduct this study, a number of buildings in the city of Lisbon were chosen with characteristics that were relevant and intrinsically associated to recent construction and architectural practices. These buildings present large glazing areas and were built after the first building thermal regulations came into effect in Portugal, Decree-Law n° 40/90 (PORTUGAL, 1990).

The methodology presented in this study included in loco measurements during summer (July-August of 2007-2008) and winter (December-January of 2007-2008 and 2008-2009) campaigns in different units of the buildings selected for the study. This allowed for the observation of the behavior of concrete cases under real conditions. Besides the experiment assessment, a set of simulations was carried out (utilizing the EnergyPlus, E^+ thermal simulation program) through building detailed models (corresponding to the monitored units) and developing simplified models capable of representing some of the typologies frequently observed in the residential sector.

A solutions matrix was created based on the simplified models, using glazing areas as the main observation parameter and a conditioning for other factors. For the mapping of different solutions (Solutions Matrix) were defined parameters associated to the elements contained in the passive solar system typical of Portuguese construction; as well as summer and winter threshold conditions, allowing for the observation and comparison of the performance of an extended range of current solutions used in the main seasons, in different years. By using these processes (experimental and numerical components) it was possible to obtain a set of results related to the interior conditions of the different solutions in the Matrix, in accordance to the thresholds established in the study. Findings revealed that it is possible to design and build residential buildings with different glazing areas, mainly of large proportions, in temperate climates like that of Lisbon, Portugal. Therefore, this study makes it possible to transition from specific situations identified in the building stock, taking into account the architecture and recent construction for residential buildings, to a diversity of solutions of interest to design practice.

In the following sections the different phases listed below are described and the main results are presented: Study Object and Sample (Section 2); Summer and Winter in loco Measurements (Section 3); Geometric Models Calibration, Constructive Solutions Matrix with Parameters Used, and Results (Section 4).

1.2. Climate

Lisbon has one of mildest climates in comparison to other capitals in Europe, typical of Mediterranean countries (according to the Köppen climate classification), located in regions of latitudes between 30° and 40° (to the north or south). As can be seen in Annex A, Figure A.1, Lisbon has well-defined seasons throughout the year, a characteristic of temperate climates. Summers are generally hot and dry with temperatures between 16°C and 37°C (average maximum is 28°C in August) and average relative humidity near 60%. Winters are typically rainy and comfortable with temperatures between 2°C and 17°C (average minimum 8°C in January) and average relative humidity close to 80%. The average annual precipitation is 774mm but between June and September it falls below 50mm. The prevailing winds are from the north and northwest.

In the European context, the representativeness of the Lisbon climate should also be noted, as it has been chosen as a representative city of one of the five reference climate zones for the European *"Keep Cool"* project (GRIGNON-MASSÉ *et al.*, 2009), where solar radiation and degree-days (heating and cooling) were used as the main parameters for characterizing the severity of summer and winter (considering data from over 30 European cities), Annex A Figure A.1b).

2. Study object and sample

Considering this study's main objective, some residential developments forming part of the Lisbon building stock were selected. These included the Navitejo, Pertejo, Alcantara-Rio and Jardins de São Bartolomeu buildings (Figure 1.b.2 and Annex B figures). This selection was made taking into account the evolution of residential buildings in Portugal, supported by bibliographic and field studies that focused on developments built in recent decades, relating to the topic of this study.

The buildings selected were designed by recognized architects in Portugal and contained glazing areas covering over 60% of their exterior envelope. They were built after the implementation of the first Building Thermal Regulation in Portugal (1990). This regulation sought to promote the adoption of constructive solutions involving the introduction of thermal insulation and double glass. Thus, the buildings chosen for this study present exterior envelope thermal transmission coefficient values (U) as follows - walls: between 0.35 and 0.68; roof: between 0.47 and 0.63; and glazing: between 2.8 e 3.2 (mostly double clear glass).

2.1. Sample

A set of residential units was selected from the buildings object for monitoring in the study (22 units, typologies of 1 to 4 bedrooms). Whenever possible, the residential units selected in each building were of the same type, had similar floor plans and the same main solar orientation. They consisted of a total of 46 environments (24 living room type and 22 bedroom type), where people tend to spend more time, with different occupation and use patterns. The following were observed: surface area to volume ratio 0.1 to 0.85, floor area ≈15m²-60m²; ceiling height 2.60m-2.65m; and glazing areas between 15% to 95% of the corresponding floor area.

It should be noted that in more than 80% of units, the glazing area is greater than *60% of the corresponding exposed side and, in some cases, this ratio was closer to 90%* (building interior view, Figure 1.b.2). Surveys (section 3.3) revealed that over 80% of the users of these units preferred this type of arrangement. In relation to shading, only 11% did not have horizontal brise-soleils, while 57% did not have any type of exterior shading devices/control for the glazing. As for climatization systems, 78% of units in the sample had some type of heating and 13% had air conditioning cooling systems.

3. In loco data monitoring

A set of in loco measurements were made during the seasons requiring cooling (July – August)[1] and heating (December – January)[2] in the selected samples during two consecutive years (two summer and two winter campaigns, between 2007 – 2009).

For the measurements, temperature and humidity sensors[3] were installed, generally in the sample residential unit living rooms and bedrooms. The uses and occupation patterns of the residential units were recorded. In addition, the residents' opinions were also registered by means of questionnaires addressing thermal comfort issues.

During the measurement periods, external conditions were obtained from the National Energy and Geology Laboratory Meteorological Station, IP (LNEG), located at *Edifício Solar* XXI, Lisbon. The choice of Meteorological Station and the adoption of respective climate records for the relevant periods were made, taking into account climate variability studies for the city of Lisbon, developed by Alcoforado and published in "ACLURE" (GONCALVES *et al.*, 2004). There is evidence of the occurrence of heat islands, essentially at night and predominantly in the winter. There is a difference in temperature of approximately ±1°C between the location of the buildings and the Meteorological Station. The in loco measurements were taken for approximately 15 days for most of the units. Care was taken so that periods consisted of no less than 7 consecutive days, in accordance to studies by Saraiva *et al.* (2005), where it is argued that the main physical phenomena influencing climate conditions in a particular place occur within a period of approximately 6 days.

In order to verify and analyze the measurements, a comfort temperature of between 20°C and 25°C was adopted, in conformity with Decree-Law n.º 80/2006 (Portugal, 2006, p. 2474, article 14°), which states that *"the comfort environmental conditions of reference are 20°C for air temperature during the heating season and a temperature of 25°C and relative humidity of 50% for the cooling season"*; in this way, air temperature is associated to the comfort temperature.

Thus, the measurement process used facilitated the analysis of the performance of sample units (comparing the interior and exterior conditions during the corresponding periods of measurements) and the obtainment of a set of important data and information to understand the thermal behavior of units with large glazing areas.

3.1. Summer monitoring

Figure 2a below presents the main results obtained for the summer periods. Generally, the interior temperatures in the different units were above 25°C over 70% of the time (80% of environments facing east and westwards and 90% facing southwards). Thus, they were within the comfort thresholds established for this study (between 20°C and 25°C) for less than 10% - 30% of the time. It should also be noted that for a considerable number of

1 In accordance with Decree-Law 80/2006 (PORTUGAL, 2006).

2 In accordance with Decree-Law 80/2006 (PORTUGAL, 2006).

3 Mini *data-loggers Testostor-175*, manufacturer TESTO (precision ±0,5°C).

environments the temperature was above 27°C in 40% - 75% of the time, reaching sometimes temperatures above 29°C (recorded up to 30% of the time). Meanwhile, rooms with glazing facing mainly northwards had temperatures between 20°C and 27°C most of the time (≈80%-95%). The interior thermal amplitude for most rooms varied ≈5ºC, with some cases between 8º-12ºC (rooms with windows open all the time). The rooms with the lowest thermal amplitude values (on average 3.5°C) had some type of shutter, as well as fixed external brise-soleils, allowing for greater flexibility, control of and adaptability to exterior conditions. In this analysis, it should also be noted that the monitored residences did not have air conditioning systems. Therefore, the way in which natural ventilation was promoted was a determinant factor in the results obtained, as was the way in which the adjustable protection devices, when present, were utilized. Furthermore, in many monitored units, mainly those without exterior protection devices, the users did not fully explore the potential for cooling using natural ventilation; and even those that had these devices, users did not always fully exploit them to control changes in the external climate.

3.2. Winter monitoring

The main results obtained during the seasons requiring heating are as follows (see Figure 2b). During the first monitoring period (Winter 1), the housing units with glazing facing mainly southwards (South/SSE/SSW) presented longer periods within the comfort temperature range, between 20ºC and 25ºC (on average 85% of the time), followed by those facing north and eastwards (70%-60% of the time), whereas the units facing westwards reached comfort temperatures only 25% of the time. In the remaining percentages, the temperatures recorded were below 20°C, with some reaching below 18°C.

It is also important to highlight the occurrence of interior temperatures above 25°C in up to 30% of the time, even in the cold season. Overheating without the use of heating systems was confirmed in rooms with large amounts of glazing facing southwards. During the second monitoring period, practically all rooms had temperatures below 18°C a large part of the time. In rooms facing east and westwards temperatures below 15°C were observed for 20 – 30% of the time, with some recording temperatures below 12°C. It is also important to note in this analysis that these results are closely related with the use of heating systems by a large proportion of users, as well as the use of protection devices (in order to avoid greater heat losses during the night).

Only 20% of the sample did not need to use some type of heating system (residential units facing southwards). Thus, the temperatures obtained for a large part of the units could have been even lower than that recorded, that is, interior comfort conditions could have become

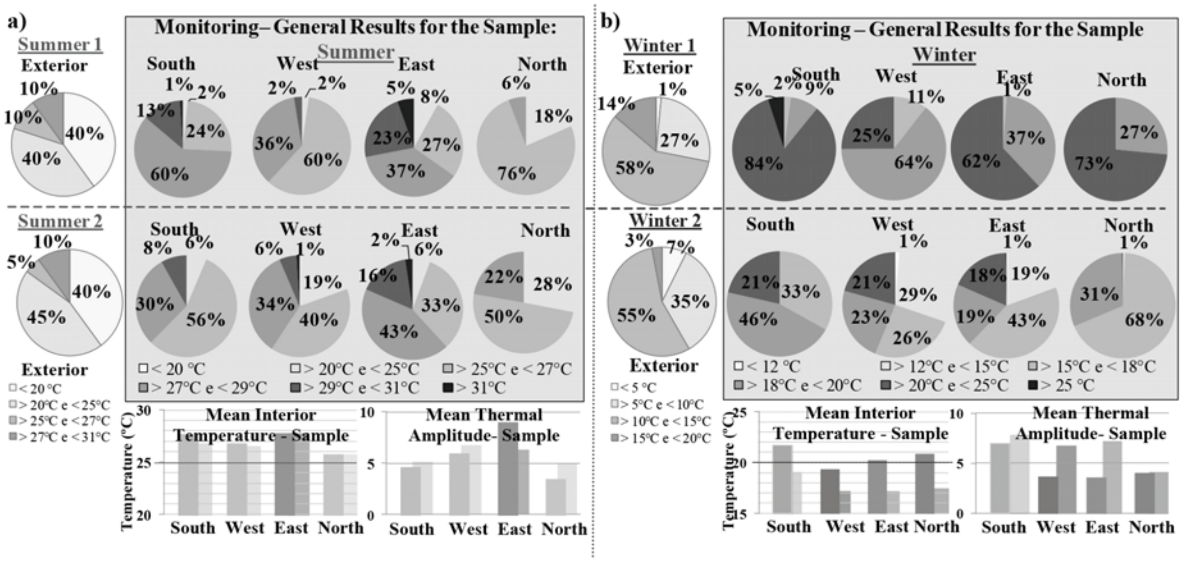


Figure 2: In loco measurements, general results (sample): summer (2007 and 2008); b) winter (2007-2008 and 2008-2009). Source: TAVARES, 2012.

aggravated without the use of these systems. Users declared that windows were kept closed most of the time and, in the units with protection devices, these were maintained (generally) opened during the day and closed during the night.

3.3. Users opinion and assessment

A survey involving the users of sample residential units found that they were extremely satisfied with the general characteristics of their units (general aspect, window privacy and dimensions: classified as excellent or good by more than 90% of interviewees). It also revealed a preference for large windows. However, in terms of their unit's interior temperature during the summer, none of the interviewees classified their apartment as optimum, and in 2/3 of the cases conditions were classified as poor or extremely poor. Regarding natural ventilation, over half of the units were classified as having little ventilation during this season.

In terms of the temperature in the residential units during winter, only 26% of those interviewed classified their apartments as excellent, where users of only 20% of the units never utilized any type of heating system.

Thus, this study confirmed the users' interest and preference for residential buildings with large glazing areas, whilst at the same time identifying the potential discomfort situations caused by the large areas of glazing in both the cooling and heating seasons.

4. Analytical studies

4.1. Model calibration and validation

Based on the information obtained from monitoring the residential units, detailed geometric models were built by using the thermal simulation program EnergyPlus, E⁺. In the detailed models, consideration was given to the residential units' characteristics and conditions under which monitoring took place during summer and winter. To ensure that these models were simulated under the same monitoring conditions, special care was taken when inputting climate data corresponding to the measurement periods (climate file), obtained from National Laboratory of Energy and Geology (LNEG, Lisbon) meteorological station, into the *E+* program.

The difference between the temperatures obtained in the in loco measurements and in simulations (seven consecutive days' observations in summer and winter) did not exceed ± 0.5ºC for most the residential units. This is equivalent to the margin of error for the equipment utilized in the measurements provided by the manufacturer.

After verifying the detailed models, simplification studies were conducted that grouped the different residential units selected by their typological characteristics. This resulted in two simplified models in the *E+* program. Simplified Model 1 (one side exposed, one thermal zone) and Simplified Model 2 (two opposite sides exposed, two thermal zones) were validated in two stages: 1) The Simplified Models were subjected to simulations under the same conditions applied to their corresponding Detailed Models; and 2) Both the Detailed and Simplified Models were subjected to the same parametric variations (summer and winter); in order to assess the capacity of the simplified models to respond to the imposed variations in the same way as their corresponding detailed models.

The calibration process showed that the simplified models 1 and 2 presented results similar to those of the detailed models (stage 1), including parametric variations during the hot and cold seasons (stage 2), where the average difference between the results of the corresponding models did not exceed ± 0.5°C in the different tests.

Thus, it was possible to obtain two simplified geometric base models, assessed, calibrated and capable of representing some of the typologies frequently observed in the residential sector (maintaining the main characteristics of different units present in existing buildings, Figure 3a).

These simplified models were then used in subsequent studies, such as those employed to define the Solution Matrix. The process used to develop the two simplified geometric models had previously been discussed and demonstrated by Tavares (*et al.* 2011; 2012). Both models were also capable of representing units containing a relationship between dimensions X and Y (in meters), as shown in Figure 3a.

4.2. Solutions matrix and parameters involved

After obtaining Models 1 and 2, a constructive solutions Matrix was developed in order to determine the influence of specific parameters on interior temperature conditions, as well as other energy issues. Parameter variation studies for the Lisbon climate (different combinations of the selected parameters) were developed, based on Models 1 and 2. Sections 4.2.1 and 4.2.2 describe the main parameters present in the Matrix. Model 1, with only one side exposed, was subjected to simulations that faced the south, west, east and north. Model 2 (2 zones), with two opposite sides exposed to exterior conditions, was subjected to simulations facing the south + north, and the west + east. Both models 1 and 2 were analyzed for mid-floor and penthouse arrangements (where the roof slab is in contact with the outside).

4.2.1. Parameters related to the non-opaque envelope (glazing)

In specific relation to buildings where glazing areas are larger than the opaque surfaces (with significant reductions in the storage, damper and retention areas), the influence of the opaque elements on the interior conditions are reduced as the opaque exterior envelope decreases. Therefore, other constructive characteristics may become more important and help provide better interior conditions.

In the proposed Matrix, for Models 1 and 2, glazing areas corresponding to 20%, 40%, 60% and 80% of the façades were adopted, located according to the main solar orientations, as in Figure 3a. The height of the glazing areas was fixed at 2.20m (corresponding to the average height of the glazing verified in the sample units). Thus, only the width was altered to obtain the different described areas, so that the center of the glazing always coincided with the façade's central point.

In addition, two types of glass were selected for both Models: colorless double-glazing (VI)[4] because this was commonly used in construction subsequent to the implementation of the 1st Thermal Regulation in Portugal; and low emissivity double glazing (V2)[5], due to its characteristics, being able to significantly reduce overheating in summer (allowing light while reducing heat), and allowing for good natural illumination with reinforced thermal insulation in winter.

Types of brises-soleils were considered for models 1 and 2, when these were used: horizontal and infinite, in conformity with the observations in the existing buildings with large glazing areas (ex. sample buildings), as in Figure 3b. In the Matrix, only the width of the brises varied (selected widths of 0.0m; 0.60m; 1.20m; and 1.90m). Thus, a 1.90m wide horizontal brise corresponded to the total shading of the glazed areas in the summer period, considering that the glazing height was always fixed at 2.20m.

[4] V1=Planilux+Planilux (U=2.9) e V2=Planistar+Planilux (U=1.8), manufacturer *Saint Gobain Glass-SGG*, Portugal.

[5] V1=Planilux+Planilux (U=2.9) e V2=Planistar+Planilux (U=1.8), manufacturer *Saint Gobain Glass-SGG*, Portugal.

	Without Device	Interior Device		Exterior Device			Natural Ventilation
		Summer	Winter	Summer	Winter		
Situation I		Open: 10h-20h (Day) 50% Closed: 20h-10h (Night) 100%		Open: 10h-23h (Day) 70% Closed: 23h-10h (Night) 100%		Combine with	I
Situation II		Closed: 10h-20h (Day) 100% Open: 20h-10h (Night) 50%	Always Open: 10h-20h (Day) 50%	Closed: - 24h-10h (Night) 100% - 10h-20h (Day) 70% Open: 20h-24h (Night) 70%	Always Open: 10h-20h (Day) 70%	Combine with	II
Situation III		Closed: 10h-20h (Day) 100% Open: 20h-10h (Night) 50% (+ 20mm insulation in interior device)		Closed: - 24h-20h (Night/Day) 70% Open: 20h-24h (Night) 70%		Combine with	III

Table 1: Description of shading device arrangements selected in the Matrix, according to Summer – Winter, day – night (associated with the different ventilation rates).
Source: TAVARES, 2012.

Furthermore, the matrix considered three shading arrangements of interior shading shutters (wooden sliding panels covering 50% - 100% of the glazing), and three arrangements of exterior shading devices - roll blinds (vertical collecting system which can cover 0% - 100% of the glazing).

Other solutions devoid of control devices (interior or exterior) were also considered in the Matrix, which could be shaded (or not) by horizontal brises of the dimensions described above. Table 1 lists the different shading device arrangements correlated with the ventilation variables adopted in the Matrix.

In this study, an air changes per hour rate (ACH) of 0.80 h^{-1} was adopted for closed windows and 3.0 h^{-1} for open windows. However, during the heating season all solutions had a rate of Rph 0.80 h^{-1} (see Figure 3c)[6].

The decisions (in the Matrix) on the type of shading devices and ventilation rates are related to the architecture observed in the buildings used in this study, in addition the observations and recordings of user behavior during the measurements. Consequently, the matrix allows the comparison of solutions with different glazing areas, for models devoid of any solar protection, to different types of brises and shading devices, and for models with little ventilation during the year to models with different rates of ventilation during the hot season.

4.2.2. Parameters related to the opaque envelope (mass and thermal insulation)

The constructive solutions observed in the sample buildings, as well as solutions found in ITE 50 (SANTOS; MATIAS, 2006) were adopted to define the constructive solutions in the matrix, given that the latter publication described the most frequent solutions in construction in Portugal. Hence, three sets of Exterior Thermal Mass[7] (exterior walls, roof slabs and interior floor slabs) and three sets of Interior Thermal Mass[8]

[6] 0,6Rph considering the statutory minimum requirements in accordance with Decree-Law n. 80/2006 (PORTUGAL, 2006). In Afonso *et al.* (1986) also singled out values of Rph in residential buildings: 3Rph corresponds to the promotion of natural ventilation through open windows.

[7] External Mass II best represents solutions in the ITE 50 publication (SANTOS; MATIAS, 2006).

[8] The set Internal Mass I shows half of the mass of the interior walls compared to set II, and III shows 50% more interior walls mass when compared to set II.

(Pillars, Beams and Interior Walls) were defined. These sets of exterior and interior thermal mass were combined to make up the three sets of Thermal Mass adopted in the Matrix (from those with least mass to those with most mass), as can be seen in Figure 3d. The thermal mass II set corresponds to the arrangements that are closest to those commonly observed in the building stock in Portugal post-1991.

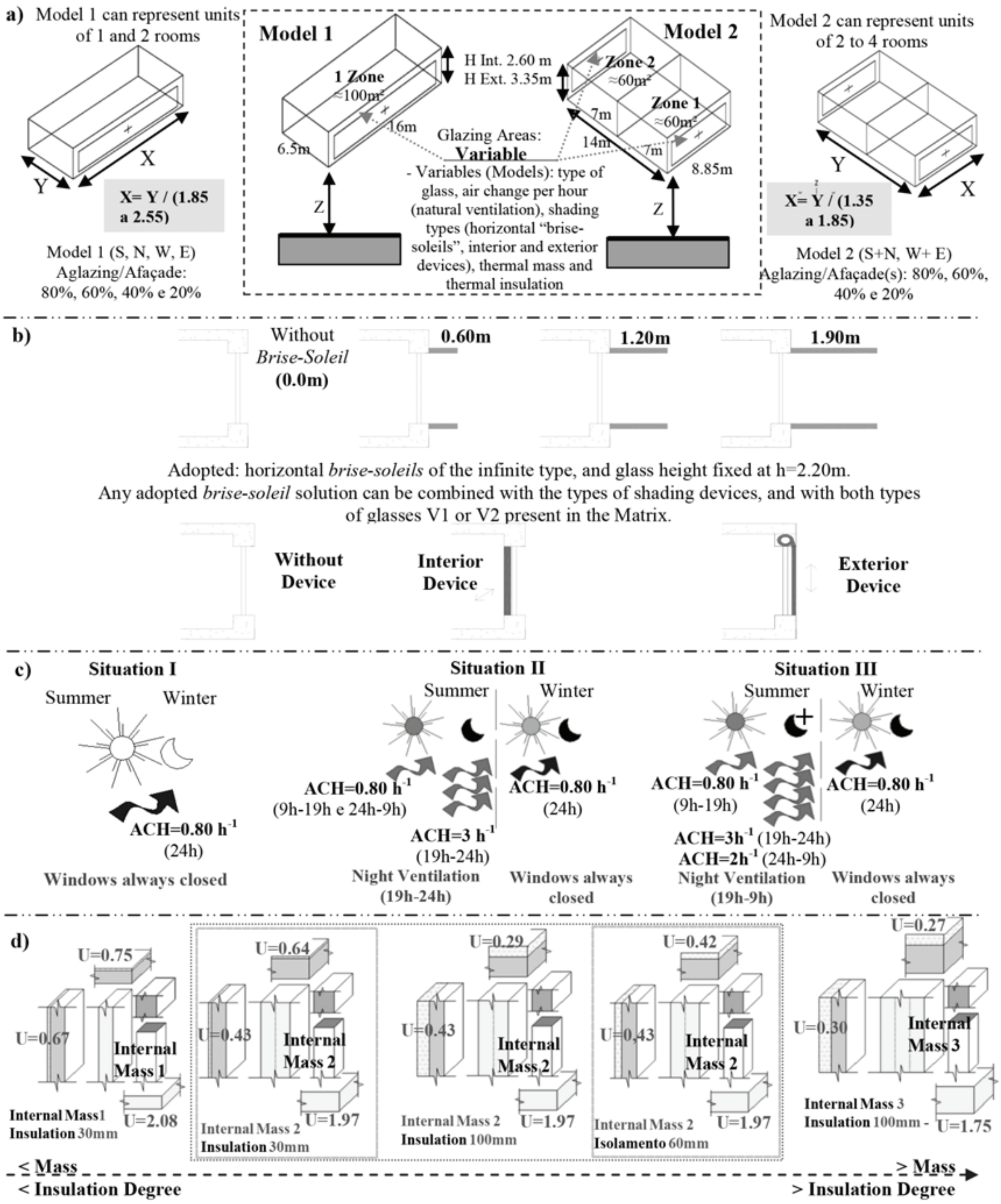


Figure 3: Parameter scheme adopted in the Solutions Matrix: a) Simplified geometric models; b) Parameters related to the Non-Opaque Envelope; c) Natural Ventilation Rates; d) Opaque Envelope Parameters.
Source: TAVARES, 201

Expanded polystyrene (XPS) was selected to represent the different types of common thermal insulation in Portuguese construction, given that the insulating materials used have thermal conductivity values very close to XPS values. In the matrix different thicknesses - 30mm, 60mm, and 100mm - of XPS were adopted, corresponding to the different thermal masses, respectively: Thermal Mass I was associated to 30mm insulation; Thermal Mass II to 30mm/60mm/100mm insulation; and Thermal Mass III to 100mm insulation. Thus, five sets of opaque envelope solutions were obtained and adopted as a result of the combination of the types of thermal mass and levels of insulation described and considered in the Matrix. These can be observed in Figure 3d with their respective thermal transmission coefficient values (U).

4.2.3 Simulation – Matrix Solutions

The dynamic simulation program EnergyPlus (E^+) was used for the thermal and energy simulations of each solution in the Matrix. Comfort and consumption conditions for the whole year were elucidated and considered. To that end, the climate file in (.epw) for Lisbon was chosen, corresponding to the climate database obtained through data interpolation, published by the Meteorological Institute between 1951 and 1980, available in the E^+ program page.

Simulations occurred in two ways for the different Matrix solutions:

A-) Floating regime (without heating or cooling systems): allows interior temperature to be obtained (at set times in °C), important for assessing the solutions in terms of interior temperature conditions.

B-) Thermostatic regime, where control temperatures are defined for summer and winter. They were set for this study in accordance with the *comfort reference* conditions recommended by Decree-Law n.° 80/2006 (PORTUGAL, 2006) and established in Section 3, at 25°C for the cooling temperature and 20°C for the heating temperature (the interior temperature varies only between the established control temperatures, 20°C and 25°C). Thus, the required amount of energy (hourly data in kWh) to maintain the interior temperature above 20°C corresponds to the heating needs, while the amount of energy required to maintain the interior temperature below 25°C corresponds to the cooling needs. It was possible to assess the performance of the different solutions considered in the Matrix for the main seasons and in annual terms, by comparing results.

4.2.4 Threshold conditions for summer and winter

In order to support the results analysis, threshold conditions were set in accordance to studies by Tavares (2012). These correspond to the interior temperature conditions that would lead to greater energy expenditures during the cooling and heating seasons. Thus, maximum temperature averages of 30°C (represented in cooling requirements as 30 kWh/m^2)[9] were adopted as a cooling threshold reference; and the minimum temperature of 13°C (represented in heating requirements as 50kWh/m^2)[10] as heating threshold reference. Therefore, any results above the cooling (30°C) or below the heating (13°C) thresholds were classified in this study as critical situation solutions, resulting in greater energy expenditure.

4.3 Results

The set of findings relating to the interior conditions of the different Matrix solutions are described below. They can be used to determine whether they fall within the established threshold conditions for this study (item 4.2.4).

4.3.1 Model 1 and 2 Results–intermediate floor

With these established objectives in mind, it can be seen that it is possible to obtain interior temperature conditions that do not result in greater energy expenditures (within the established study thresholds, see section 4.2.4) for residential units corresponding to Models 1 and 2, located in an intermediate floor with different glazing areas and orientations, as in the Matrix, with façades consisting of 20% to 80% glazing. For the whole range of options, see Figure 4a.

In general, all the Matrix solutions corresponding to Models 1 and 2 in intermediate floors, with the use of interior or exterior protection devices had interior conditions within the established range and, therefore, did not show any tendencies towards greater energy expenditures in either seasons (heating and cooling).

However, greater attention needs to be paid to cooling issues (summer) for model 1 solutions with glazing areas larger than 60% of the façade, and for Model 2 with glazing areas above 80% in at least one façade, in particular those solutions that use brises smaller than 0.60m without resorting to any other type shading device.

9 This study does not apply Decree-Law n. 80/2006; however, cooling (30 kWh/m²) and heating (50 kWh/m²) requirements threshold values similar to those found in this document are adopted for the typological models in the study.

10 This study does not apply Decree-Law n. 80/2006; however, cooling (30 kWh/m²) and heating (50 kWh/m²) requirements threshold values similar to those found in this document are adopted for the typological models in the study.

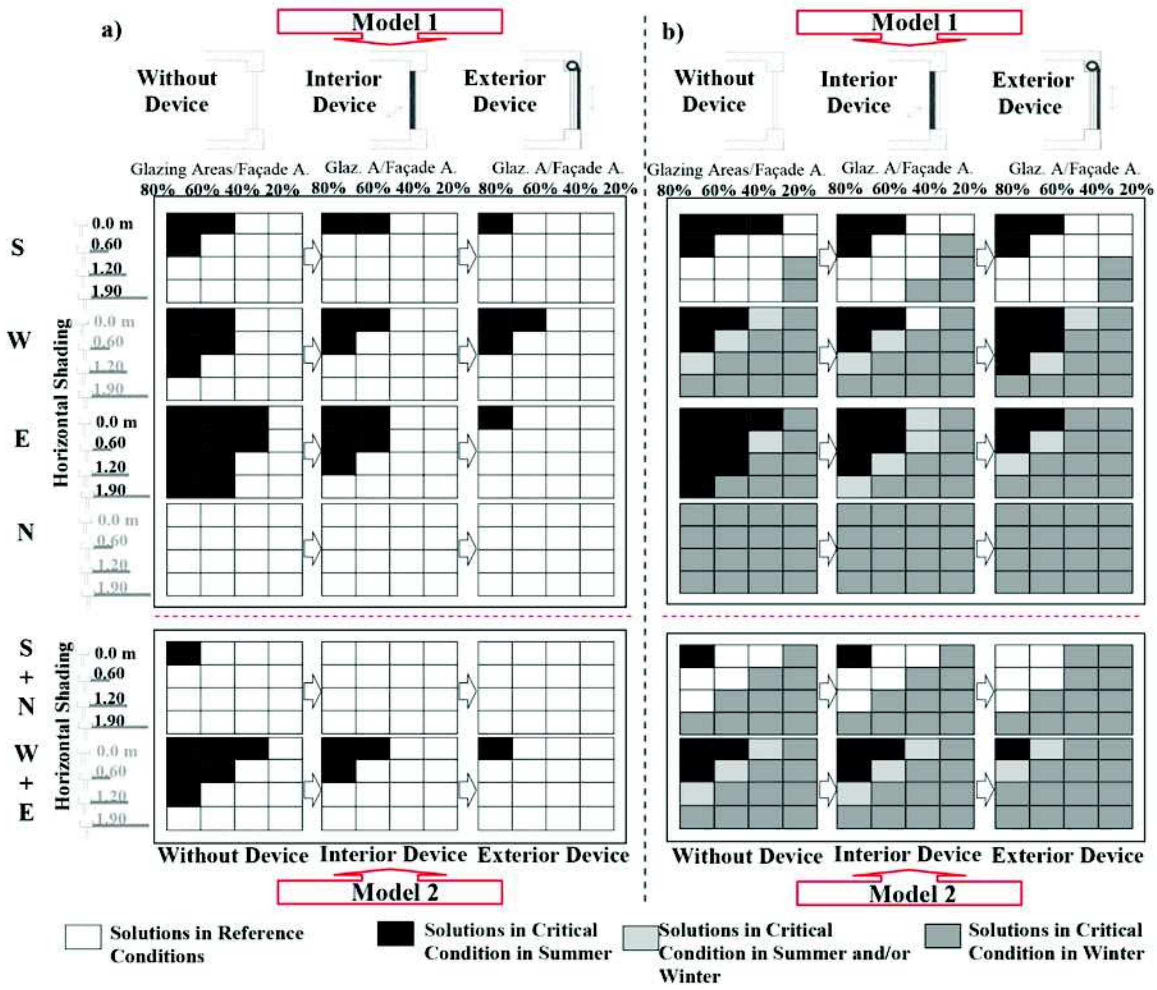


Figure 4: Results scheme for Models 1 and 2 in: a) intermediate floor; b) Top floor (Thermal mass I e II with 30mm of thermal insulation).
Source: TAVARES, 2012.

4.3.2. Models 1 and 2 Results – Top floor (insulation 30mm)

For most of the Matrix solutions for Models 1 and 2 in the top floor with thermal mass types I or II, that is, 30mm insulation (Figure 4b), results show that temperatures can oscillate between critical conditions in the winter to critical conditions in the summer and vice versa, depending on the size of glazing areas, orientation, glass type, the presence of brise-soleils of different sizes and ventilation rates. In other words, only a limited range of solutions and interior temperature conditions do not lead to greater energy expenditures in both seasons. Solar protection devices significantly reduce cooling energy needs; however, when analyzed in terms of the heating season they can lead to an increase in heating energy needs.

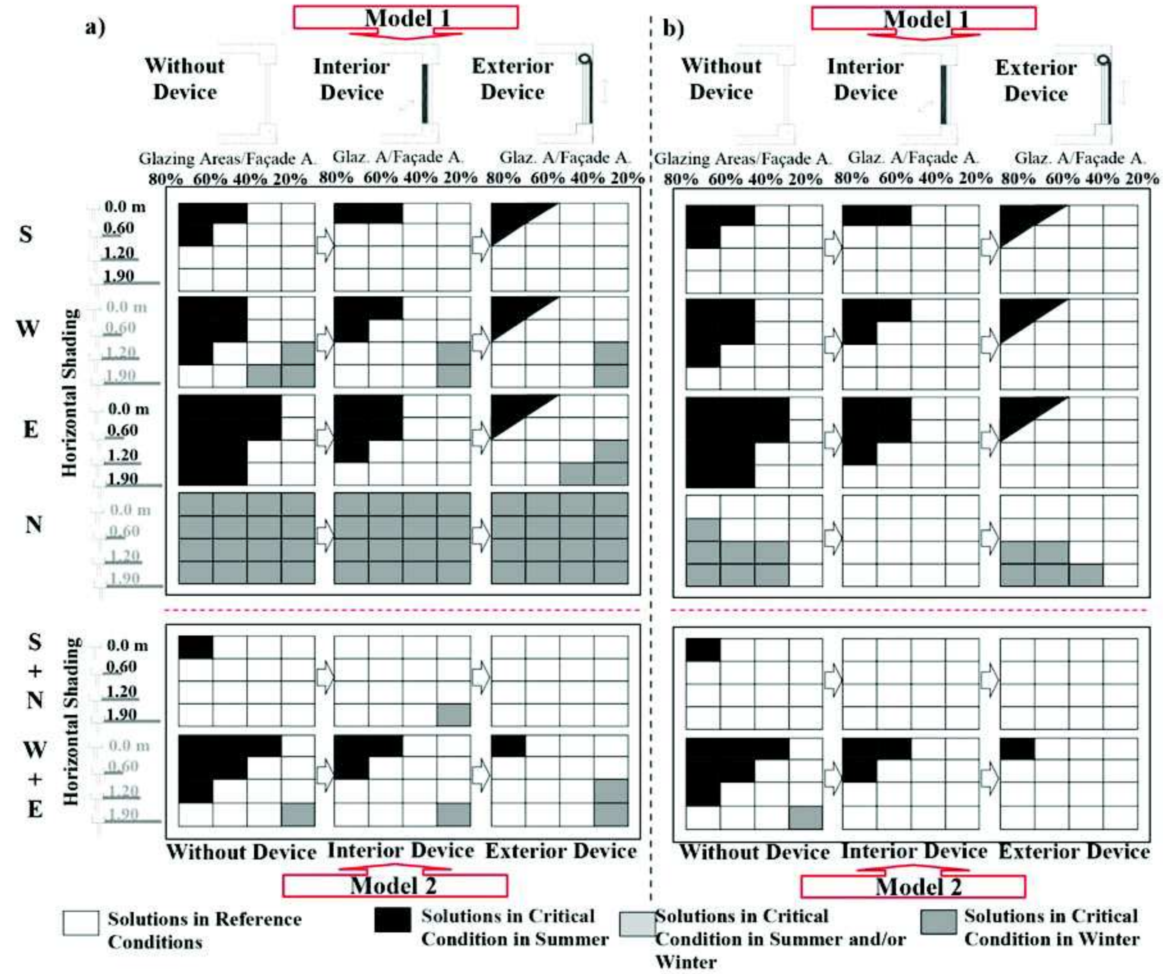


Figure 5: Results scheme for Models 1 and 2 in Top floor arrangements: a) Thermal mass II with 60mm thermal insulation; b) Thermal mass II and III with 100mm thermal insulation.
Source: TAVARES, 2012.

Results show, however, that it is important to consider more carefully the following:

- The solutions (mainly of Model 1) with glazing areas corresponding to more than 60% of the façade with brises smaller than 0.60m. This combination tends to result in greater energy expenditure during the cooling season;

- North-facing Model 1 solutions, regardless of the size of the glazing area and solar protection type. They tend to result in greater energy expenditure during the heating season.

However, most solutions with interior conditions within the reference thresholds were south-facing Model 1 solutions and south + north facing Model 2 solutions.

4.3.3. Models 1 and 2 Results – Top floor (insulation 60mm and 100mm)

Matrix solutions relating to top floor arrangements in Models 1 and 2 Matrix, with thermal mass II or III associated to 60mm (Figure 5a) and 100mm (Figure 5b) insulation, resulted in a number of options that did not tend to present greater energy expenditures and critical interior temperature conditions. Nonetheless, they were most often found with the use of shading devices.

For glazing areas of over 60% of the façade, more attention is due to cooling issues (summer), especially when brise-soleils were smaller than 0.60m and without the use any other solar protection (interior or exterior) devices; with the exception of north-facing Model 1 solutions. However, when glazing areas take up less than 40% of the façade and brises are larger than 2.20m wide (mainly north-facing façades), it is important to consider the effects of these solutions in the heating season (winter).

5. Discussion

In the case of the selected models (Models 1 and 2 in intermediate and top floor, that is, with or without an exposed roof), it can be seen that the results are directly associated to the existing *relationship* between:

- The exterior envelope area (opaque and transparent) and the internal volume, also known as *surface area to volume ratio* (quotient Ae/V). For Model 1 (with smaller surface-area-to-volume-ratio in comparison to Model 2) a wider range of solutions falling within the threshold conditions is observed. Moreover, a wider range of solutions were also observed in intermediate floors in both models, when compared with top floors (greater surface-area-to-volume-ratio). In other words, building exterior form has a major influence on thermal losses because the more compact the exterior building and/or unit form (with reduced exterior surface and smaller area exposed to the external environment) the lower the heat losses and the better its global thermal balance.

- Transparent and opaque envelopes areas.

a) The larger the glazing area in relation to the opaque envelope, the greater the tendency towards critical situations during the cooling season; hence, in these cases, more window shading (summer) in association with natural ventilation (when external temperatures are lower than internal temperatures) are essential in order to achieve the best performance results during the hot season;

b) The smaller the glazing area, the greater the tendency towards critical situations during the heating season, due to a smaller solar catchment area in winter. The thermal insulation degree and the introduction of devices next to the glazing become essential for heat retention and, hence, for obtaining better performance results in this season.

6. Conclusions

The methodology of this study consisted of two stages where concrete examples led to obtaining results for an extended range of solutions considering the Lisbon climate.

In relation to the in loco measurements, the assessment of the thermal performance of buildings with large glazing areas subjected to exterior climate conditions (winter and summer) permitted the analysis of interior temperature conditions, affected by the behavior of the occupants and conditioned by constructive solutions and architectural choices. It was possible to observe situations of discomfort in units with significant glazing areas in both seasons of the year. Generally, during both summer analysis periods, the units presented temperatures above 25°C, 90% of the time, while in the heating season (when most occupants used heating systems) temperatures below 20°C were registered over 50% of the time.

The analytical study results (Solutions Matrix developed based on the methodology proposed) revealed that: *"It is possible to obtain interior temperature conditions that will not lead to greater energy expenditures"* (within the thresholds established for this study), for residential units corresponding to Models 1 and 2, located in intermediate as well as top floors, with different glazing areas (façades with 20% to 80% glazing) and orientations, as in the Matrix; a number of options and solutions were presented that could be adopted in design practice.

However, more attention should be paid to cooling issues (summer) in solutions with glazing areas taking up more than 60% of the façade, in particular, those solutions with horizontal brise-soleils that are less than 0.60m wide and devoid of any other solar protection devices. Furthermore, more attention should also be paid to solutions with glazing areas taking up less than 40% of the façade (top floor) with horizontal brises wider than 1.20m (mainly north-facing), during the heating season (winter).

Therefore, this study enables project managers to directly observe and compare constructive solutions (representative of the residential units) for a typically Mediterranean climate, such as Lisbon. And in this way, assess which solutions provide the greatest comfort and lower energy needs in terms of environmental conditioning, in relation to glazed areas. It is thus possible to obtain a set of indicators at an early stage of the project, demonstrating their impact on the internal conditions of the residential units. In particular, with regard to those solutions where glazing areas are larger than opaque vertical envelope areas.

Annex A: Lisbon Climate Data

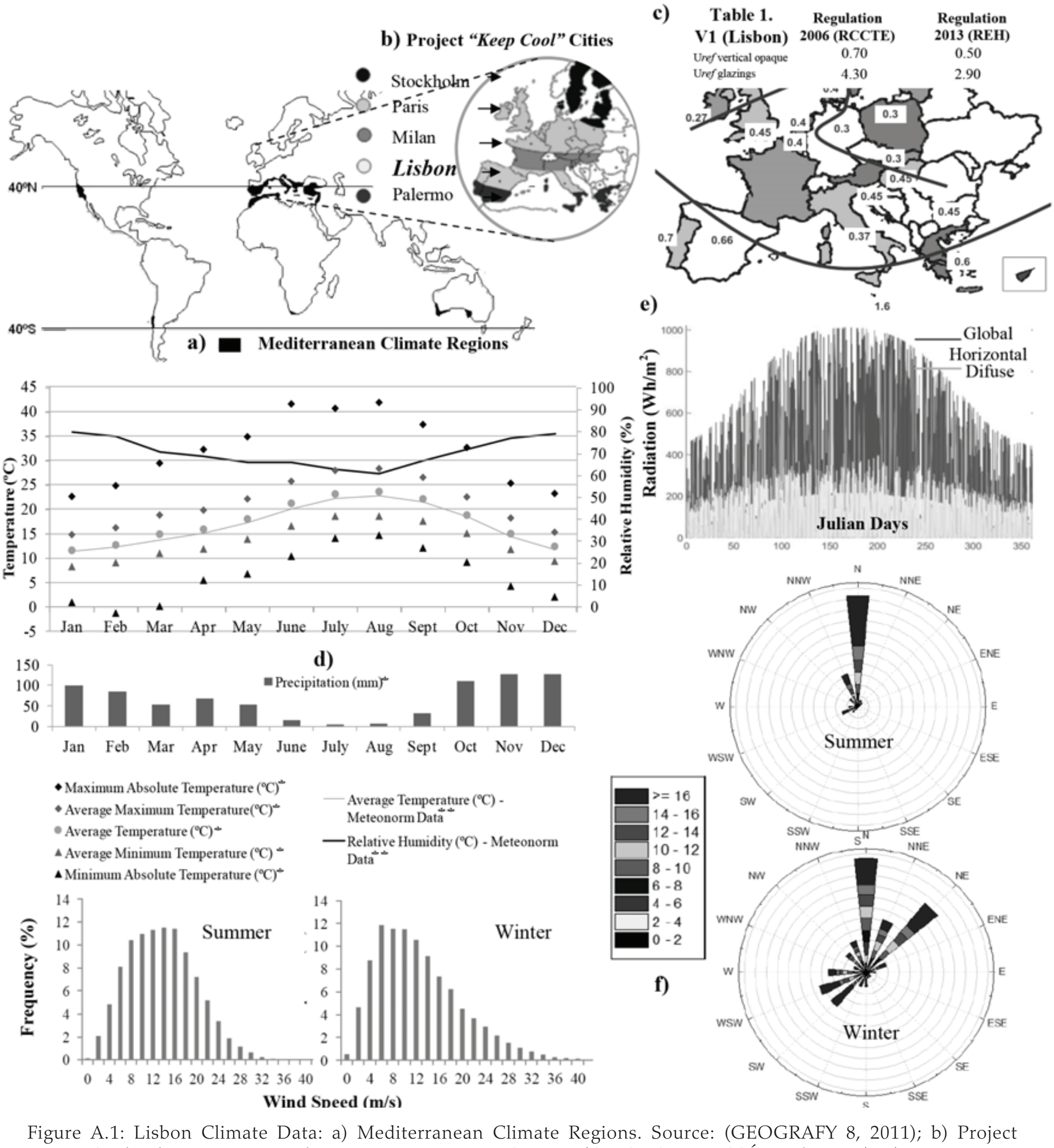


Figure A.1: Lisbon Climate Data: a) Mediterranean Climate Regions. Source: (GEOGRAFY 8, 2011); b) Project "Keep Cool" climate zones and representative cities. Source: (GRIGNON-MASSÉ *et al.*, 2009); c) Exterior vertical opaque elements thermal transmission coefficients indicative values Map (U W/m2.ºC) after Directive n.º 2002/91/CE. Source: (MALDONADO, 2008); d) air temperature data (in ºC) and precipitation (in mm), Source: *Climatologic Standards Portuguese Institute of the Sea and *Atmosphere – IPMA (1981-2010) and ** Climate Data Software Meteonorm;* e) horizontal global and diffuse radiation for a meteorological type hourly sampling interval of a typical year. Source: (COSTA, 2011); f) wind rose and seasonal frequency distribution of wind speed during the Summer and Winter. Source: (TEIXEIRA, 2013).

Annex B: "Study Object" Buildings – Floor Plan Type and Solar Exposure Periods (Façades)

Figure B.1: Pertejo, Parque das Nações Buildings –Lisboa (Floor Plan Type and Solar Exposure Periods.
Source: TAVARES, 2012.

Latitude: 38°47'03.93"N Longitude: 9° 05' 52.47"W Intergaup Office

Periods of Insolation							
P1	Solst.S.	Solst.W.	Equin.	**P2**	Solst.S.	Solst.W	Equin.
Façade1	DBK to 11:30h	DBK to 10:30h	DBK to 10:00h	Façade 1	5:30h-14h	DBK to EOD	Nascer to15:30h
Faç.2	5:30h-14h	DBK to EOD	DBK to 15:30h	Faç. 2	11:30h toEOD	10:30 to EOD	11h EOD
Faç.3	11:30h to EOD	10:30 to EOD	11h to EOD	Faç. 3	DBK to 5:30h and 14h to EOD	-	15:30h to EOD
Faç.4	DBK to 5:30h and 14h to EOD	-	15:30h to EOD	Faç. 4	DBK to 11:30h	DBK to 10:30h	DBK to 10:00h

DBK: daybreak EOD: end of the day

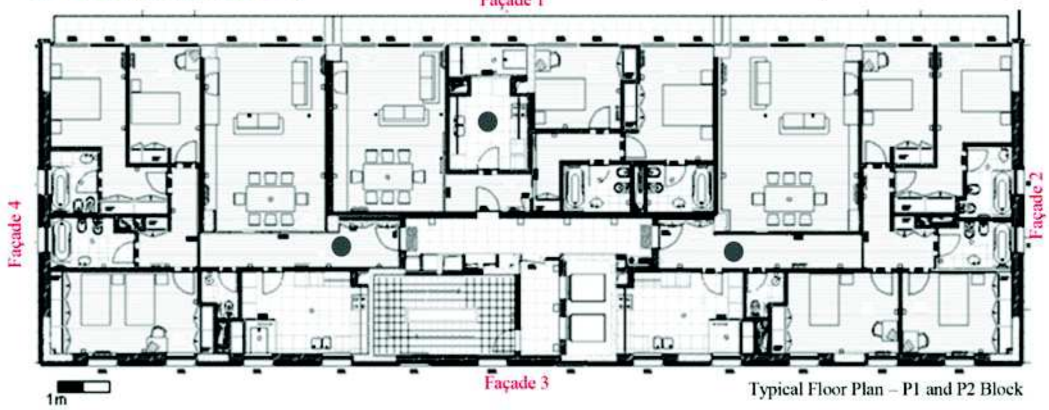


Figura B.2: Jardins de São Bartolomeu, Alta de Lisboa Buildings - Lisboa (Floor Plan Type and Sun Exposure Periods).
Source: TAVARES, 2012.

Latitude: 38°46'46.40"N Longitude: 9° 08' 57.86"W CAS Architects

Periods of Insolation							
A/B/C	Solst.S.	Solst.W.	Equin.	**D**	Solst.S.	Solst.W.	Equin.
Façade.1	DBK to 10h and 18h to EOD	-	DBK to 8h	Faç.1	12:30h to EOD	13:30h to EOD	13h to EOD
Faç.2	DBK to 12:30h	DBK to 13:30h	DBK to 13h	Faç.2	DBK to 10h and 18h to EOD	-	DBK to 8h
Faç.3	10h -18h	DBK to EOD	8h to EOD	Faç.3	DBK to 12:30h	DBK to 13:30h	DBK to 13h
Faç.4	12:30h to EOD	13:30h to EOD	13h to EOD	Faç.4	10h -18h	DBK to EOD	8h to EOD

DBK: daybreak EOD: end of the day

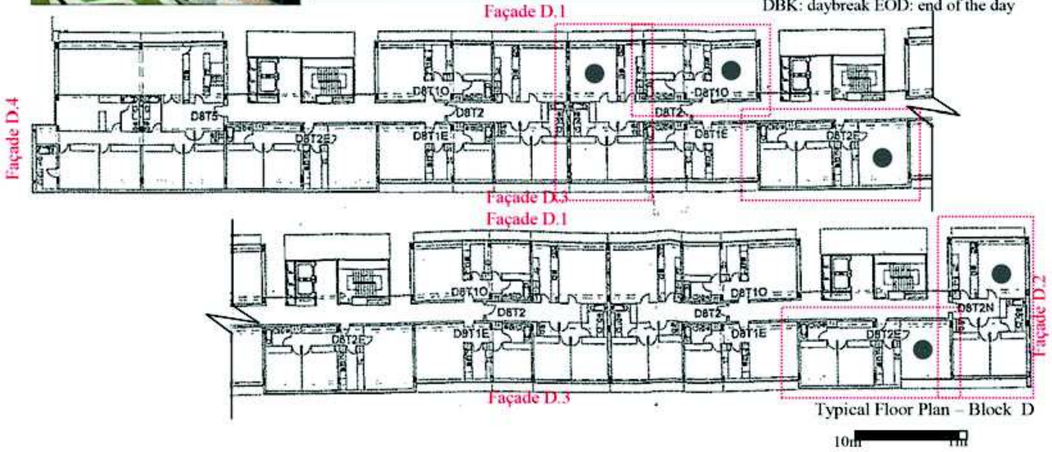


Figura B.3: Alcântara-Rio, Alcântara Buildings- Lisboa (Plant Typo and Sun Exposure Periods).
Source: TAVARES, 2012.

Latitude: 38°42'18.91"N Longitude: 9° 10' 30.44"W Frederico Valsassina (FVArchitects)

Periods of Insolation							
	Solst.S.	Solst.W.	Equin.		Solst.S.	Solst.W.	Equin.
Façade1	DBK até 9h e 17:30h até EOD	-	DBK to 7h	Fac.7	10h to18:30h	DBK to EOD	8h to EOD
Faç.2	DBK to 9:30h and 18h to EOD	-	DBK to 7:30h	Faç.8	12:30h to EOD	13:30h to EOD	13h to EOD
Faç.3	9:30h to18h	-	7.30h to EOD	Faç.9	9:30h to 18h	-	7.30h to EOD
Faç.4	12.30h to EOD	13h to EOD	12:45h to EOD	Faç.10	12.30h to EOD	13h to EOD	12:45h to EOD
Faç.5	9h to 17:30h	DBK to EOD	7:30h to EOD	Faç.11	DBK to 9:30h and 18h to EOD	-	DBK to 7:30h
Faç.6	DBK to 12:30h	DBK to 13:30h	DBK to 13h				

DBK: daybreak EOD: end of the day

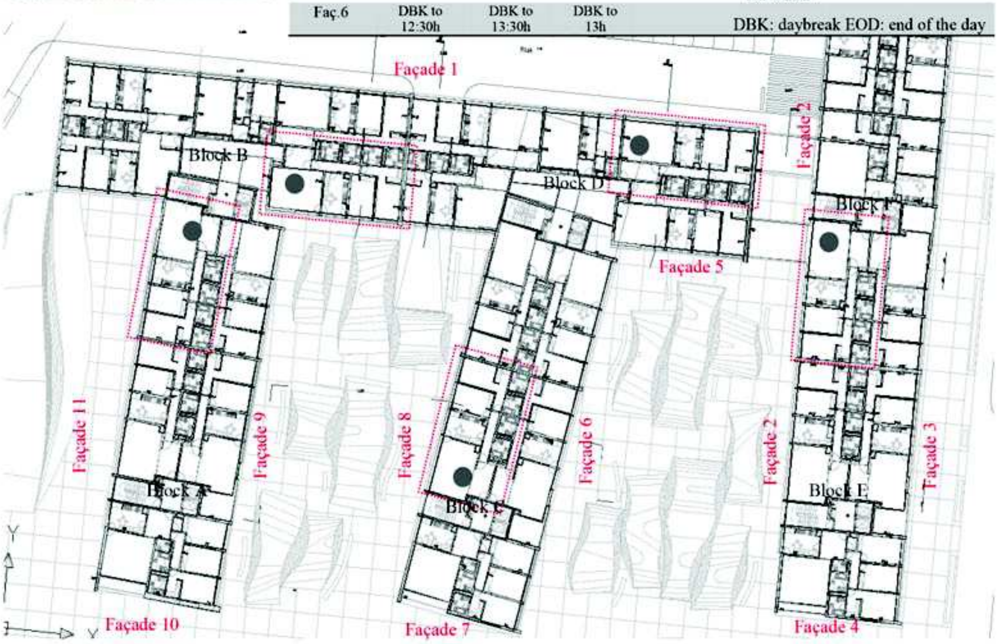
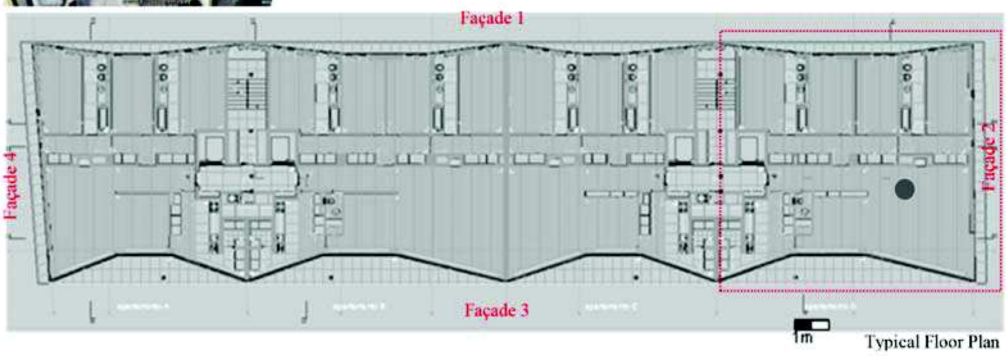


Figure B.4: Navitejo, Parque das Nações Buildings- Lisboa (Floor Plan Type and Sun Exposure Period).
Source: TAVARES, 2012.

Latitude: 38°46'30.03"N Longitude: 9° 5'32.44"W Aires e Mateus Architects

Periods of Insolation (Navitejo 1- N1)			
	Solst. Summer	Solst. Winter	Equinoxes
Façade 1	DBK to 8h and 16:30h to EOD	-	-
Façade 2	DBK to 12h	DBK to 12h	DBK to 12h
Façade 3	8:30h to 16:30h	-	-
Façade 4	12h to EOD	12h to EOD	12h to EOD

DBK: daybreak EOD: end of the day



Typical Floor Plan

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Author's note

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Márcia Cristina Pereira Tavares
Faculty of Architecture. Technical University of Lisbon. Lisbon, Portugal.
CV: http://lattes.cnpq.br/0251334236029422
marciatave@gmail.com

Hélder José Perdigão Gonçalves
National Laboratory of Energy and Geology. Lisbon, Portugal.
helder.goncalves@lneg.pt

Jorge Novais Telles de Faria Corrêa Bastos
Faculty of Architecture. Technical University of Lisbon. Lisbon, Portugal.
jnbastos@fa.utl.pt