Thermal Inertia and Natural Ventilation –

Optimisation of thermal storage as a cooling technique for residential buildings in Southern Brazil

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A thesis submitted in partial fulfillment of the requirements of the Open University for the degree of Doctor of Philosophy

October 2004

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Abstract

The present investigation examines the role of thermal inertia as a cooling technique in the warm-humid climate of Southern Brazil. The aim of the research is to find out the limitations and applicability of thermal inertia, as well as to arise the aspects that should be taken into consideration when using this strategy in that climate. Emphasis is given on the optimisation of thermal inertia on residential buildings.

The performance of thermal inertia is evaluated first through a field experiment. The experimental data allowed discussing some aspects, which affect the performance of thermal inertia. Analytical studies are then developed through the use of numerical simulations. The findings provide useful information, which are translated to design guidelines for building designers.

Results of the present research have demonstrated that thermal inertia in buildings can not be considered as an isolated strategy.

The thesis comprises three parts. The first part focuses on the theoretical studies and it encompasses the literature review on thermal inertia covering concepts and some studies developed on this issue. The second part presents the results of the thermal inertia assessment. First, a field experiment is carried out, where four residences with different levels of thermal inertia are monitored during summer in Southern Brazil. Then, main observations of the field study lead to the analytical work where parametric and correlation studies are developed both based in simulations. In the parametric studies, aspects such as the level of thermal inertia of the walls, the influence of the roof/ceiling construction, the potential of night ventilation, window size and shading are evaluated. Further evaluations are performed through correlation analysis.

In the third part, the findings derived from the results are used to define a series of design guidelines for building designers. The recommendations focus on the optimisation of thermal inertia in residential buildings in hot-humid climate

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Acknowledgements

This work would not be possible without the help of the following persons and institutions:

- Simos Yannas – for the supervision, guidance and fruitful advice;
- Roberto Lamberts – for the friendship, suggestions and all help given;
- Federal University of Santa Catarina (Brazil), through the laboratories LabEEE and LabCon – for the loan of dataloggers;
- CAPES (Brazilian Government) – for providing the financial support;
- My friends: Ana Ligia Papst de Abreu, Luis Gomez, Janete Gomes, Raul Moura, Sofia Goinhas, Camila Branco e Gilberto Branco – for their friendship and emotional support;
- My colleagues from Architectural Association School (London) and LabEEE (Brazil) – for the companionship and contribution;
- The owners of the studied houses of field work– for allowing measurements to be taken in their homes;
- Luciano Dutra – for sharing this experience with me;
- Special thanks to my family – for giving me the strength to continue working.

Introduction

Problem Statement:

Climatic condition in Brazil varies substantially across the country, thus it requires application of different techniques for energy-conscious architecture. Proposed regulations in Brazil classify Brazilian climate in nine bioclimatic zones (ABNT, 1998) and provides guidelines for each zone, establishing minimum criterion of thermal performance for social housing. The minimum criterion for summer condition in such houses establishes that the indoor maximum temperature can not exceed maximum external temperature in rooms of prolonged occupancy.

The climate in Southern Brazil is characterised by mild winters and hot-humid summers. The important issue for designers in warm-temperate climates concerns the balance between the often-conflicting summer and winter requirements. For example, thermal inertia can be an advantage for mild winter, resolving the heating requirements, but may be a problem for hot humid summer as thermal inertia needs to have openings under control during daytime to avoid excess heat be accumulated in the structure. However there is a preference for open-air living in such climate to get the fresh air, even if the external air temperature is warmer than the indoors.

The flow of outdoor air with a given speed through a building extends the upper limit of the comfort zone, beyond the limit for still air conditions and may provide a physiological cooling effect. Thus, daytime ventilation may improve the feeling of comfort. Hence, the term 'comfort ventilation' is suggested by Givoni (1991). Therefore, assuming an indoor air speed of 1.5-2.0 m/s, comfort ventilation is applicable, according to Givoni (1991), mainly in regions and seasons, which the outdoor maximum air temperature does not exceed 28 - 32°C. In February (the hottest month in Florianópolis climate - object of this study), the average of maximum temperatures is about 29ºC, but daily maximum value can easily reach about 36ºC.

The traditional house design in warm-humid climates is the preference for elevated, lightweight, ventilated buildings while the design principles for hot-dry climates is based on the use of thermal mass, assisted by night ventilation and on the use of water for evaporative cooling. Recently, however, these traditional design principles are being questioned. Many researches have investigated the effectiveness of thermal inertia as a cooling technique in warm and humid climates:

Results of a project that was mounted to produce an answer to the controversy of lightweight and heavyweight construction for warm-humid climates can be seen in Szokolay (1996). A model was simulated for the climate of Cairns (north of Queensland) considering 63 constructional variants. The building with heavyweight floors and walls with insulated roof had the worst performance when no shading and ventilation were implemented. However, the same heavy configuration showed the best performance when shading and ample ventilation were provided. Some other recommendations were made, taking into account the variables examined: roof absorptance should be low; major windows should face north, minor ones south; concrete slab-on-ground floor with tiled or other hard finishing would give best results; the insulated tiled roof performs best and ventilation of at least 10 ac/h in summer, but this should be reduced to 1 ac/h in winter. In a more recent paper [Szokolay,2000], the author concludes that the heavyweight versus lightweight argument for warm-humid climate house design is unproductive. He complements that both kinds of design can be similarly good and there are other attributes to be considered than only thermal mass. He also suggests an extension of selection criteria to include psychological factors, taking into consideration the effect of air movement.

The lightweight ventilated buildings as typical passive design for tropical hot-humid climates is also questioned by [Soebarto, 1999]. The use of massive construction is tested, including the effects of using radiant barriers and roof insulation, changing the building orientation and shading condition and using different floor and roof claddings. The analysis were mainly conducted through simulations, but monitoring results of a case study in Jakarta (Indonesia) were also used to confirm the analysis. The results demonstrate that double brick walls would perform the best during the day, but they would make the temperatures late in the evening and early in the morning the highest amongst the other alternatives due to the heat stored in the mass. The use of radiant barriers in the roof provides the most significant improvement in the indoor thermal comfort. Adding roof insulation, however, would increase the indoor temperature. Also, results showed an improvement of the indoor temperature by closing most of the windows during the peak time of solar radiation (from 11 a.m. to 5 p.m.) and open for the rest of the hours. Although some results have shown the advantage in using construction that are more massive, to achieve acceptable results, it is important to take account some aspects that can affect the application of thermal inertia in warm-humid climates. These include the presence of thermal insulation or radiant barrier in the roof, the behaviour of the occupants and the means for achieving rapid dissipation of heat by convection.

Although some results have shown advantages in using more massive construction, this issue still needs further clarification.

Thermal inertia has been used as a climate moderator as massive building envelopes can attenuate the temperature fluctuation and reduce the indoor peak temperature. The benefits of the effect of thermal inertia depends on several parameters such as climate conditions, building thermal properties, ventilation, thermal insulation, occupancy and internal heat gains. It is important to understand the relation of these parameters in the performance of thermal mass in order to achieve the best result.

The thermophysical properties of building materials can influence the performance of the whole construction. The building material must hold a proper density, high thermal capacity and a high thermal conductivity value to store heat in an effective way.

Location and distribution of thermal mass is also important. It is not enough to add just thermal mass to the building. The additional thermal mass should have adequate surface area that is able to exchange energy with the internal air. Also, surfaces exposed to solar radiation, such as the outer building envelope and the roof, which is exposed to solar radiation during most hours of the day, would require a heavier construction with a higher time lag. Moreover, interior surfaces, which are receiving direct solar radiation through the building's openings, should be evaluated carefully and summer shading should be considered to avoid the excess of heat. According to [Balcomb, 1983], especially in a sunny day, the rate of energy inflow at the point receiving solar radiation (an area approximately the size of the window), is much greater than most masonry materials can accommodate for very long. Thus, most of the energy will be redistributed by convection and infrared radiation.

The use of insulation material can deteriorate the performance of a thermal storage wall. Also, a lightweight finishing material such as a carpet, when placed on a heavyweight concrete slab floor will interfere in the absorption of solar radiation or other heat input and will react in a different way. The use of false ceilings and walls and floor coverings can compromise the thermal performance of the available inertia. Consequently, these arrangements have influence in the thermal behaviour of the whole building and make thermal mass performance a more difficult problem to treat.

The role of thermal mass is associated to night period. During the summer nights, since the outdoor temperatures are usually lower than indoor temperatures, it is possible to cool the building by natural night ventilation. Ventilated air enhances convective heat loss from mass elements and dissipates the heat to the outdoor heat sink. Ceiling fans can also be used to increase indoor air movement and raise the convective heat transfer [Balaras, 1996].

Moreover, it is important that designers keep in mind that users represent the final determining factor on the effectiveness of any building system, including thermal mass. By changing the use of internal spaces and covering surfaces one can drastically reduce the effectiveness of thermal storage. Also, the use of thermal inertia is not sufficient if the users do not apply the correct ventilation strategy to guarantee the heat dissipation.

This work investigates the role of thermal inertia as a cooling technique in the climate of Southern Brazil. The aspects that should be considered when applying this strategy in that climate are evaluated. The influence of thermal inertia and that of natural ventilation on cooling processes are examined together with their implications for occupant thermal comfort. This research is addressed to residential buildings only.

Methodology:

The first part of this research concentrates on understanding the main concepts involving thermal inertia. A literature review is carried out covering the theory and aspects that have influence on thermal inertia performance.

The second part presents the analysis used in the assessment of the thermal inertia when applied in residential buildings in the climate of Southern Brazil. To accomplish the assessment, first a field experiment was carried out in four residences located in Florianópolis (Brazil). Houses with different levels of thermal inertia in their structure were chosen and measurements of temperature and humidity were performed in summer period. The assessment is made through profiles of internal temperatures and humidity, statistical values such as mean, maximum and minimum of temperatures and temperatures swing, as well as frequency of temperatures above 29ºC. The results helped to draw the first conclusions on thermal inertia efficiency in Southern Brazil climate by comparing the four residences.

Next, the main aspects pointed out in the field experiment are investigated in the analytical studies. TAS Building Designer tool was used to perform the analytical part. Before simulation, the process of building modelling and calibration was developed to assure the capability of the model in predicting indoor temperatures taking into account the thermal inertia characteristics. Once validation had been completed, parametric variations were, then, performed. Aspects such as the level of thermal inertia of the walls, the influence of the roof/ceiling construction, the potential of night ventilation, window size and shading were evaluated. The major purpose of the parametric studies is to determine the extend to which these features should be used to improve the performance of a building with higher thermal inertia. Thus, further evaluations are performed through correlation analysis.

The final part of the work covers the results of this research, translating them to ways of improving thermal inertia performance. The findings derived from the assessments of thermal inertia are used to define a series of design guidelines. The recommendations focus on the optimisation of thermal inertia in residential buildings in hot-humid climate.

Aim of the research:

The main objective of this research is to investigate the impact and limitations of the use of thermal inertia as a cooling technique for the climate of Southern Brazil. Also, to examine the aspects that should be taken into consideration to assure the best possible performance of thermal inertia in that climate.

Structure of the thesis:

The thesis comprises three parts: Part I - Theoretical Review, Part II - Empirical and Analytical Studies and Part III - Design Guidelines.

The first part (chapter 1, 2 and 3) focuses in the concepts and principles involving thermal inertia. A review of the thermal properties of materials and the parameters affecting the performance of thermal inertia are discussed.

The second part presents the results of thermal inertia performance assessments. In the empirical work (chapter 4), the monitoring of temperature and humidity carried out in four residences with different mass levels during summer period in Florianópolis (city located in southern Brazil) is showed and results discussed. Some conclusions lead to the analytical work where Parametric Studies and Correlation Analysis were developed both based in simulations. Firstly, the building modelling and calibration process is described (chapter 5). Then, parametric variations (chapter 6) are performed to evaluate some aspects, which should be taken into consideration when applying higher thermal inertia in buildings. Finally, the correlation analysis (chapter 7) allows examining some characteristics aiming at to find relation between them.

In the third part, the findings are translated to design guidelines (chapter 8) aimed at the improvement of the thermal performance of domestic buildings and optimisation of thermal inertia in hot-humid climate. Moreover, the conclusions (chapter 9) helps to determine the extent to which the evaluated parameters should be used to improve the indoor thermal conditions when the designer wish to take advantage of thermal inertia in that climate.

PART I

THEORETICAL STUDIES

UNDERSTANDING THERMAL INERTIA

Part I of this thesis comprises the literature review on thermal inertia covering concepts and some studies developed on this issue.

In chapter 1, fundamental concepts are described as well as some basic equations and methods used to express and quantify thermal inertia. Also, the principles involved in the heat transfer mechanisms are examined.

The aim of chapter 2 is the understanding the factors affecting the performance of thermal inertia. It covers, in a summarised way, results of some researches illustrating how these parameters can influence the effectiveness of the thermal inertia.

The review presented in chapter 3 encompasses some experimental and analytical works that evaluate the effectiveness of thermal inertia in different warm climates and also some studies assessing the potential of night ventilation and its influence on thermal inertia performance.

Chapter 1. Principles of Thermal Inertia:

1.1. Introduction:

This chapter presents a literature review on the topics related to thermal inertia principles and it starts with the concepts, as well as the preliminary methods used to quantify the heat storage capability of a building. It is followed by a review in the physical principles, which stipulate the form how thermal inertia can affect the thermal response of a building. Finally, the chapter describes the ways thermal inertia of building components can be represented.

1.2. Main Concept and Preliminary Methods:

The term **thermal inertia** is used in Yannas and Maldonado Ed. (1995) to describe a building's overall capacity to store and release heat. The higher the thermal inertia of a building the slower the rate at which its indoor temperature rises and drops. Hence, the thermal inertia of a building fabric may be used to reduce heat flow to the interior of the building in overheating seasons.

The use of higher heat capacity structures also helps in the reduction and time delay of the cooling load peak, decreasing the energy consumption in air-conditioned buildings.

The thermal inertia of a building could have a positive effect on the indoor conditions also during the winter period. The energy available from the solar gains and internal gains during the day is stored and then slowly released into the indoor environment at a later time, when there is a need for it, satisfying part of the heating load (Balaras, 1996).

Thermal inertia or thermal mass is usually associated to the storage material, which is the construction mass of the building itself. In general, it is contained in walls, partitions, ceilings and floors of the building, which are constructed of materials of high heat capacity.

These both terms are widely used by researches and any distinction are made between them. In this thesis, in the literature review section, the terms thermal inertia and thermal mass will be quoted according to the studies reported. Afterwards, only the term thermal inertia will be used to describe the building's thermal characteristic regarding its capability to store and release heat.

The phenomenon of heat flow and heat storage has been studied and several methods to quantify the heat storage capability of a building has been developed. Concepts such as *decrement factor*, *sol-air temperature*, *time lag* and *finite differences* have been introduced along the years since late 30's and early 40's (Diaz, 1994). Some of them will be reviewed below.

Asan and Sancaktar (1998) investigate the effects of wall's thermophysical properties on time lag and decrement factor and present the definition of these concepts as: "*During the transient process, in which the outside temperature changes during a period of a day, a heat wave flows through the wall from outside to inside and the amplitudes of these waves show the temperature magnitudes, and the wavelength of the waves shows the time. During the propagation of this heat wave through the wall, its amplitude will decrease depending on the termophysical properties of wall materials. When this wave reaches to the inner surface, it will have an amplitude, which is considerably smaller than the value it had at the outer surface. The time it takes for heat wave to propagate from outer surface to the inner surface is named as* ***"time lag"*** *or phase lag and the decreasing ratio of its amplitude during this process is named as* ***"decrement factor"*** *or attenuation factor*".

The method called **response factor**, as explained by Muncey (1979) is used "*to calculate the response of a system to an excitation pattern of interest by summation of the responses to a pattern of elementary excitations that together equal to the excitation pattern*". This method of calculation, commonly used in the USA, was developed by Stephenson and Mitalas (1967) and it is the main basis for the method recommended by ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers).

Response factor is also employed by TAS Building Thermal Analysis Program, which is used in this research as the analytical tool (see chapter 5). The method used by TAS for the analysis of heat flows combines that employed by finite difference methodologies with fast and accurate techniques borrowed from response factor theory.

The **Admittance method** was developed in Britain and it is used to characterise the thermal inertia of a building, considering the thermal response to harmonic excitations (non-steady state). Admittance gives a measure of the ability of a building component to store and release energy over the daily cycle and can be defined as the ratio of heat flux variation to temperature variation during a 24-hour cycle. This method was developed by Loudon (1968) at the Building Research Establishment, further studied by Petherbridge (1974). The 1970 Guide (IHVE Guide – The Institution of Heating and Ventilating Engineers) first introduced the concept of thermal admittance and it has been adopted by

CIBS Guide (1975, 1980) since then. These guides are, nowadays, called CIBSE – The Chartered Institution of Building Services Engineers.

A study by Milbank (1974) analyses the thermal response of buildings to cyclic energy inputs using the admittance procedure. He stresses that "*the admittance method is primarily a manual procedure, which seeks to balance the conflicting needs for simple calculations and accurate answers*" when estimating thermal response in buildings. As explained in the study, the solutions to the equations, which represent the temperature distribution due to conduction through a building element, generally fall into one or two types: those in which the time variations of temperature and energy are steady-cyclic, i.e. repeatable over a number of days, and those where the temperature and energy vary in a unpredictable way from a day to another. Solutions of the first type have the simplest form and it is from there that the admittance procedure has its source. Solutions of the second type are more complex and are the basis of other techniques such as the response factor.

The internal surfaces of exposed heavy materials, such as concrete, brick or stone have a large capacity for storing part of the cyclic energy gain. This characteristic gives them a high admittance and consequently, the temperature swing in such rooms is small. The unit for admittance (Y) is W/m^2K. Values of admittance for several constructions components are given in CIBSE Guide section A3.

The total admittance of a room can be calculated by the sum of the products of all room surface areas (A) and their respective admittance values (Y), represented by the following expression:

$$\Sigma AY \qquad (1)$$

The units will be, then, given by W/ K.

According to Balcomb (1983), the admittance can be expressed by:

$$Y = \sqrt{\frac{2\pi\lambda\rho c}{P}} \qquad (2)$$

Where P represents a period of 24-hour cycle.

Usually, materials that have a high density, also have a high thermal conductivity, consequently these materials are good for heat storage. It means that, if the product $\lambda\rho c$ is high, the heat-storage capability of the wall will be high, which represents the definition of admittance, according to the equation above.

The concept of thermal inertia of a wall or of the building structure as a whole is closely related to its weight, i.e. the combination of density and thickness of the material, as pointed out by Givoni (1976). As one can see, the admittance method does not consider the thickness of the material in the calculation and thermal inertia, in this case, is only characterised by the values of its density and the wall surface dimensions.

The admittance method can be used for the purpose of indoor temperature prediction, and allows the calculation of the peak environmental temperature for any proposed building. The technique is described in CIBSE Guide, section A8.

Moreover, the meaning of admittance for harmonic excitations is correspondent to the meaning of the U-value (described later in this work) for the steady state conditions. As explained in Petherbridge (1974): *"Whereas thermal transmittance is the reciprocal of thermal resistance under steady state conditions (i.e. U = 1/R), admittance is the reciprocal of impedance under the corresponding cyclic conditions."*

Balcomb (1983) introduced the concept of **Diurnal Heat Capacity,** based in the principles of admittance method. Due to the importance of diurnal ambient cycles or solar energy and outside temperature, it became significant to characterise the building response on a 24-hour frequency. This conclusion lead to the concept of Diurnal Heat Capacity, which is defined by Balcomb as "*the amount of heat stored in a building during the first half of a 24-hour cycle and returned to the space during the second half of the cycle*". Moreover, it is the amount of heat that is stored per degree of temperature swing and it is given in units of Wh /K m^2.

The values of diurnal heat capacity of materials vary as a function of material thickness and thermal properties. If a infinitely thick wall is considered, the values of diurnal heat capacity can be 60.7 Wh/Km^2 for a concrete wall, 36.7 Wh /K m^2 for a brick wall and 9.4 Wh /K m^2 for a softwood partition.

The diurnal heat capacity of a whole room or building can be determined in a similar way to the admittance procedure, by aggregating the effect of all surfaces acting in parallel. It is the sum of all the diurnal heat capacities values for all surfaces that enclose a room, given by the following expression:

$$DHC = \Sigma \text{ A dhc} \qquad (3)$$

The units will be, then, given by Wh/ K.

It will be necessary first classify each surface of the room according to the coupling between the surface and the solar gain. The method is explained in Balcomb (1983) and the author categorizes the surfaces as radiation coupled (surfaces in the direct sun or other surfaces located in the direct gain room) and convection coupled (surfaces that are convectively coupled only). This method considers zero diurnal heat capacity in all covered surfaces, such as walls or floors covered with heavy fabric, rugs, carpets or pictures and also surfaces hidden behind cabinets. In addition, the diurnal heat capacity corresponding to furniture also needs to be calculated. According to the Balcomb's work, this can be estimated as 11 Wh/ K for each m^2 of floor area for normal furnishings.

Besides being a useful measure of the heat storage capacity of a room, the diurnal heat capacity can also be useful to estimate temperature swings in a room or building.

This aspect was studied by Diaz (1994), where he made use of the diurnal heat capacity method for the calculation of internal temperatures swings and compared the results with those from field measurements and thermal simulations. The results showed good agreement and proved that the diurnal heat capacity procedure can be used to predict internal temperature fluctuation both for winter and summer conditions.

Some other more recent concepts related to thermal inertia will be described in the next section.

1.3. Thermal Inertia and the Heat Transfer Mechanisms

Three physical principles stipulate the form in which the thermal inertia can affect the thermal response of a building: heat transfer, heat distribution and heat storage.

The mechanism of **heat transfer** begins during the day, when the external wall temperature increases as a result of the heat balance between the gain caused by incident solar radiation and the losses by the convection and radiation. As the time passes, some of the heat is absorbed by the wall and the temperature increases according to the material's thermal properties and the boundary conditions. The heat moves, then, through the wall, towards the inside surface. During the night, a reverse process takes place, as the temperature outside decreases and there is no solar radiation. Hence, the wall temperature decreases, depending again on the thermal properties of the materials and the boundary conditions. All the heat flux happens from the higher temperatures locations to lower temperatures places, in an effort to reach a balance. Higher outdoor wind velocity increases convective losses. Similarly, on the inside wall surface, increasing the air movement enhances the heat losses and the dissipation of the stored heat (Santamouris and Asimakopoulos Ed, 1996). Thus, higher the thermal inertia of the building, slower the mechanism of heat transfer through its structures will be.

The mechanism of **heat distribution** within a room can be by convection (forced or natural) or by radiation (short wave or infrared). Most of the heat that flows from the building material surfaces to the indoor air is by radiation and a smaller, but important proportion of this exchange is carried out through convection. The fact that the radiation exchange within a room is dominant is the main reason that direct gain is a viable solar strategy (Balcomb, 1983).

Forced and natural convection are essential for heat dissipation. In the internal surfaces of the building, heat is first conducted from the hot surface to an interior thin layer adjacent to it. Air has a small heat capacity and tends to rise as heating decreases its density. Air velocity and temperature changes are limited to a thin region next to the surface – the boundary layer, where the regime is laminar. However, depending on the conditions, at some distance, turbulent air flow may occur. This phenomenon displaces cooler air at some other location within the building and results in the establishment of convective loops. Sometimes the hot air simply accumulates at the top of the room, resulting in temperature stratification. Whenever the air motion is due entirely to the action of gravitational forces, the heat transfer mechanism is known as natural convection. When the heat transfer rate is enhanced by introducing a forced flow over the surface, it is known as forced convection (Santamouris and Asimakopoulos Ed, 1996); (Balcomb, 1983).

The temperature distribution within the building materials also varies with time, boundary conditions and material thermal properties

Heat Storage takes place in the normal materials of the building. The use of thermal mass for heat storage in buildings can have a dual purpose. During the heating seasons, the thermal mass can store desired heat, which can be used later, when temperature outside drops. During cooling seasons, it also can keep temporarily unwanted excess heat, which can be removed later in the day.

The main material properties, which are related to the process of heat storage, are thermal conductivity (λ), specific heat (c) and density (ρ). As mentioned before, the higher the product $\lambda\rho c$, the higher the heat-storage capability of the material.

To conclude, the effectiveness of thermal storage depends on several parameters, such as materials' properties, the exposed surface area, the thickness of the storing elements and its location and orientation within the building (as an external or an internal partition), among others.

1.4. Further Concepts related to Thermal Inertia

The following definitions are basic physical concepts, but they are presented here to describe the ways thermal inertia of building components can be represented. Moreover, these concepts also characterize how the heat flow develops through a building component. The following concepts are described according to Givoni (1976):

The reciprocal of the thermal conductivity ($1/\lambda$) is the thermal resistivity of the material. This parameter describes the resistance of materials and air spaces to heat transfer.

Both conductivity and resistivity are independent of the size and thickness of the building elements. On the other hand, the heat flow across a building element (wall or roof) depends not only on the thermal conductivity of the material but also on the thickness of the element. The greater the thickness, the lower will be the rate of heat flow. Therefore, the **thermal resistance** (r) of an element is expressed by d/λ.

As explained by Lechner (1991), under steady-state conditions, for example, 2.5 cm of wood has the same thermal resistance as 30.5 cm of concrete, mainly because of the air spaces created by the cells in the wood. However, the delay in heat conduction is very short for 2.5 cm of wood because of its low heat capacity. Concrete, on the other hand, presents a much longer time delay due to its higher heat capacity.

The reciprocal of the thermal resistance is the thermal conductance (c) of the element, given by λ/d.

When computing the rate of heat flow between indoor and outdoor air, the thermal resistance of air layers adjacent to the surfaces (i.e. the reciprocals of their surface coefficients: $1/h_i$ and $1/h_e$) must be added to the thermal resistance of the wall itself. Thus, the total resistance (R) of a single layer wall to the heat flow between the air on either side is given by:

$$R = 1/h_i + d/\lambda + 1/h_e \qquad (4)$$

The reciprocal of the total thermal resistance (R) is termed **Thermal Transmittance (U-value)** and it determines the rate of heat flow through a given building component. It is defined as $U = 1/R$, given in units of $W/(m^2\,K)$:

When the wall is composed of several layers differing in thickness and conductivity, the overall thermal resistance (R_T) of the composite wall is calculated by the sum of the separate resistance of each layer. Therefore, the total transmittance (U_T) is defined by $1/R_T$.

The ratio between the heat absorbed and the heat stored in the materials depends mainly on the heat capacity of the envelope.

According to Givoni (1976): "*The term **Heat Capacity** of a wall or roof refers to the amount of heat required to elevate the temperature of a unit volume of the material or unit area of the surface by one degree. In the first case, it is referred to as the Volumetric Heat Capacity of the material and in the second as the heat capacity of the wall*" (or component). The volumetric heat capacity is the product of specific heat (c) by density (ρ), in units of J/m^3 K or (kWh/m^3 K). The heat capacity by unit area of surface is the product of density (ρ) by thickness (d) and by specific heat (c) of the components, in units of J/m^2 K or (kWh/m^2 K). The ***Volumetric Heat Capacity*** term is used to characterise a *material* while ***Heat Capacity*** is used in the description of *building components*. The unit of J/ m^2 K will be adopted in this thesis.

In a multi-layer wall or roof, the total heat capacity is calculated by the sum of the separate heat capacity of each layer, given by the expression:

$$HC_T = \Sigma\, d_i\, \rho_i\, c_i \qquad (5)$$

The thermal conductivity and heat capacity of the materials, as well as the thickness of the building components and the order of the layers in composite constructions, can be combined in several ways. Each of these combinations of thermophysical properties is important under certain conditions. Some combinations of the thermophysical properties are described below:

The depth that the diurnal heat wave reaches within the storage material depends on the thermal diffusivity property. **Thermal Diffusivity** is defined as the ratio between the thermal conductivity (λ) and the volumetric heat capacity, in units of m^2/s.

$$\propto = \lambda / \rho c \qquad (6)$$

Where ρ is the density, c is the specific heat and the product ρc is the volumetric capacity. The thermal diffusivity is a property of the *material* and not of the component and determines the way heat is transmitted from the surface to the depth of material.

As explained in Yannas and Maldonado (Eds. 1995), in general diffusivity is higher for materials of high thermal conductivity and low heat storage capacity. For common building materials, the value of thermal diffusivity is about 5 x 10^{-7} m^2/s, while wood has a value three times lower. Materials with higher thermal diffusivity values can be more effective for cyclic heat storage (24 hours for instance) at greater depth than materials with lower values.

The time it takes for a change in surface temperature to reach a certain depth of the component is defined as **Time Constant**. This concept was used by Givoni (1976) as "*a simplified method to describe the heat storage capability of a building*". The time constant is a property of the *building component* and it is the product of the thermal resistance (d/λ) by the heat capacity. It has a dimension of time (h):

$$t = (d/\lambda)\ (d\rho c) \qquad (7)$$

Mathematically, the time constant can be expressed by:

$$t = d^2 /\lambda/\rho c = d^2 /\propto \qquad (8)$$

Where d is the depth and $\propto$ is the thermal diffusivity.

As an example, a lightweight construction such as a plasterboard partition has a time constant less than 1 hour, while a construction consisting of 1 m of concrete has a time constant of about 50 hours.

The thermal reaction of the first centimetres of the internal surfaces of a room to the variations of the internal heat gains and the subsequent effect in the indoor temperatures can be expressed in the concept of **Thermal Effusivity**. Thermal effusivity is described in Yannas and Maldonado (Eds.1995) as "*the capacity of a material to absorb and release heat"* and characterises "*how easily heat can be absorbed at the surface of a material*". Effusivity tends to be higher when both thermal conductivity and specific heat storage capacity are high. The thermal effusivity (b) of a homogeneous material is defined as the square root of the product of thermal conductivity, density and specific heat and its unit is $Ws^{0.5} / (m^2\ K)$. It is given by the following expression:

$$b = \sqrt{\lambda \rho c} \qquad (9)$$

According to Liman and Allard Ed.(1995), while the thermal diffusivity varies over half an order of magnitude, the values of thermal effusivity varies over two orders of magnitude: from b = 2000 for heavy concrete to b = 20 for light fibreglass. Material such as wood has a b value of about 400.

These values of effusivity apply to isolated components of a space. However, to be useful, the concept must be able to correctly reproduce the thermal behaviour of a whole space. During PASCOOL experimental project (Liman and Allard Ed., 1995), a simple parameter has been found to characterise the thermal response of a building zone to a step change in heat gain - the mean thermal effusivity b_m. The parameter b_m is calculated as the area-weighted average of the b-values of the exposed wall surface materials. The procedure to calculate b_m is closely related to the calculation of the mean U value of a zone and it is also equivalent with the procedure to determine the diurnal heat capacity for a zone. If the value b_i of each internal surface S_i is known, the mean thermal effusivity can be defined as following:

$$b_m = \Sigma (b_i S_i) / S_{tot} \qquad (10)$$

Where only the exposed surface layers are taken into account and S_{tot} is the sum of the areas S_i .

As the b values vary over two orders of magnitude, Liman and Allard report suggests that, it can be a good approximation to sum only those walls areas which correspond to exposed massive materials of considerable thickness – more than 5 cm. According to this, the calculation should include partition walls, which are exposed on both sides, and glazed areas should be neglected as they have insignificant thermal storage capacity.

PASCOOL report concludes that "*the concept of effusivity is closely related to admittance, but has an advantage over the harmonic method because it includes naturally a description of non-periodic heat storage, which is explored in the modelling of cooling by night ventilation".* And continues: *"Effusivity characterises the apparent thermal inertia and allowing a rapid investigation of the influence of basic design changes, it is useful for the development of design guidelines for dynamic thermal response*".

The Admittance, Heat Capacity and the Mean Thermal Effusivity methods will be used later in this research only to characterise the degree of thermal inertia of the residences monitored in the field experiment (see chapter 4).

Chapter 2. Parameters affecting the performance of thermal inertia:

2.1. Introduction:

The effectiveness of thermal inertia is determined by some parameters and conditions. It is important to understand the relation of these parameters and how they can affect the performance of thermal inertia to be able to achieve best results. The optimisation of thermal inertia depends on climate conditions, buildings thermal properties, ventilation, thermal insulation, occupancy and internal heat gains. The thermal mass location and distribution, as well as the size of windows in a room also have influence on the performance. The following review summarises findings of some researches, which are used to illustrate how these parameters affect the effectiveness of thermal inertia.

2.2. Climate conditions:

Givoni (1994), explains that "*the maximum temperature at which the storage mass can still be utilized depends on the indoor air upper limit for human comfort in unconditioned buildings. This limit, in turn, depends on the ambient vapour pressure and the indoor air speed. The vapour pressure depends on the local climate and thus sets a climatic limit for the applicability of this system*". Taking into account these two factors, the upper temperature limit for nocturnal ventilation cooling may range, according to Givoni (1994), at still air conditions from about 25°C in semi-humid regions with vapour pressure of 18 mmHg (15.3g/kg dry air) to 20 mmHg (17 g/kg dry air) to about 28°C in arid regions with vapour pressure below 15 mmHg (12.8 g/kg dry air). However, his work suggests that this limit can be extended by increasing the indoor air speed, without introducing the warmer outdoor air. If a ceiling fan is used to increase the indoor air speed to about 2 m/s, this limit is shifted to about 28°C in semi-humid regions and 30°C in arid regions. In humid regions, with vapour pressure above 22 mmHg, the outdoor minimum temperature is usually not enough, and the diurnal range is too small, to permit any useful nocturnal cold storage for convective ventilation cooling. Givoni (1994) points out that "*at some season most hot regions experience climatic conditions when night temperatures are suitable for convective cooling*" and finally that "*a diurnal temperature range of about 10℃ is required to obtain useful lowering of the indoor daytime temperature by nocturnal cooling of the structural mass*".

Szokolay (1985) also suggests that the use of thermal inertia is more appropriate in climates where the diurnal variation of the external temperature is above 10 K, as the mass of the building would help to reduce the outside peak of temperature and to keep the internal conditions within the comfort range by absorbing the excess of heat. The temperature diurnal variation is also mentioned in a study developed by Van der Maas et al.(1994), which shows that "*to use outdoor air for cooling at night, the temperature swing should be quite large with a mean temperature and humidity in the comfort range*". In addition, "*provisions should be made to avoid hot air from entering the building, by decreasing the ventilation during the day".*

In a more recent work, Shaviv at al. (2001) calculate the influence of thermal mass and night ventilation on the maximum indoor temperature in summer for different locations in the hot climate of Israel. They found that "*the maximum indoor temperature depends linearly on the temperature difference between day and night at the site*" and conclude that "*thermal mass with night ventilation is effective as passive cooling strategy depending on the temperature swing at the site*". The found relation can serve as a simple graphical design tool for predicting the effectiveness of thermal mass and night ventilation as passive cooling design strategy. From this design tool, one can see that "*for heavy thermal mass and night ventilation of 20 ach, temperature swing should be greater than 6°C, in order to achieve an effective T_{max} of about 3°C*". Where T_{max} is "*the reduction in maximum indoor temperature compared with the maximum outside temperature*" ($T_{max} = T_{max,Out} - T_{max,\ In}$) and heavy thermal mass, in this case, means "*heavy floor, like cement tiles on concrete floor, concrete ceiling and external and internal walls of 10cm concrete blocks, with plaster on both sides*".

According to the traditional principles, there is no benefit from thermal inertia in warm-humid climates, since the diurnal range is usually small and the mean relative humidity is around 80%. Nevertheless, this traditional approach has been questioned and recent studies (see item 3.1) have shown that thermal inertia can also be useful in warm-humid climates, although other attributes have to be considered than only thermal mass.

The climate of Florianópolis, which is the context of this thesis, will be described in detail in section 4.1.

2.3. Thermal Properties of Building Materials:

The thermophysical properties of materials have influence in the performance of the system. As stated before, high density in building materials is also an indicator of high thermal conductivity, i.e. they have poor thermal resistance. In the other hand, insulation materials have a low thermal conductivity and a high thermal resistance, which makes good insulators materials, poor for heat storage. As a result, when heat is applied on materials of different properties, it will have a different effect on them.

For the material effectively store heat, it must exhibit higher values of density, thermal capacity and thermal conductivity. Moreover, all the combinations of thermophysical properties of materials are important under certain circumstances. Some of these combinations and the way they have influence on the heat wave through the material have been already described in the section 1.3.

2.4. Ventilation:

The role of ventilation on the performance of thermal inertia is mainly associated to the nighttime. In the warm periods, outdoor temperatures at night are usually lower than indoor temperatures, so it is possible to use the night air to cool the building structure. As explained by Balaras (1996): "*Ventilated air enhances convective heat losses from mass elements and dissipates the released heat to the lower temperature outdoor heat sink*".

Before going into the night ventilation interaction with thermal inertia, some basic description of natural ventilation process is necessary, as follow:

Natural ventilation is primary used for indoor air quality control and also to provide thermal comfort in summertime. In general, there are two main contributions of mass airflow to the enthalpy balance of a room: the airflow coming from outdoors, which is infiltration or fresh air ventilation, and the interzonal airflow rates due to the air mass transfer between zones of a building. The driven forces for natural ventilation that influence the infiltration and/or the ventilation rates in buildings are the effect of the wind and the stack effect. Wind creates a pressure distribution around the building according to the atmospheric pressure. The phenomenon of stack effect is due to density differences between inside and outside a building or between zones. The thermal behaviour of a building is strongly coupled to ventilation and air infiltration. At the same time, airflow depends on the different thermal levels of the building zones. In the absence of wind, these differences are the only driving forces for ventilation (Allard Ed., 1998).

There are many problems that may prevent building occupants from implementing natural ventilation in a building. The main barriers are: safety, noise, air pollution, shading for solar control, draught prevention and ignorance from occupants about how to take best advantage of natural ventilation strategy. There are also barriers faced by the designer during the building design process, such as building regulations in general and fire regulations, the need to provide shading, privacy and daylighting and again, the pattern of use by the occupant.

This is also a special issue when natural cooling by night ventilation is put into practice. For natural ventilation to be effective during warm periods, it is important to have the ventilation strategy under control (by reducing the ventilation rate during the day) and practical solutions have to be found by designers to resolve ventilation openings for night ventilation purposes, which satisfy security requirements, as well as provide protection for privacy, noise, insects, etc (Van der Maas et al, 1994).

Givoni (1991) divides cooling by ventilation in two types of strategies: comfort ventilation and nocturnal convective cooling. The distinction between them is suggested because some building elements, such as structural materials and thermal properties of the building's mass, require different designs for the effectiveness of each one of these ventilation strategies. Comfort ventilation provides direct human comfort by seeking to enhance convective cooling of the occupants by increasing the indoor air speed. This technique is used mainly during daytime. Therefore the temperature limit of applicability of comfort ventilation is the comfort limit at the enhanced air speed. If the indoor air speed is of about 1.5 – 2.0 m/s, comfort ventilation is applicable mainly in regions and seasons when the outdoor maximum air temperature does not exceed about 28-32°C, depending on the acclimatisation of the local population, and where the diurnal temperature range is less than 10°C.

Night ventilation or nocturnal convective cooling consists in cooling the structural mass of the building by ventilation during the night, using the lower outdoor temperature as a heat sink. The cooled fabric can absorb the heat flow in the following day and provide comfort by reducing both the indoor air and wall surfaces temperatures. This is the main principle for the interaction between night ventilation and the building thermal inertia. The climatic applicability of nocturnal ventilation cooling was described in the section 2.2.

According to Givoni (1991), to enhance night cooling effect, the building should be closed during daytime to avoid bringing the warm outdoor air into the rooms. In this regard, night ventilation can not be combined with daytime comfort ventilation (by natural means) as it will reduce the temperature differences between indoor and outdoor, decreasing the effect of the mass heat sink.

Ventilation techniques rely in windows openings (natural ventilation), ceiling fans (mechanical ventilation), or other method used to increase the indoor air movement and rise the convective cooling.

When the climatic conditions do not allow the use of night ventilation, because outdoor air temperature or humidity levels are high, it is still possible to precool the building using air-conditioning system during off-peak hours. Part of the cooling load will be passively covered by the building cooled mass, provided that the building is well insulated and it is not ventilated during the day. Hence, it is possible to reduce the energy consumption of air-conditioned buildings, since the operation time of the system will be reduced. Precooling the thermal mass of a building is a thermal storage approach for cooling of commercial buildings (Balaras, 1996); (Keeney, K and J. Braun, 1997).

Some researches covering the aspect of interaction of night ventilation and the building thermal inertia will be reviewed in the section 3.2.

2.5. Thermal inertia and insulation:

Insulation materials have a high value of thermal resistivity, which means that a building component with an insulation layer have a poor thermal transmittance. Finishing materials can also behave as an insulating. It should be noted that, when considering the structural mass available for thermal storage, building elements, which are insulated from the indoor air, e.g. floors covered by carpets, etc should not be taken into account for storage purposes. An insulation material will produce a rise in the temperature on the surface exposed to the heat wave, but will transfer very little toward the inner layer, whereas a highly conductive dense material will store much more heat with small increasing in its temperature.

As low U-values means that the component has a high total thermal resistance (R), this characteristic can represent the degree of insulation in such building component. Carlo et al (2003) describes the simulations carried out to establish some thermal properties recommendations for the building envelope, to be employed by the energy efficiency new Building Code for the city of Salvador, located in the Northeast of Brazil. Among other thermal parameters, the study tried to estimate limits of thermal transmittance of walls for that location. The energy consumption in commercial buildings was used as a parameter for comparison. U-values ranging from 0.273 W/m^2K to 5.263 W/m^2K were modelled for two types of external walls: mass walls and light walls. The analyses show that "*the energy consumption of the prototype building with external mass walls tends to significantly increase only when U-values are higher than 3.7 W/m^2K*". This U-value corresponds to a solid clay brick wall, widely used in Brazil. However, the energy consumption of the model with external light walls shows a significantly increasing for U-values higher than 0.5 W/m^2K. The light wall used here is described as "*new materials and components that are becoming used in the Brazilian construction industry*". From these results, the following thermal transmittances of walls were recommended for that location:

"*For mass walls, no limitation was imposed, as 3.7 W/m^{2}K represents a 10 cm solid brick wall, but for light walls higher insulation was requested (U= 1.2 W/m^{2}K) in order to keep the energy consumption similar to the mass walls*". These results are showed here to illustrated that, in terms of their insulating qualities, massive walls would not have to meet as severe requirements as light walls.

2.6. Occupancy and Internal Heat Gains:

The efficiency of thermal inertia in warm climates depends on the correct management by occupants and the amount of internal gains by appliances.

Internal gains originate from any sources that generate heat inside the building. The internal heat gain or the heat generated within a space depends on the building type and use. Sometimes, internal gains consist of radiant heat, which is partially stored in the building construction's material, eventually reducing the cooling load. In general, sources of internal loads consist of some or all of the following: occupants, artificial light and appliances (any mechanical or electrical equipment operating in the space) (Santamouris and Asimakopoulos eds, 1996).

Van der Maas at al (1994) stresses that the use of thermal inertia is not sufficient if the users do not apply the correct ventilation strategy. It is important to have the ventilation and exposed thermal mass under control because the occupant can deprive the available inertia by using false ceilings and walls and floor coverings. Furthermore, the night ventilation / daytime closure technique is shown to be effective but contrary to people's preference for open-air living (Szokolay, 1996).

Results from monitoring experiments in four buildings in Spain (Diaz, 1994) suggest that if solar gains are minimised, the distribution and exposure of mass within the building can have a more significant role in the improvement of internal conditions than the quantity of thermal mass itself. The performance of thermal mass may be neutralised by the effect of heat gains through the structure of non-insulated elements or by excess of internal gains. This experiment also showed the influence of internal gains when the night ventilation was provided. When the spaces were occupied, it was observed that the effectiveness of night ventilation could be reduced by the effect of internal gains.

It is important that the designer keeps in mind that users represent the final determining factor on the effectiveness of any building system, including thermal mass.

2.7. Openings:

Selections of the type of glazing as well as its proportion to the total wall area are very important towards achieving a desirable indoor environment. Windows have a significant role with critical responsibility in connecting the indoor environment of buildings to the outdoor.

Several reports show that the extents of glazed areas in buildings surfaces, as well as their internal thermal mass, are directly affecting their internal condition.

The role of windows becomes rather more important when designing buildings that depend on passive heating or cooling system. The window sizing study (Al-Sallal, 1998) carried out for a one-story earth sheltered house located in the city of Fresno, California has shown that, although increasing the south window area can provide more auxiliary heat savings, it has negative impact by increasing the heat gain during the summer. In the other hand, reducing the window area to a point that lowers solar saving fraction from 69% to 60% does not reduce the effectiveness of passive heating systems considerably. The solar saving fraction is used to evaluate a building's solar performance and it is defined as "*the extent to which a solar design reduces a building's auxiliary heat requirement relative to a reference building*". Al-Sallal (1998) also adds that, "*to size windows during the design process in that climate, one should start by passive cooling issues before passive heating ones*", as a "*good orientation and provision of thermal mass and insulation can solve most of the heating problems*".

Kontoleon and Bikas (2002), consider the influence of the type of glazing and the glazed openings percentage (GOP) in the south wall of a zone in winter and summer, on the indoor temperatures and energy efficiency. The studied zone comprises masonry walls with insulation in the centre plane, concrete horizontal slabs with and without insulation and three types of glazing (double - DG, double with low emissivity – DG-ε and double with reflective film - DGR-ε). The zone model is situated at latitude 40° N and the walls formation is typical in Mediterranean climate. The specific results obtained in the study, made it clear that overheating can be avoided and energy savings can be achieved with the proper selection of GOP as well as the type of glazing and position of slab insulation. The analysis of the thermal zone in winter revealed that in buildings with double-glazing and insulated slabs, overheating is observed when GOP exceeds 70%. By changing the position of insulation to the outer surface, overheating is almost avoided. In summer, overheating can be avoided with GOP < 60% and exterior insulation in the horizontal surfaces, unless the DGR-ε type of glazing is used; in this case, overheating occurs for GOP > 80%. From an energy consumption point of view, it has been concluded that in winter (with insulation in the outer face of the slabs and double glazing with low-ε coating) the optimum GOP, which minimizes the energy consumption is 70%, while in summer it drops to 40% with DG-ε glazing and to 60% with DGR-ε glazing.

The analysis of window from the thermal point of view is very complex, especially in climates where heating is essential in winter and cooling is required in summer. A window must provide a maximum heat gain in winter during the day and the minimum heat loss at night. On the other hand, in summer, the same window must be protected to reduce heat gain by solar radiation during the day, but allow thermal dissipation during the night. To solve this problem, a moveable-shading device can be used, so the window can be fully shaded during summer, but also can be exposed to solar radiation in winter (Kolokotroni and Young, 1990). However, the role of solar radiation in providing daylighting should also be considered. Shaviv and Capeluto (1992), which investigates the relative importance of some design parameters in a hot-humid climate, also illustrate the need for careful design of summer day window shading. According to their results window shading is "*the first geometric design parameter in importance, which the architect should devote more attention during the decision-making process*".

In a study developed by Corbella and Corner (2002), several simulations were carried out for a tropical environment in a summer situation, considering different window elements and adequate management for diurnal and nocturnal occupancy periods. Results have shown that, by modifying windows elements (using double glass type, well tight windows and using solar protection devices), and the ways windows can be manipulated (opening and closing times), substantial saving in energy consumption can be achieved. According to their result, the daily consumption of air conditioning can be reduced by five times for nocturnal occupation buildings, and in almost four times in commercial buildings.

2.8. Thermal Inertia location and distribution:

According to Balcomb (1983), internal walls are much more effective to heat storage than external walls because each of the two surfaces can work for storing the heat, increasing the effectiveness. In addition, research in diurnal heat capacity has shown that there is little to be gained by increasing the thickness beyond the amount required by structural requirements or the thickness determined to give the maximum heat storage capability. Over the daily cycle, the active thickness suggested by Balcomb is typically about 10 cm for lower density materials and about 18 cm for high-density materials.

Balcomb also points out that the exposure of mass within the building has a significant role; hence covering the surfaces will reduce the effective thermal capacity of a space.

Nevertheless, two cases can be discerned depending on whether the heat storage material receives energy by solar radiation or by infrared radiation. The direct heat gains (energy received by solar radiation) are experienced by the outside of the building envelope and by the internal surfaces that may be absorbing solar radiation through openings. Indirect heat gains are experienced by opaque elements inside the building (infrared radiation or room air convection). According to Balaras (1996), direct locations are much more effective than indirect, for placing heat storage mass.

It seems that, in warm-temperate climates, both winter and summer conditions should be taken into account, since the exposure of mass surface to the solar radiation is the key factor for the effectiveness of thermal inertia. Once again, the issue of protecting the internal mass of solar gains in summer and to take advantage of solar radiation in winter is pointed out.

The exposure and location of thermal mass were also explored by Diaz (1994). Some analyses were carried out through parametric studies to evaluate the effect of thermal mass on the internal temperature of a single-zone space. A cube with a homogeneous concrete structure for the envelope was used as the reference zone. The effect of solar radiation and internal heat gains were studied by considering two cube types: unprotected (exposed to the external environment) and protected (insulated or adjoined to other zones). Diaz (1994) comments that the aspect of exposure of mass surface trends to vary according mainly to the internal gains and /or whether the space is night ventilated or not. The mass to floor ratio MFR is used for the measure of the exposure of internal surfaces to the internal air and it can be expressed as the ratio of the total area of internal surfaces to floor area. Most cases indicated that the addition of envelope exposure helps to improve thermal conditions by reducing internal swings and internal temperature. The exceptions are: when the structure is not protected and the rate of internal gain is constant. Higher values of MFR improve thermal performance of the interior when the internal gains are higher during the day than at night. The condition of the envelope regarding direct solar radiation is again an important issue. If there is no solar radiation falling upon the envelope of the room, the exposure of mass surface area prevails over thickness to improve thermal condition. It means that if additional thermal mass is going to be introduced into the cube, it would be more effective to spread it throughout the area of the walls rather than to concentrate it on their thickness. Moreover, regarding the aspect of location, some of the work’s conclusions are as following: The floor is the location where the thermal mass has lesser impact on the internal temperature. For rooms exposed to the exterior on the four sides, the position of mass on the roof results in lower swings and temperature than on any other location. When only one of the walls is an external element (protected cube), it is on that wall where the position of mass creates the greater impact on the temperature. On the internal walls of the protected cube, the placement of the thermal mass is the least effective even with the effect of internal gains. As the structure becomes heavier, the location of the thermal mass loses its importance.

The roof is one of the most sensitive building elements in hot climates, because it is exposed to solar radiation the most part of the day. A heavier roof construction is required, but sometimes the use of insulation in the roof is recommended due to the cost of massive constructions (Balaras, 1996). However, one should be careful when adding insulation in the roof in climates where cooling is the main issue. The results of the study (Shaviv and Capeluto, 1992) show that winter performance is very sensitive to the roof's insulation and the better it is, the less energy is required for heating. On the other hand, this is not the case in summer, when the better the roof's insulation, the more energy is required for cooling. The reason is that the poorly insulated roof allows night cooling by heat conduction and by long wave radiation. Consequently, higher transmittance in the roof is recommended.

The role of the roof in hot climates will be further illustrated in the session discussing the results of some experimental and analytical works (see 3.2).

2.9. Discussion and conclusion:

The concept of thermal inertia of a wall or of a building structure as a whole is closely related to its weight (Givoni, 1976). The difference in density between structural materials used in building construction is often reflected in the classification of building structure as heavyweight, mediumweight and lightweight (Yannas and Maldonado Ed., 1995). Generally, the higher the density of a material, the higher the resulting thermal capacity. A building of a timber frame construction is thermally lightweight, whilst a masonry construction is referred to as heavyweight.

However, these terms do not always reflect the effective thermal inertia of the building. The reason for that is because occupied buildings combine a wide variety of structural and non-structural materials, all of different properties, as well as in non-homogeneous combinations. Consequently, these arrangements have influence in the thermal behaviour of the building. Several studies point out the influence of the finishing materials on the effectiveness of thermal inertia. A lightweight material, such a carpet, when placed on a heavyweight concrete slab floor will interfere in the reception of solar radiation or other heat inputs and will react in a different way. The use of false ceilings and walls and floor coverings can completely degrade the available inertia.

Some studies have shown that thermal mass is best increased by maximizing surface area rather than increasing thickness (Balcomb, 1983); (Diaz, 1994). The influence of exposed surface is also mentioned in the thermal effusivity study. For any given heat gain in a room, the fluctuations in surface temperature decrease with the increasing in thermal effusivity and surface area. Moreover, it is the ventilated area of exposed thermal mass that is important to the dissipation of the heat through ventilation to be effective (Van der Maas et al, 1994). Therefore, optimum thickness will not be explored in this thesis and only the influence of finishing materials and the necessary exposed area in the performance of thermal inertia will be further studied.

The effectiveness of thermal inertia is also influenced by solar gains through non-shaded openings. On a sunny day, the rate of heat inflow is much greater than most materials can accommodate for very long, then the heat will be redistributed by convection and long wave radiation. This is aggravated by people preference for open-air living in hot-humid conditions. Occupants can influence the effect of the thermal mass through their behaviour, allowing solar radiation to strike the thermal mass or allowing ventilation by opening windows when temperatures outside are too high. These procedures can increase the indoor temperature above the comfort limits, reducing the effectiveness of the thermal inertia. The window issue will be investigated in this work by assessing mass to opening ratio and by establishing limits of glazed openings percentages.

Chapter 3. Effectiveness of thermal inertia:

3.1. Introduction

This chapter presents a review in some experimental and analytical works that evaluate the effectiveness of thermal inertia in different warm climates. Results of the different experiences are described. Moreover, studies assessing the cooling efficiency of night ventilation and its influence on thermal inertia performance are also reviewed.

3.2. Experimental and analytical works, which characterize the performance of thermal inertia in different warm climates:

3.2.1. Experience in Managua and Southern Spain:

An experimental study (Diaz, 1994) aiming the optimisation of thermal mass for indoor cooling in non-domestic buildings was carried out in the warm climates of Managua (Central America) and southern Spain. In this study, the fieldwork was divided in two parts. First, an overview of the effect of thermal inertia and night ventilation was undertaken through the recording of spot temperature measurements at different times of the day in two administrative buildings in Managua. The second phase of the fieldwork were undertaken with the monitoring of four buildings located in southern Spain for a period of one week per building. The data analysis was followed by parametric studies in a single zone space.

Some of the analytical results of this work were already showed in the previous chapter. This section describes the general results obtained from both field experiments.

The first experiment was carried out on two case study buildings located in Managua and the study focuses on the comparison between lightweight and heavyweight constructions types. Some conclusions were undertaken as follow:

The lightweight building responds more quickly to the temperature variations of the outside. Consequently, internal temperatures at night drop close to the more comfortable outdoor level, although during the day the interior temperatures reach values, which are beyond of the limits where thermal comfort can be restored by natural ventilation. This effect is particularly beneficial in residential buildings, where nighttime comfort is important. On the other hand, when lightweight components are used for office spaces, indoor conditions at working hours often result in overheating, so the use of air conditioning is necessary. The effect of solar radiation through the roof and walls is greater due to the little resistance of the small inertia of the envelope, increasing the internal temperatures progressively during the day. Also because of the high internal gains of these spaces, mechanical cooling needs to be provided.

The results of the above study support the importance of thermal mass as an environmental moderator for daytime occupied buildings, such as office buildings, in warm climates. The increase of thermal capacity in the building envelope stabilizes the internal temperature, keeping conditions cooler than the outside during the daytime hours (occupied hours) although at night the interior remains warm.

The second experiment was carried out in four buildings situated in the area of Seville. Two recent and two traditional buildings of different construction types were objects of the study, which aimed at identifying thermal characteristics related with the effect of the building mass.

Results from this monitoring experiment suggest that the effect of thermal mass of the buildings have to be considered in relation to the heat gains since the effectiveness of thermal inertia may be reduced by insufficient dissipation of heat gains. Results from one of the buildings indicated that a massive envelope may not be sufficient to reduce internal temperatures if it is not protected and if the mass to floor ratio of the room (the ratio of the total area of internal surfaces to floor area) is not enough, especially with the additional effect of internal gains. The higher peak temperatures were also recorded in the building, which has non-insulated and relatively lightweight envelope walls. Among the monitored buildings, the building with a smaller portion of its wall exposed to the exterior, more massive structure and the higher mass to floor ratio value, presented better performance with lower temperature swing and peak temperature and the effect of night ventilation was the more evident.

3.2.2. Southern Europe:

Maldonado et al (1997) describes the studies carried out in the frame of the PASCOOL Project to document and assesses the thermal behaviour of buildings in Southern Europe during summertime and to characterise the contribution of passive cooling in buildings. Twenty-three buildings from nine European countries were surveyed and monitored for a short period and the data collected served the basis for sensitivity analysis with thermal simulations. The selections comprehended buildings of typical constructions, including traditional and recent, residential and non-residential. Although the sensitivity studies covered the effects of many aspects such as shading, ventilation, window orientation, insulation and others, the effect of thermal inertia was also included in the analysis.

Results regarding the performance of thermal inertia are summarized below:

- Despite of building type, the best thermal performances were obtained from heavyweight, well-shaded, traditional masonry buildings in moderate summer climates. A high ventilation rate at night and a low rate during the warm daytime hours led to the best performance.
- Heavyweight buildings in the warmest climates of Southern Europe also exhibited stable indoor temperature patterns, but at mean values above the normally accepted range for thermal comfort, i.e. over 30°C. These buildings depended on cooling ventilation, ceiling fans or on mechanical air-conditioning to achieve acceptable conditions for occupants.
- Insufficient thermal inertia use to lead to overheating or excessive energy consumption. A low thermal inertia may be due to lightweight construction or result from lightweight internal finishing. Where the shading of glazed surfaces is not carefully considered, the situation is worst. In this case, night ventilation becomes of little use, as there are no means for coolness storage in the building structure.

The results above indicate that best thermal performance for heavyweight buildings depends on many parameters, such as shading, night ventilation, and low ventilation during the hotter hours of the day. They also point out, again, the influence of lightweight internal finishing.

3.2.3. Experience in Australia:

In an early study, Szokolay (1981) suggested the design of a hybrid building for warm-humid climates. Hybrid in the constructional sense: a massive part, sitting on a concrete slab-on-ground, for housing all day-time activities (kitchen, dining, living rooms) and an elevated, lightweight cross-ventilated part, which would still provide a slight advantage for night-time occupation.

The controversy of lightweight versus heavyweight construction for warm-humid climates is outlined by Szokolay (1996), in a more recent study. This work describes the results of a research, showing the advantage of massive construction for warm climates. A simple box-like building was taken as the vehicle for simulations and the warm-humid climate of Cairns, located in the north of Queensland was chosen. The model was simulated considering 63 constructional variants for the hottest month (January) and for the coldest month (July). The building with heavyweight floors and walls with insulated roof had the worst performance when no shading and ventilation were implemented. However, the same heavy configuration showed the best performance when shading and ample ventilation were provided. Some other recommendations were made, taking into account the variables examined: roof absorptance should be low; major windows should face north, minor ones south; concrete slab-on-ground floor with tiled or other hard finish would give best results; the insulated tiled roof performs best and ventilation of at least 10 ac/h in summer, but this should be reduced to 1 ac/h in winter.

In a recent paper [Szokolay, 2000], the discussion about the dilemmas of warm-humid climate house design continues. This latter work leads to the definitive conclusions that the heavyweight versus lightweight argument for warm humid climates is unproductive because "*both kinds of design can be similarly good and that there are other attributes to be considered than only thermal mass*". His work also confirmed that it is the interaction of variables that determines the thermal response of the house, rather than the optimisation of individual variables. The paper also shows a list of characteristics of well-performing heavyweight constructions. The list is summarised below:

- The floor should be a concrete slab-on-ground, with a hard finish.
- The walls should have at least a 105 mm brick or 150 concrete block (solid or filled) inner skin, with at least 50 mm resistive insulation on the outer side of this, and some external protective layer.
- Windows need not to be large, but ample night ventilation must be facilitated. If there is hardly any breeze at night, a substantial ventilation shaft up to the roof ridge level may provide a sufficient stack effect to create around 10 ac/h or more. Alternatively, a centrally located ceiling fan can be used. It is important to provide air intake openings in all rooms, preferably near the floor level.

3.2.4. Experience in Jakarta - Indonesia:

The typical passive design suggested for residential buildings in tropical hot-humid climate is a lightweight building with many openings on the north and south walls to allow continuous natural ventilation, shaded by wide overhangs. This traditional passive design is questioned by Soebarto (1999), whose results attempt to show other alternatives that can be more suitable for this climatic region. The use of massive construction, which is a common practice in Asia, is tested. Further investigations include examining the effects of using radiant barriers and roof insulation, changing the building orientation and shading conditions, and using various floor and roof claddings. The analyses were mainly conducted through simulation, but monitoring results of a case study in Jakarta (Indonesia) were also used to confirm the analysis.

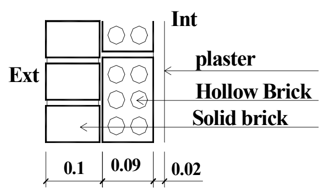
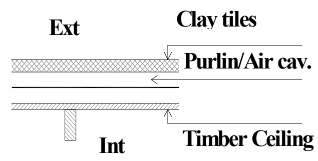
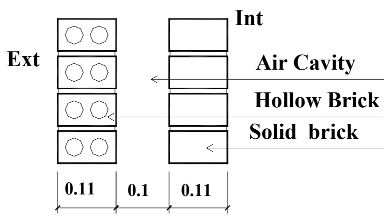
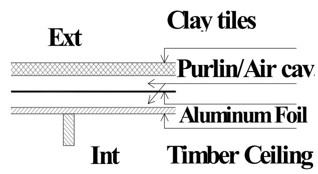
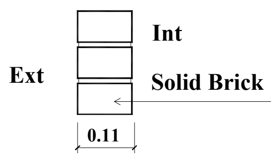
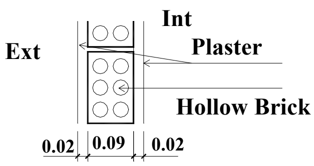
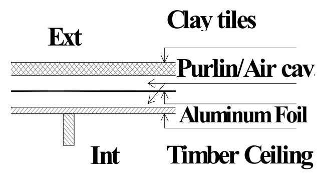
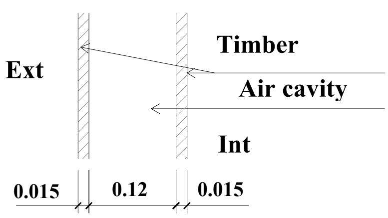
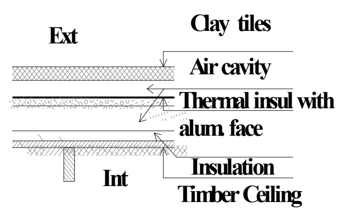
The first simulation was to test the performance of heavyweight construction against the suggested traditional lightweight construction. Four wall material assemblies were tested: single brick, double brick, non-insulated and insulated timber frames with timber sidings. The results showed that in the hottest week, the peak indoor temperatures in a house with single brick walls were about 3 K lower than with non-insulated timber frame walls. Double brick walls, would perform the best during the day, but they would make the temperatures late in the evening and early in the morning the highest amongst the other alternatives due to the heat stored in the mass. Insulating the timber walls did not improve the performance of non-insulated timber walls, as the insulation would trap the heat inside. The monitoring of the case study building revealed similar results.

The simulation studies also showed that during the peak hours most heat gains were from the roof, whereas the windows were the second source of heat gains. The results showed how installing radiant barrier could significantly improve the performance of the house. It reduced the indoor peak temperature by almost 7K. Adding roof insulation, however, would increase the indoor temperature. As discussed previously, adding insulation in the house construction in these climates may be a disadvantage, as the insulation would hold the heat inside. In other simulation, changes in the schedule of opening the windows were applied. The results presented an improvement of the indoor temperature by closing most of the windows during the peak time of solar radiation (from 11 am to 5 pm) and open for the rest of the hours. The indoor temperature could be 3 to 4 K lower than the outside temperature. Opening the window from 6 o'clock in the afternoon until the next morning would bring the indoor temperature close to the outdoor temperature, which would have dropped during the night.

3.2.5. Experience in Southern Brazil:

A fieldwork was developed by Papst (1999) to analyse the performance of four different single-family dwellings, with different heat capacity in their walls and roofs (see table 3.1), located in the climate of Florianópolis, southern Brazil. Internal and external temperatures were measured for nine months and the results were evaluated through distribution of internal temperatures, temperatures swing (temperature daily range), time lag, percentage of hours within the comfort zone and number of hours which the temperature were above or under specific values.

Table 3.1. Heat Capacity of the residence's envelope. Source: Papst (1999)

<table>
<tr><th>Wall configuration</th><th>Wall Heat Capacity ($kJ/m^2.K$)</th><th>Roof Configuration</th><th>Roof Heat Capacity ($kJ/m^2.K$)</th></tr>
<tr><td>
Dwelling 1</td><td>257</td><td></td><td>32</td></tr>
<tr><td>
Dwelling 2</td><td>258</td><td></td><td>32</td></tr>
<tr><td rowspan="2">

Dwelling 3</td><td>170</td><td rowspan="2"></td><td rowspan="2">32</td></tr>
<tr><td>153</td></tr>
<tr><td>
Dwelling 4</td><td>41</td><td></td><td>63</td></tr>
</table>

The results obtained showed that the house with higher thermal capacity in the wall and radiant barrier in the roof (Dwelling 2) presented ambient peak temperatures lower than external peaks, resulting the lowest values of temperature swings compared with the other houses.

During the months with higher solar radiation, the house with high thermal capacity in its walls but without insulation or radiant barrier in the roof (Dwelling 1) showed worst performance than the house with lower thermal capacity in the envelope but using radiant barrier in its roof (Dwelling 3).

Measured data for the period covering summer and winter were plotted over a bioclimatic chart (after Givoni, 1992). The bioclimatic chart present the comfort zone and building design strategies needed to restore the thermal comfort. From this analysis, the results showed that, with the use of thermal inertia, the percentage of hours of internal conditions within the comfort zone is higher compared to the percentage of hours of internal conditions of the houses with lower thermal inertia. However, for the house with higher thermal capacity, the percentage of hours that are out of the comfort zone (which corresponds to the necessary building design strategies) is lower for the heating purposes than for cooling systems. It means that the use of thermal inertia in that case, provided better performance for winter than summer condition.

The general results showed that the house with higher thermal inertia (dwelling 2) has the better performance with lower peak temperature and temperature swing. However, although this house has the highest thermal capacity, the configuration of its walls leads to further questions. The presence of the air- cavity in the wall could have influenced the results due to thermal resistance of the air. The U-value for this type of wall is 1.62 $W/m^2.K$, smaller than the U-value for the wall of the dwelling 1 (2.01 $W/m^2.K$), which has the same value of thermal capacity.

In addition, materials such as hollow bricks are less effective for heat storage than solid bricks. On the other hand, hollow bricks have some insulation property due to the air present in the hollows. Hollow and solid bricks are widely used in buildings in Brazil, as illustrated by the residences assessed in this study.

The usual behaviour of occupant in such climate is to allow ventilation during day time, so the results could have been influenced by the warm air coming inside. Also, night ventilation was not adopted for any of the studied cases.

Hence, the results of this study may encourage further investigation, especially taking into account some aspects that may have influenced the application of thermal inertia for that specific location.

3.3. The influence of night ventilation

Night ventilation strategy works by using natural or mechanical ventilation to cool the surfaces of the building material at night and it is said more effective where a building includes a reasonably high thermal mass to absorb the heat during the day. According to Kolokotroni and Aronis (1999), the use of night ventilation can affect the internal conditions during the day by: reducing peak air temperatures; reducing air temperatures throughout the day, and in particular during the morning hours; reducing slab temperatures; and creating a time-lag between the occurrence of external and internal maximum temperatures.

There are many recent researches, which explore the cooling efficiency of night ventilation and confirm that night ventilation combined with thermal mass is one of the most efficient techniques for improving the indoor thermal conditions and reducing the time for air conditioning use. Also, they point out some parameters that the efficiency of night ventilation is related to. Some results of these studies are described as following.

The cooling potential of night ventilation as a technique that can contribute to decrease the cooling load of air conditioning system (A/C) and improve the comfort levels of free floating buildings is investigated by Geros et al (1996). Measurements were carried out under free floating and air conditioning operational conditions. Based on the results a theoretical model was developed to calculate the thermal behaviour of the building for the same period, under completely free floating or completely air conditioning conditions and with or without night ventilation. This comparative approach showed that under free floating conditions, the application of night ventilation techniques contributes to decrease the peak indoor temperature of the building during the next day up to 2.5 °C, while under air conditioning conditions, the corresponding temperature decrease was close to 1°C and the cooling load was reduced to about 19%. Moreover, the results showed that "*the exact contribution of night ventilation for a specific building operating under free floating conditions or A/C conditions has to be calculated as a function of the buildings characteristics, the climatic conditions, the applied air flow rate and the assumed operational conditions*".

Diverse studies also illustrate that thermal mass with night ventilation can reduce the maximum indoor temperature in building in summer. Givoni (1998) examines the effectiveness of mass and night ventilation in lowering the indoor temperatures through an experimental study. Buildings with different mass levels were monitored in summer in a site in South California. The low mass building is of conventional Californian stud wall construction with interior gypsum drywall and external walls of "*fiberglass batt*". The ceiling is also insulated with *fiberglass batt* in the attic. The high mass building has solid concrete walls (10 cm thick), insulated externally with rigid foam and plastered. Internal partition is also of solid concrete. The monitoring was conducted under shaded, unshaded, closed and open conditions. The effect of mass in lowering the maximum daytime indoor temperatures was evaluated in closed and in night ventilated buildings. The results have shown that night ventilation had only a very small effect on the indoor maximum of the low-mass building. However, it was very effective in decreasing the indoor maximum temperatures for the high mass building below the outdoor maximum, especially during the heat wave periods. It is demonstrated by the result in an extremely hot day (outdoor maximum of 38°C), in which the indoor maximum temperature was only 24.5°C (a reduction of 13.5 °C). Using simulations to examine different levels of night ventilation and thermal mass, Shaviv et al (2001) also found that "*in the hot humid climate of Israel it is possible to achieve a reduction of 3 to 6°C in a heavy constructed building without operating an air conditioning unit. The exact reduction achieved depends on the amount of thermal mass, the rate of night ventilation, and the temperature swing of the site between day and night*".

Blondeau et al (1997) deals with a two-step analysis of night ventilation as a way to improve comfort or reduce the cooling loads of office buildings in summer. First, experimental data was carried out to assess the influence of some previously defined parameters on daytime temperature and night ventilation efficiency. They are climatic, building and technical parameters. Then, the experimental results are extended through the use of numerical simulations in order to test other configurations of the building. From the experimental results, was found that "*in spite of unfavourable meteorological conditions, night ventilation succeeded in decreasing the diurnal indoor air temperatures from 1.5 to 2°C, resulting in a significant comfort improvement for the occupants*". When dealing with the required building characteristics for an optimum cooling efficiency, the comparison between measured temperatures in three different size night-ventilated rooms have demonstrated that further research is necessary to characterize the building potential for night ventilation. They say "*even if the concept of equivalent thermal effusivity of the room has led to real progress in the definition of the coolness storage capacity of the fabric, we have shown it can not correctly represent the building cooling potential in that it does not take into account the coupling between walls and air volume of the rooms*". As both walls and furniture are similar in each of the three monitored rooms, observed temperatures differences show that cooling efficiency strongly depends on the volume of the room: "*the* *smaller it is, the greater is the volume to surface area ratio and the more efficient is the convective heat transfer"*. In the second part of the study, simulations were carried out to assess the coupling between night ventilation and mechanical cooling. Such couplings between passive and active techniques are called mixed mode cooling systems. They are used when night ventilation cannot guarantee a minimum comfort level, so mechanical cooling is the solution. However, in such cases, night ventilation can reduce the daytime cooling requirements of the buildings and the periods in which active cooling is needed. The main results from simulation shows that "*care must be taken when night ventilation is intended to be used in the frame of a mixed mode cooling strategy"*, especially when defining the air conditioning temperature set point as "*night-ventilation contribution becomes smaller as the required indoor temperature level increases"*. The results show that for a 22°C temperature set point, it only leads to a 12% decrease of the cooling energy, while it covers more than a half the cooling need for a 26°C temperature set point. Moreover, "*cooling the building during daytime amounts in a decrease in the temperature differences between indoor and outdoor and thus decreases night ventilation efficiency"*.

This issue is also demonstrated by Geros at al (1999), when investigating, by using both experimental and theoretical tools, the potential of night ventilation in three real scale different buildings. When a heavy thermal mass building under A/C operation was evaluated, the results have shown that " *the higher the set point temperature, the higher the energy conservation, as the difference between the operational temperature of the building and the night ambient temperature is higher and thus the cooling potential increases*". In addition, "*the set point temperature affects seriously the temperature reduction in the early morning hours. In particular, for set point temperatures equal to 25, 27 and 29°C the average early morning indoor temperature reduction is close to 0.8, 1.5 and 2.5°C, respectively"*. For the same building, under free-floating conditions, it was found that the use of night ventilation techniques decreases the next day peak indoor temperature by up to 3°C. It was also showed that the higher the airflow rate, the higher the reduction of the overheating hours. On the other hand, for the building described as of low to medium thermal capacity, under free-floating conditions, the impact of night ventilation is not important, as the decrease of the next day peak indoor temperature was close to 0.2°C. Finally, this evaluation also pointed out the problem of efficient coupling of the airflow with thermal mass of the building, which was presented in the third studied building. Convective exchanges between the fresh air and the building walls were very poor due to the short circuit airflow. Analyses showed that, only part of the flow has really contributed to decrease the temperature of the building's thermal mass.

In addition, when typically air-conditioned office buildings in UK were investigated by Kolokotroni and Aronis (1999), it was found that this kind of typically constructed building would modestly benefit from natural night ventilation. The results showed that mechanical night ventilation would result in increased energy consumption because of the power required for the fans during the night, although a reduced plan capacity would be an advantage. They concluded, *"if typical offices are modified to incorporate features assisting the application of night ventilation, then cooling energy could be saved when mechanical ventilation is used and further reduced in the case of natural ventilation"*. The features suggested by the work are: exposed thermal mass, airtight constructions and minimisation of internal and solar heat gains.

3.4. Discussion and conclusion:

Some results (Diaz, 1994) lead to the conclusions that, for summer condition, lightweight constructions are more advantageous for residential buildings, which are occupied at night. They say that occupants can benefit from the rapid response of the light building construction to the temperature variation of the outside. Hence, internal temperatures at night decrease, eventually reaching comfort level. However, the internal conditions during daytime are out of comfort levels in the most part of the day.

It was also illustrated by results from (Soebarto, 1999), which showed that more massive walls, such a double brick, can exhibit best performance during the day, although they would make internal temperatures higher late in the evening and early in the morning, due to the heat stored in the mass. This characteristic makes buildings occupied during night time, such as residential buildings, uncomfortable for the occupants if any other measure is taken to compensate.

However, when other aspects are considered, such as shading of glazed surfaces, night ventilation, small portion of wall exposed to the exterior and use of hard finishing materials, the heavyweight construction showed best thermal performance in both residential and office buildings. (Maldonado et al, 1997); (Diaz, 1994); (Szokolay, 1996; 2000).

The greater exposure of internal surfaces to internal air to guarantee heat dissipation is also an important factor to improve the thermal performance of thermal inertia. (Diaz, 1994).

Some results showed that radiant barrier in the roof can significantly improve the performance of heavyweight buildings. In addition, closing windows during peak time of solar radiation also improves the internal conditions of buildings with higher thermal inertia. (Soebarto, 1999); (Papst, 1999)

All works have confirmed that the performance of thermal inertia depends upon particular circumstances such as site conditions, building type, building materials, occupancy behaviour, etc.

It is useful to note that some of the reviewed works were developed for climates, which are warm-humid all year around. Climates such Mediterranean or Subtropical as in Southern Brazil are characterised by hot summers and mild winters and the designer should consider the balance between the conflicting solutions for summer and winter requirements.

These results encourage further investigation in how to improve thermal inertia in residential buildings for the climate of Southern Brazil, taking onto account the aspects pointed out above. Moreover, the focus of this thesis is the application of thermal inertia for summer condition only, since the employment of this strategy in warm-humid climates is still a challenge for designers.

As seen from the reviewed works in night ventilation effect, the cooling efficiency of this strategy is based mainly on the airflow rate, on the thermal capacity of the building and the efficient coupling between the airflow and thermal mass. It was also demonstrated that the daily amplitude of the external temperature defines the cooling potential of night ventilation, as well as the relative difference between indoor and outdoor temperature during the night period. Over again, the importance of the exposed thermal mass was pointed out.

In this thesis, night ventilation will be explored only in residential buildings. The potential of night ventilation when applied to a higher thermal inertia building will be investigated in the parametric studies in chapter 6. Also, the influence of night ventilation on the reduction of the indoor peak temperature will be assessed in section 7.3.

PART II

EMPIRICAL AND ANALYTICAL STUDIES

ASSESSING THERMAL INERTIA

Part II presents the results of the thermal inertia assessment.

Chapter 4 describes the field experiment, where four residences with different levels of thermal inertia were monitored during summer. The assessment is made through profiles of internal temperatures and humidity, statistical values such as mean, maximum and minimum of temperatures and temperatures swing, as well as frequency of temperatures above 29ºC.

The process of building modelling and calibration is covered in chapter 5.

Conclusions from fieldwork and literature review led to the parametric studies, presented in chapter 6. Aspects such as the level of thermal inertia of the walls, the influence of the roof/ceiling construction, the potential of night ventilation, window size and shading are evaluated. The aim of the parametric studies is to determine the extend to which these features should be used to improve the performance of a building with higher thermal inertia.

In chapter 7, further evaluations are performed through correlation analysis.

Chapter 4. Field Studies:

4.1. Introduction:

This chapter describes the fieldwork carried out in Florianópolis – Brazil, in summer season. Continue monitoring of temperature and humidity was carried out in 4 residences with different mass levels to observe the thermal response of their internal spaces according to the particular thermal mass characteristics of each case. Two of the houses have higher thermal inertia in its components and the other two are conventional constructions, with lower inertia in the envelope. The results of the measurements are showed and discussed.

The aims of field studies are:

a) To check the influence of some parameters previously defined in the literature review on the daytime temperature.

b) To draw the first conclusions about the performance of thermal inertia in Southern climate of Brazil.

c) To provide data for calibration of the software that will be used in the parametric analyses.

d) To obtain information throughout measurements results, regarding thermal performance of the houses with higher thermal inertia compared with the lower thermal inertia buildings.

4.2. The Climate of Florianópolis:

The context of this work is the city of Florianópolis, which is located in Southern Brazil, in the coast of Atlantic Ocean at Latitude of 27º 40’ South.

Figure 4.1: Florianópolis location (Source: IBGE).

The climate in Southern Brazil is characterized by mild winters and hot-humid summers. The following description of the climate of Florianópolis was taken from Goulart (1998), which was based on 10 years of hourly meteorological data recorded in airports of main Brazilian cities:

The annual mean temperature is 20.5ºC. The hottest month is February, presenting a mean temperature of 24.5ºC and the coldest is July with a mean temperature of 16.6ºC. The annual mean daily range of temperature is 7.8ºC. In February, the mean maximum temperature is about 29ºC and the mean minimum is 21.1ºC, producing a daily range of temperature of about 7.9ºC. In July, the daily swing of temperature is about 8.1ºC, ranging from a minimum mean of 13ºC to a maximum mean temperature of 21.1ºC (see figure 4.2).

The daily minimum temperatures occur at 6:00 h during summer period and 7:00 h during wintertime, while the daily maximum temperatures usually occur at 13:00 h in summer months and about 14:00 h in winter.

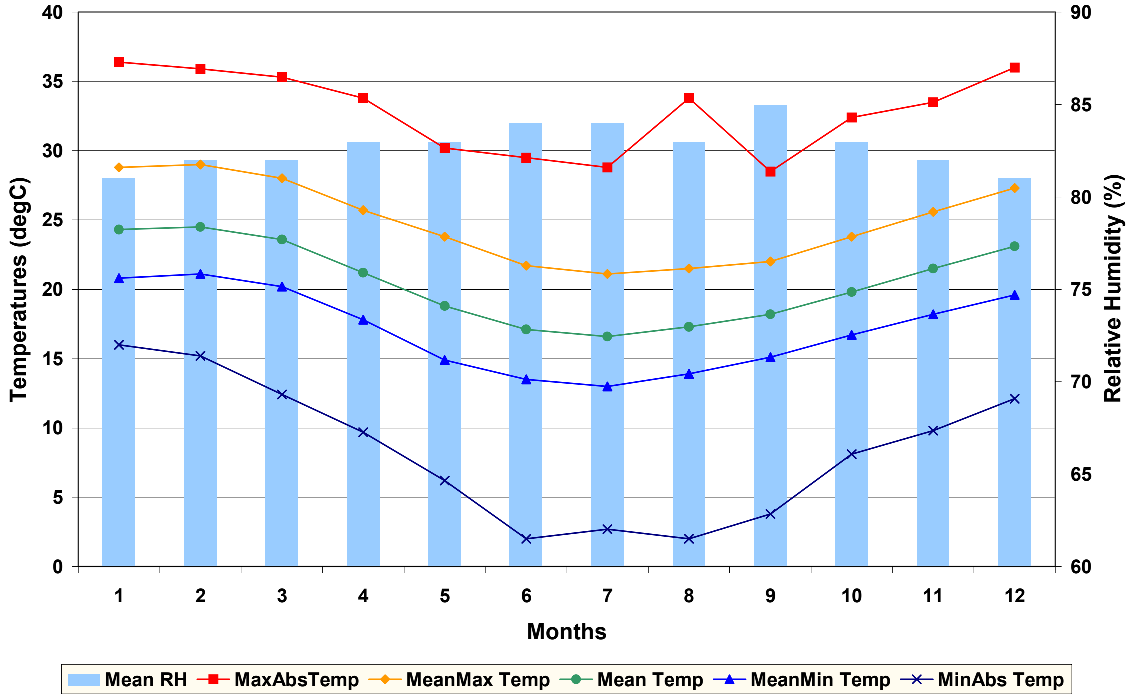


Figure 4.2: Temperatures and mean relative humidity for Florianópolis city. Source: Goulart (1998).

The annual mean relative humidity is 83% and the monthly mean values do not vary much from the annual mean. The average of moisture content is 3.6 g/kg, varying from 3.0 in July to 4.3 in January. The annual average of Wind velocity is 3.5 m/s and the prevailing wind direction is North all year around.

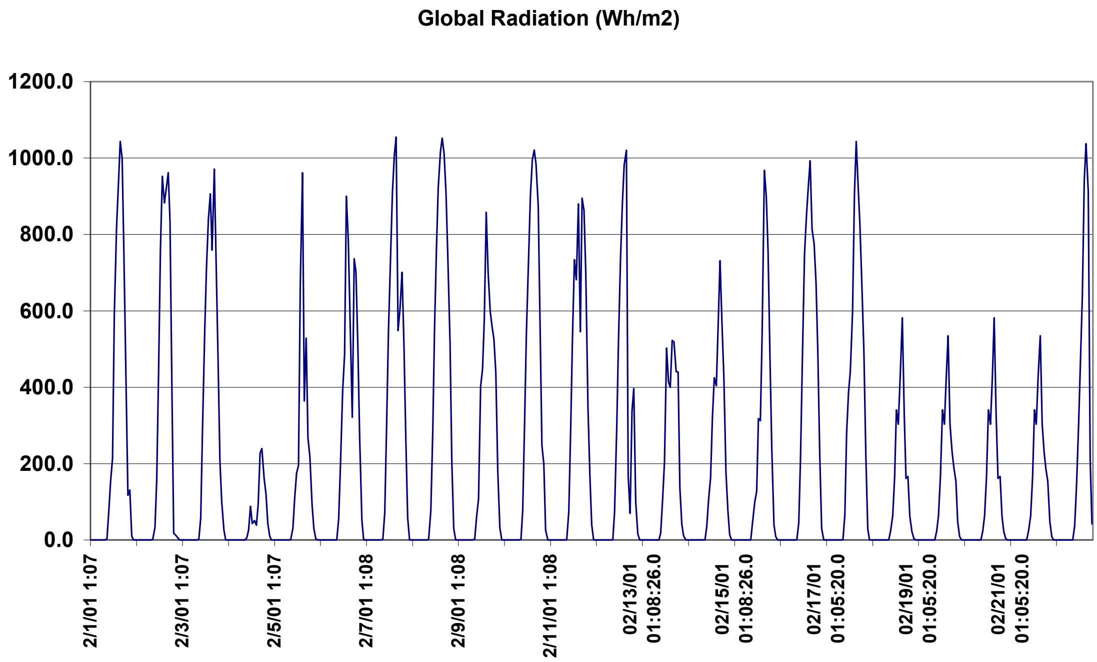


Figure 4.3: Daily Global Irradiation for February (1/2 to 22/02) – Source: Labsolar (Solar Energy Laboratory of Federal University of Santa Catarina).

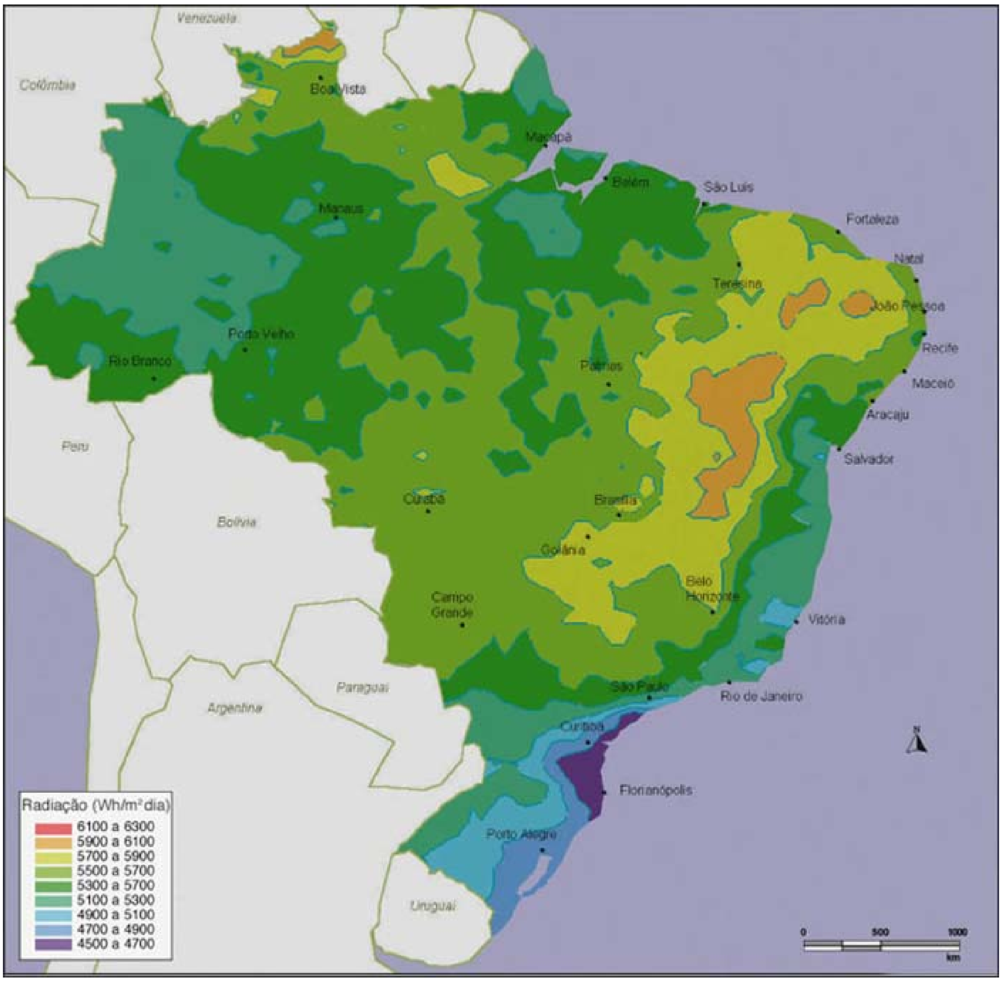


Figure 4.4 – Solar Radiation in Brazil – typical annual average (Wh/m^2.day).

The figure 4.3 shows the distribution of daily global solar irradiation for the period from 1/2/2001 to 22/02/2001.

The figure 4.4 shows the annual average value of solar radiation in Brazil, in Watt-hour per square meter per day (Wh/m^2.day), according to the Atlas of Solar Irradiation in Brazil (Source: INMET - Instituto Nacional de Meteorologia and Labsolar/UFSC).

In Florianópolis, the average period of insolation in summer is 190 hours, while in winter is 162 hours (according to INMET — Brazil).

4.3. General Description of the Field Experiment:

The fieldwork consisted of continuous recording of air temperature and relative humidity and the measurements were carried out in four houses located in Florianópolis, during one month approximately (from January 26th to March 6th – this is the summer season in Brazil).

Measurements of external/internal temperatures and external/internal relative humidity were performed with dataloggers Tiny Data Loggers (Gemini Data Loggers) and some dataloggers HOBO Temp Data Loggers (Onset Computer Corporation). The first are properties of Architectural Association School and the latter were lent by the laboratories: LabEEE e LabCon of UFSC (Federal University of Santa Catarina).

To establish accuracy of the group of loggers, firstly, the instruments were activated with 1 min of interval and placed in a sealed recipient, thermally insulated for some hours.

Data Loggers HOBO® have operating temperature from -40°C to +120°C and storage temperature from -40°C to +75°C. The temperature accuracy is 0.7 K and resolution is 0.4 K. Tiny Data Loggers have operating temperature from –40°C to +125°C and resolution of 0.2 K. The relative humidity sensors operate in a range from 0 to 95%, non-condensing situation.

The figure 4.5 shows the results of calibration of the instruments. The distribution of temperatures resulted homogeneous and the differences were found according to the accepted accuracy described by manufacturers. Higher differences were found between the loggers 19, 25 and 1568 and the others. These three instruments were placed in the same house.

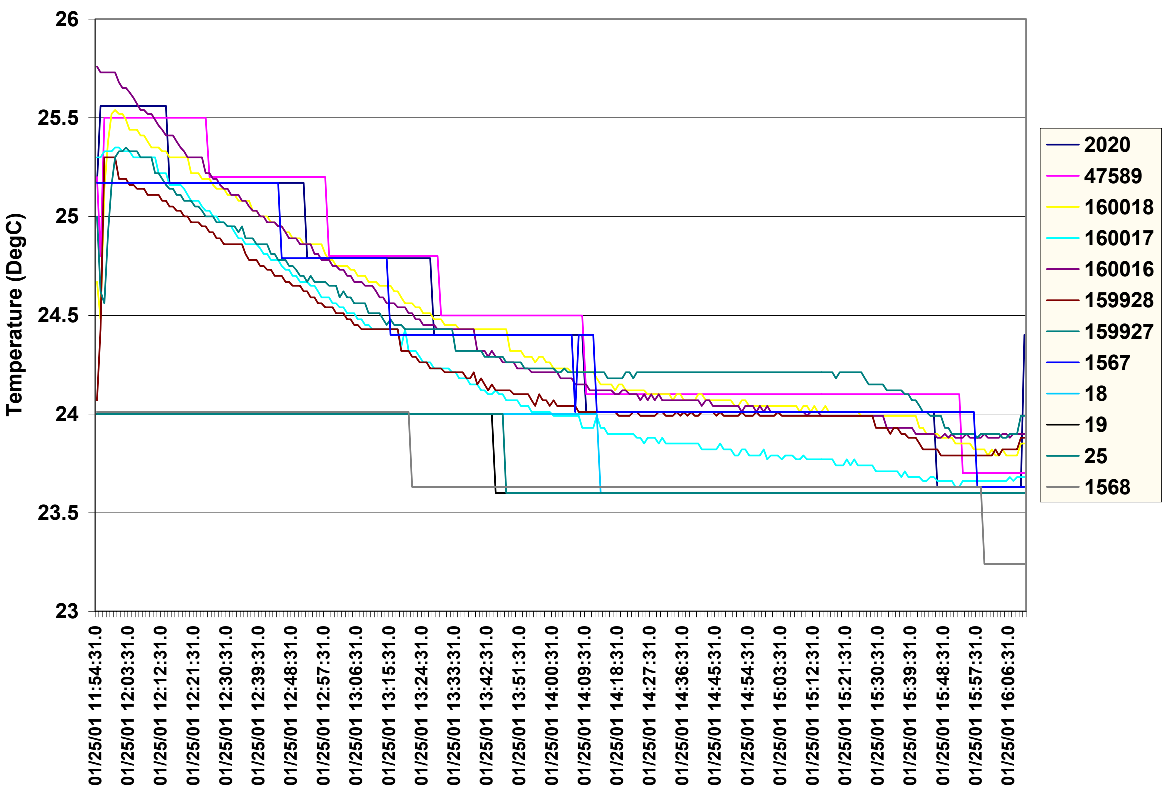


Figure 4.5: Results of the calibration of the instruments.

The instruments were, then, installed in the houses in two or three different internal ambient. External sensors were also placed to compared with the internal conditions.

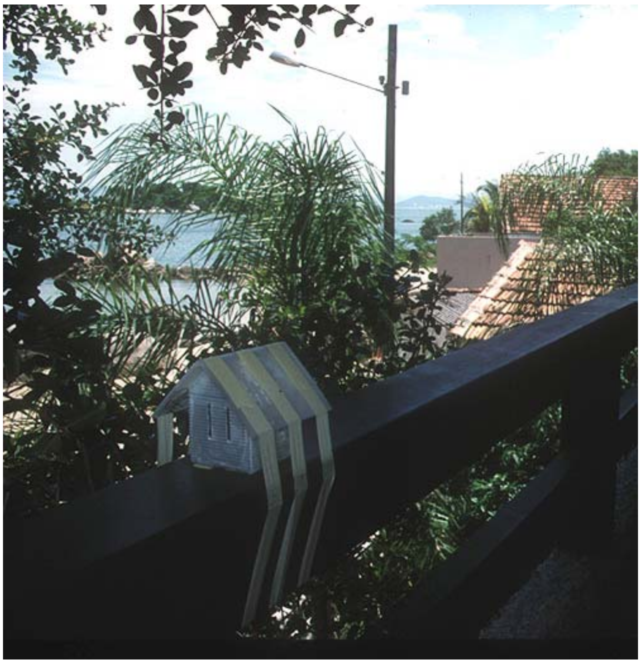


Figure 4.6 – Box used to protect the external instrument.

To collect external temperatures for comparison with room temperatures, the loggers were placed in a plastic box, internally covered with aluminum foil for weather and solar radiation protection. The box has lateral openings allowing air circulation (see fig.4.6).

From the date of the installation of the instruments, the recorded data were offloaded each 10 or 12 days with the aim of checking the measurement process. During these visits, construction characteristics of the houses were also collected as well as occupancy behaviour.

4.4. Case studies:

The case-studies residences are typical middle income family houses. Two of them have higher thermal inertia walls (granite block), a third is made of conventional construction (brick walls) with medium thermal inertia and the fourth house has wooden walls, characterising low thermal inertia construction. All of them are two-storey single family houses. The description of the case-studies are following:

House 1: This house is located some 15 m from the sea in a low density area. The microclimate is influenced by the presence of the sea and vegetation. Due to its location, this private residence receives strong South wind directly. This house has external and internal walls made of granite block without finishing. The roof is of clay tiles with a rough plastered concrete slab ceiling and the floor is of slate.

Three rooms were monitored: a living room in the ground floor; a TV room (with a west-facing wall) and a study-room (with an east-facing wall) both located in the upper floor.

This house does not have constant use. The occupancy is more frequent during summer period and some weekends along the year. In these periods, a couple with a young child lives in the house and there is a housekeeper during daytime.

All monitored rooms have horizontal sliding window with single glazing and wooden frame. When the house is occupied, doors and windows use to be open all day. In the upper floor, the openings use to be closed around 3-4 p.m. to avoid insects. However, in the ground floor, they use to be closed only in the evening.

Figure 4.7 – House 1 – main facade and indoor view.

House 2: This house is located nearby the house number 1, but it is located in a more dense area, some 500 m from the sea. The residence is built of conventional construction, plastered single brick walls, which is widely used in Brazil. The roof is of clay tiles with timber ceiling. The ground floor has tile flooring and the upper floor has timber floor. The living room, dining room and kitchen are connected as a large one ambient. The stairs to the upper floor works as an integrating element, allowing free air circulation between the two floors. The main facade has Southwest orientation.

Two rooms were monitored: the living/dining room in the ground floor and a bedroom in the upper floor.

The windows are of single glazing with iron frame and all openings have external shutter. When the house is occupied, the windows use to be open during daytime and closed in the evening. The shutters provide a little ventilation during the night-time.

A couple live in the house all year.

Figure 4.8 – House 2 - main facade and indoor view.

House 3: The third house is located in an urban and high density area. The house has stone external walls and plastered single brick internal walls. The roof is of asbestos on a concrete slab ceiling. The main facade has Southwest orientation.

Three rooms were monitored: a study-room in the ground floor and two different rooms in the upper floor.

Measurements in the upper floor were carried out in two phases: in the first two weeks, a bedroom was monitored (facing Northwest); in the final weeks, a dining room was monitored (the facade, which contains the window, is Southwest). The study-room and the bedroom have carpet finishing in the floor and the dining room has tile flooring.

The openings are single glazing with aluminium frame. The windows have screen protection against insects in 50% of the opening area, as they are horizontal sliding window types. Because of the screen, the windows are kept open and the rooms are naturally ventilated all time in summer season.

The occupancy is constant all year and four adults use to live in the house. When the measurements were taken, only two people were occupying the house and they used to be out during the working hours.

Figure 4.9 – House 3 - main facade and indoor view.

House 4: The last case study is also located in a high density area in the same region of the house 3. It has double wooden walls and clay tile roofing with timber ceiling. The ground floor has tile flooring and the upper floor has timber flooring. The main facade is Northeast.

Two rooms were monitored: the living room in the ground floor and the master bedroom in the upper floor.

The occupancy is constant all year and a couple and two young children plus a housekeeper inhabit the house.

The windows are single glazing with wooden frame and they use to be open during daytime and closed in the evening. There is a ceiling fan in the bedroom, which uses to be turned on during the night.

This case study was obtained later and the measurements were carried out from February 14th.

Figure 4.10 – House 4 - main facade and indoor view.

In order to characterise the degree of thermal inertia of the four houses studied in the field experiment, the methods of Admittance, Heat Capacity and the Mean Thermal Effusivity were applied to the monitored rooms. The values will allow relative comparisons among the buildings, picturing the degree of thermal inertia according to these concepts.

Table 4.1.Characterisation of Thermal Inertia of the monitored rooms - House 1.

HOUSE 1	**Heat Capacity** (kJ/m^2K)		**Admittance of the Room** ΣYA (W/°C)	**Thermal Effusivity** (bm) $Ws^{0.5}/m^2K$
Study-room	Walls	454	239.3	2168
	Ceiling	113		
	Floor	118		
TV Room	Walls	454	233	1823
	Ceiling	113		
	Floor	103		
Living Room	Walls	454	586.8	2046
	Ceiling	125		
	Floor	223		

Table 4.2.Characterisation of Thermal Inertia of the monitored rooms - House 2.

HOUSE 2	**Heat Capacity** (kJ/m^2K)		**Admittance of the Room** ΣYA (W/°C)	**Thermal Effusivity** (bm) $Ws^{0.5}/m^2K$
Bedroom	Walls	168	290	1003
	Ceiling	32		
	Floor	338		
Living Room	Walls	168	288.9	1423
	Ceiling	360		
	Floor	209		

Table 4.3.Characterisation of Thermal Inertia of the monitored rooms - House 3.

HOUSE 3	**Heat Capacity** (kJ/m^2K)		**Admittance of the Room** ΣYA (W/°C)	**Thermal Effusivity** (bm) $Ws^{0.5}/m^2K$
Dining Room	Ext. walls	378	319.7	1617
	Int. Walls	168		
	Ceiling	106		
	Floor	104		
Bedroom	Ext. walls	378	227.8	1405
	Int. Walls	168		
	Ceiling	106		
	Floor	96		
Study-room	Ext. walls	378	233.5	1485
	Int. Walls	168		
	Ceiling	95		
	Floor	201		

Table 4.4.Characterisation of Thermal Inertia of the monitored rooms - House 4.

HOUSE 4	Heat Capacity (kJ/m^2K)		Admittance of the Room ΣYA (W/°C)	Thermal Effusivity (bm) $Ws^{0.5}/m^2K$
Bedroom	Ext.Walls	23	158.6	330
	Int. Walls	15.6		
	Ceiling	32		
	Floor	12		
Living Room	Ext. walls	23	122	451
	Int. Walls	15.6		
	Ceiling	12		
	Floor	209		

The concept of Heat Capacity was used to characterise the building components and in a multi-layer element, the total heat capacity was calculated by the sum of the separate heat capacity of each layer. The proceeding of calculation is the same adopted by the Brazilian Standard (ABNT, 1998).

As seen in the literature review, the higher the density of a material, the higher the resulting heat capacity. It is well represented by the walls of House 1 and external walls of House 3.

Admittance of the room was calculated by the sum of the products of all room surface areas (A) and their respective admittance values (Y) taken from CIBSE Guide section A3. As described in the section 1.2, the internal surfaces of exposed heavy materials, such as concrete, brick or stone have a large capacity for storing part of the cyclic energy gain. This characteristic gives them a high admittance and consequently, the temperature swing in such rooms is small. According to the admittance concept, the living room of House 1 has a higher capacity for storing heat due to characteristics such as density of the wall's building material and its surfaces dimensions. In the other hand, both rooms of the House 4 have the smallest admittance because of its wooden walls.

The mean thermal effusivity b_m was calculated as the area weighted average of the b-values of all exposed surface materials of every studied room (see section 1.4, equation 10). In general, according to Liman and Allard Ed.(1995)it can be defined that a light construction has a b_m value about 300 and a heavy construction b_m is about 1500. The rooms of House 1 have the highest mean thermal effusivity values (b_m about 2000), representing a heavyweight building, while the rooms of House 4 have b_m values of about 400, representing a lightweight construction.

According to the methods, it can be concluded that House 1 represents a high thermal inertia building, while House 2 represents a medium thermal inertia building and House 4 characterise a low thermal inertia construction. Despite of the heavy external walls, only the dining room of House 3 has characteristics of a high thermal inertia construction, whilst the remaining rooms can be considered as medium thermal inertia.

It is worth saying that the effect of furnishing was disregarded in all calculations. As furniture can alter the convection exchange between the wall surface and the air, ignoring this parameter can affect all results the same or some of the houses more than others.

4.5. Results of the Monitoring:

The measurements were carried out from January26th to March 6th. However the graphs showed in this section represent a smaller period (from 14/02 to 28/02). The main reason for that is to allow comparisons among the four houses, since the fourth case study was only obtained by February 14th. All results of monitoring can be seen in the appendix A1.

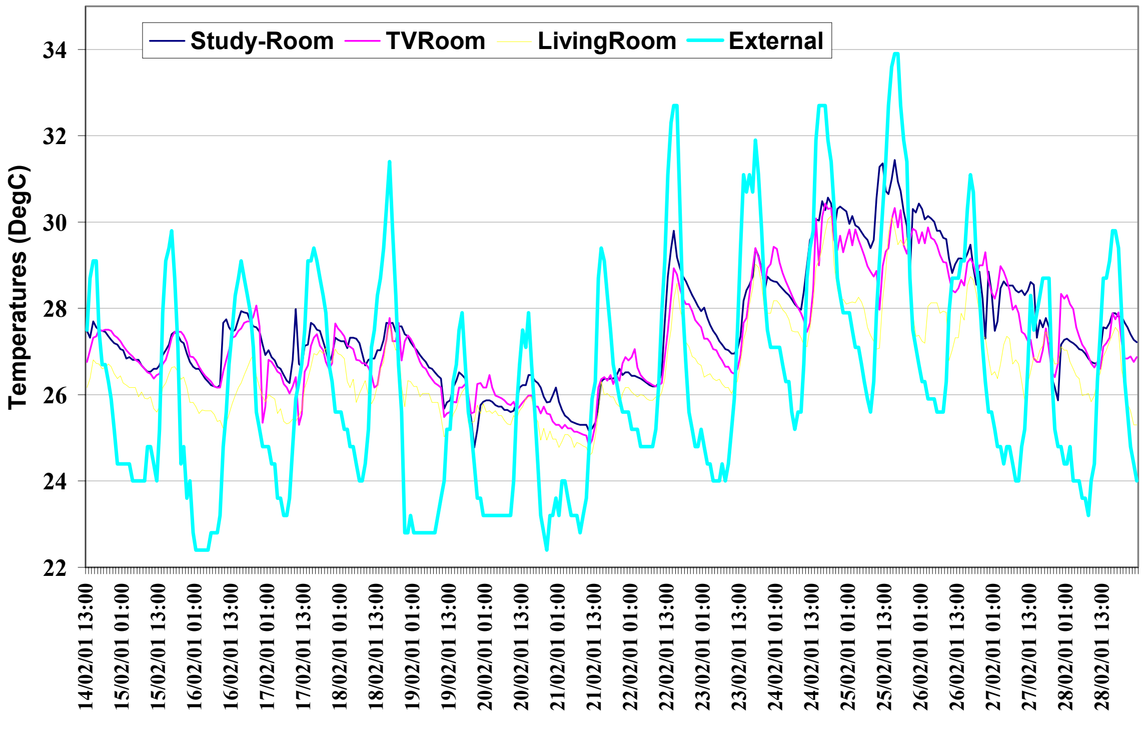


Figure 4.11 – House 1 – Temperatures (ºC) - from 14/02 to 28/02.

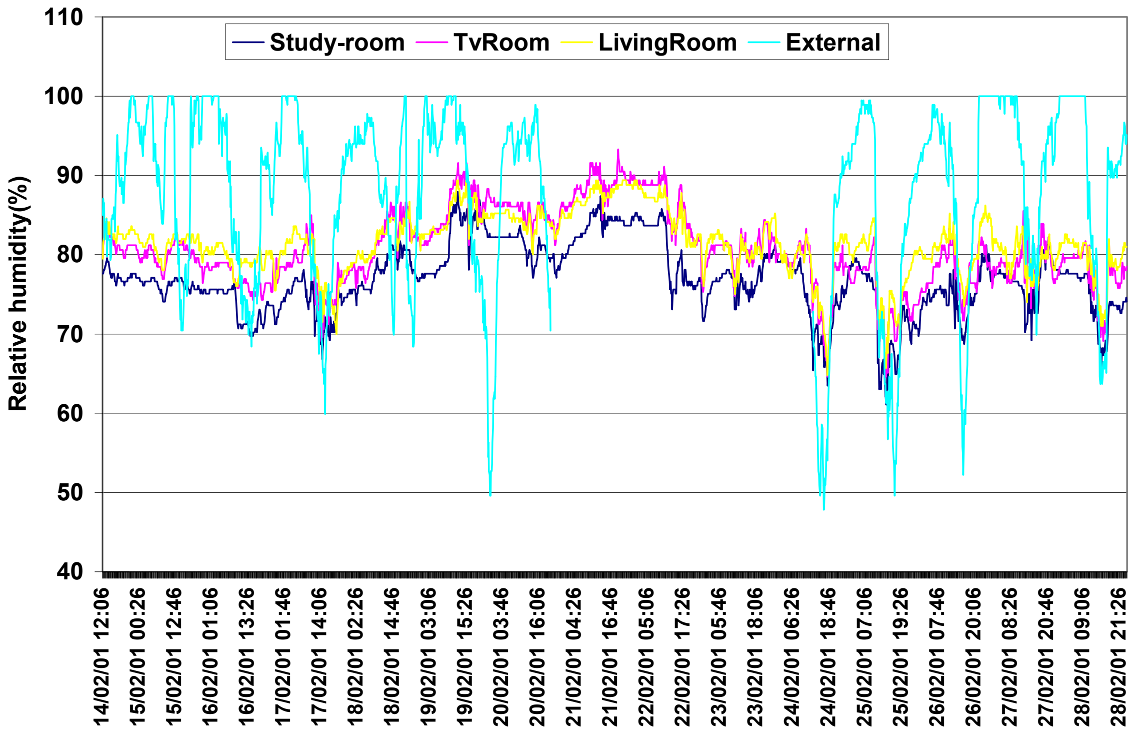


Figure 4.12 – House 1 – Relative Humidity (%) – from 14/02 to 28/02.

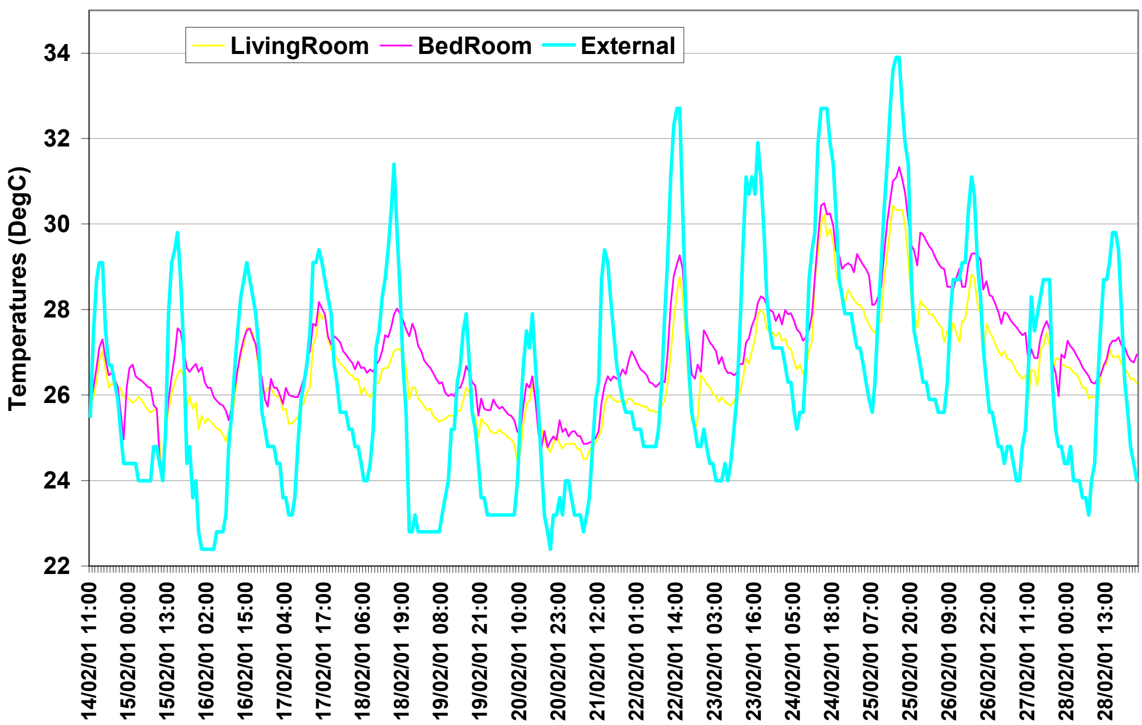


Figure 4.13 – House 2 – Temperatures (ºC) - from 14/02 to 28/02.

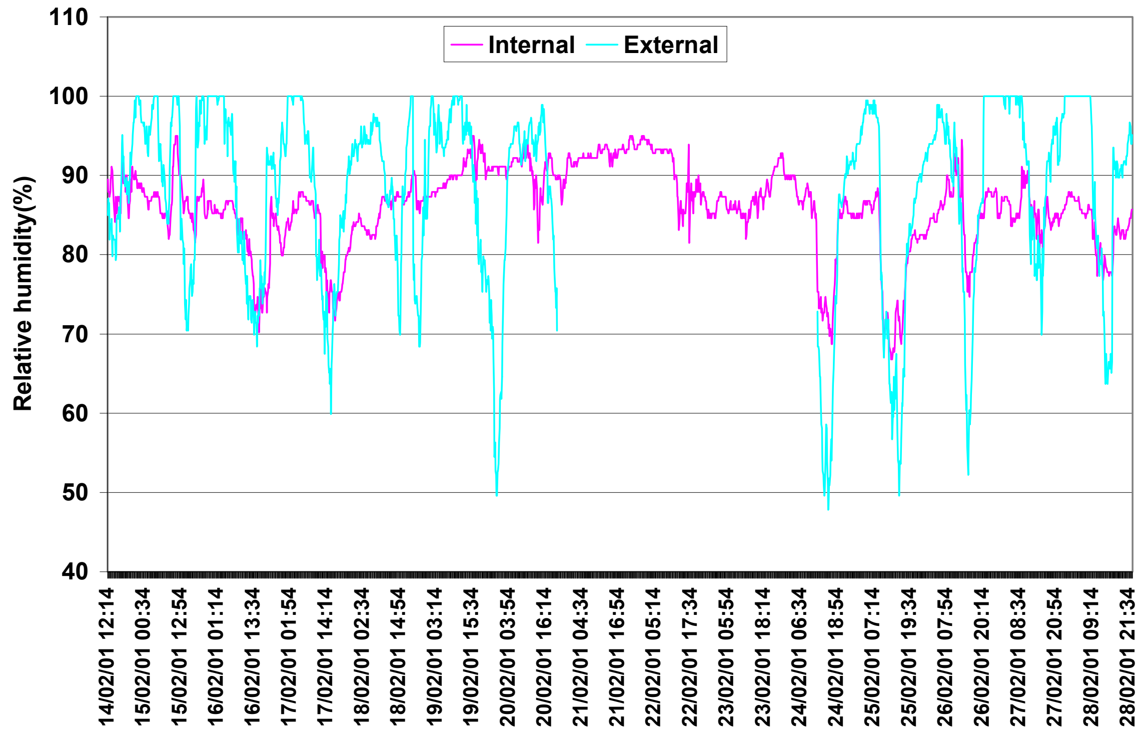


Figure 4.14 – House 2 – Relative Humidity (%) – from 14/02 to 28/02.

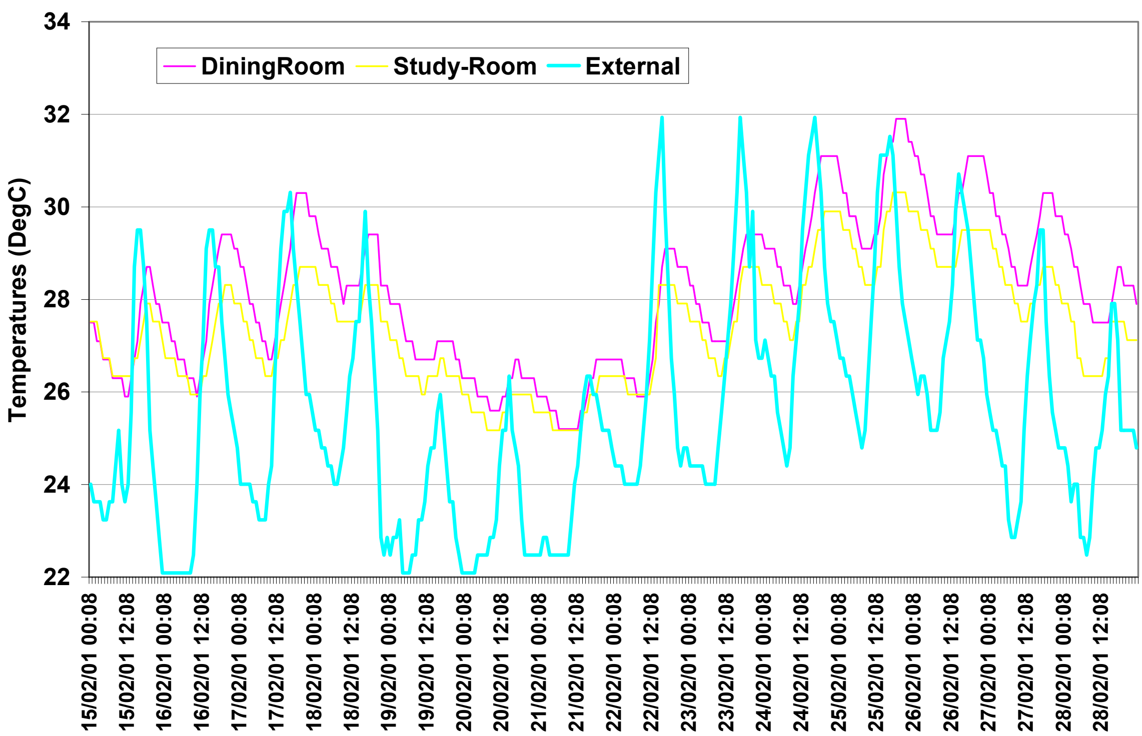


Figure 4.15 – House 3 – Temperatures (ºC) – from 15/02 to 28/02.

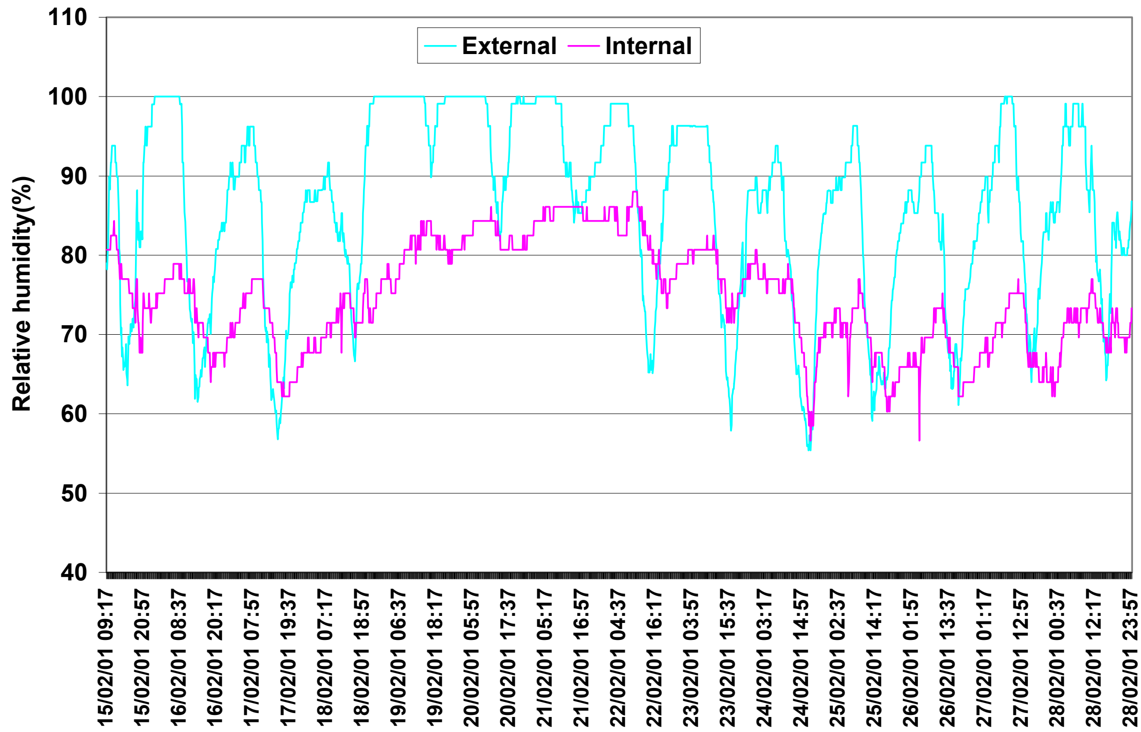


Figure 4.16 – House 3 – Relative Humidity (%) – from 15/02 to 28/02.

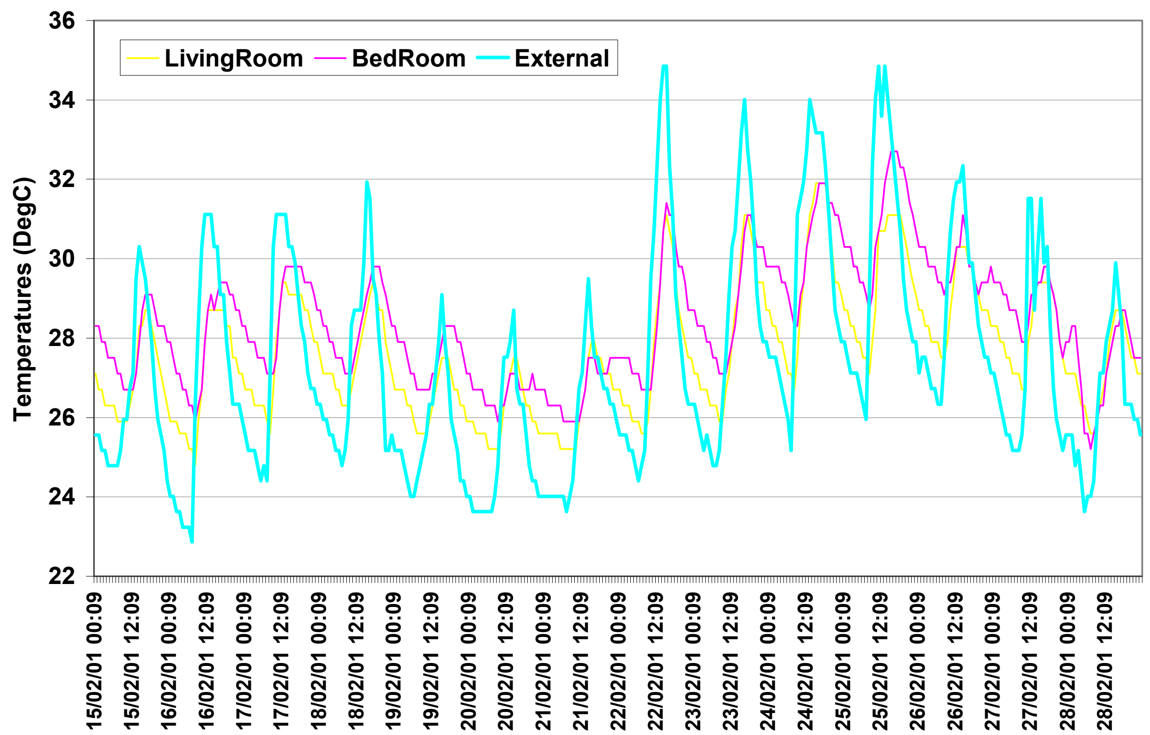


Figure 4.17 – House 4 – Temperatures (ºC) – from 15/02 to 28/02.

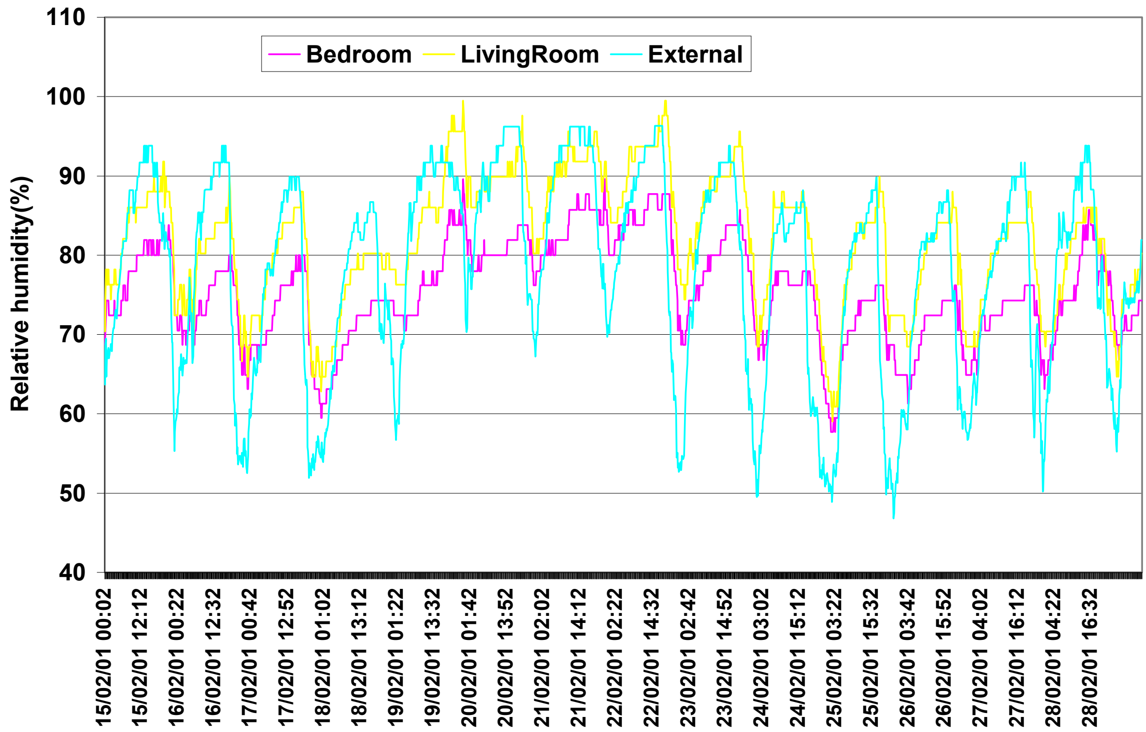


Figure 4.18 – House 4– Relative Humidity (%) – from 15/02 to 28/02.

By observing the graphs the following conclusions can be drawn:

- The houses with higher thermal inertia in their components showed a smaller swing of indoor temperature compared to the external variation. On the other hand, the indoor temperature of House 4 (wooden wall) follows the outdoor pattern closely, reaching almost the same maximum and minimum values due to the low thermal inertia of its entire envelope.
- A delay in the internal peak temperature occurrence compared to the external peak temperature occurrence is more evident in the houses of higher thermal inertia (1 and 3).
- In the house 2, of conventional brickwork, the daily range of internal temperature is also lower than the external variation but the internal peak temperature occurs almost at the same time than the external peak.
- The higher thermal capacity of houses 1 and 3 decreases the variation of internal temperatures but when the external temperatures go down, the interior remains warm due to the heat stored in the mass.

- The houses of higher thermal inertia did not show the best internal condition all the time. The custom of keeping doors and windows open during daytime damages the inertia effect as the internal temperature increases due to warm air that comes in.
- In all residences, the rooms located in the ground floor showed internal temperatures lower than rooms located in the upper floor. Although all monitored houses do not present roof insulation, this difference is more evident in houses 2 and 4, because both have wooden ceiling (below the roof) instead of concrete slab. There are two possible explanations for this: The first one can be the influence of the heat coming from the roof due to solar radiation, which is very intense in this time of the year. The other explanation can count on the stratification phenomenon.
- During the night, external temperatures fall to near 22º C, showing that there is a potential for night ventilation technique.
- Despite of the instrument that was used to measure external relative humidity in houses 1 and 2 has presented some problems, the results are showed here for comparisons purpose. By the graphs, it can be observed that the indoor relative humidity varies from approximately 60% to 90% in all cases.

4.6. Analysis:

From the measurements results, the following analysis were carried out:

4.6.1. Statistical Analysis:

Two weeks of measurements were chosen to make a simplified statistical analysis: from 14/02 to 28/02. The aim of this evaluation is to compare maximum, mean and minimum values of external and internal temperatures and relative humidity, mean daily range of temperature, as well as to find out the frequency of temperatures above 29°C. The tables below show the results.

Table 4.5. Statistical Values for House 1

House 1	Air Temperature (ºC)						Rel. Humidity (%)		
	Max_{abs}	Mean	Min_{abs}	Daily Swing (mean)	Freq>29°C	$Swing_{Out}$ / $Swing_{In}$	Max_{abs}	Mean	Min_{abs}
Study-room	31.4	27.5	24.8	2.0	15.8 %	3.3	87.9	75.7	61.1
TV Room	30.4	27.3	24.8	2.0	13.0 %	3.3	91.6	79	64.6
Living Room	30.1	26.6	24.6	1.9	3.6 %	3.5	89.4	80.2	64.8
External	33.9	26.2	22.4	6.6	16.4 %	-	100	87.7	47.8

Table 4.6. Statistical Values for House 2

House 2	Air Temperature (ºC)						Rel. Humidity (%)		
	Max_{abs}	Mean	Min_{abs}	Daily Swing (mean)	Freq>29°C	$Swing_{Out}$ / $Swing_{In}$	Max_{abs}	Mean	Min_{abs}
Bedroom	31.3	27.1	24.1	2.2	11.1 %	3	-	-	-
Living Room	30.4	26.5	24.0	2.2	3.9 %	3	95	84.6	66.8
External	33.9	26.3	22.4	6.6	16.4 %	-	100	87.7	47.8

Table 4.7. Statistical Values for House 3

House 3	Air Temperature (ºC)						Rel. Humidity (%)		
	Max_{abs}	Mean	Min_{abs}	Daily Swing (mean)	Freq>29°C	$Swing_{Out}$ / $Swing_{In}$	Max_{abs}	Mean	Min_{abs}
Dining Room	31.9	28.2	25.2	2.4	35.4 %	2.6	88	74.7	56.6
Study-room	30.3	27.4	25.2	1.8	13.1 %	3.5	-	-	-
External	31.9	25.6	22.1	6.3	13.1 %	-	100	86.3	55.4

Table 4.8. Statistical Values for House 4

House 4	Air Temperature (ºC)						Rel. Humidity (%)		
	Max_{abs}	Mean	Min_{abs}	Daily Swing (mean)	Freq>29°C	$Swing_{Out}$ / $Swing_{In}$	Max_{abs}	Mean	Min_{abs}
Bedroom	32.7	28.4	25.2	2.8	38.1 %	2.5	89.6	75.4	57.7
Living Room	31.9	27.6	24.8	3.5	19.9 %	2	99.5	81.8	59
External	34.8	27.4	22.9	7.1	26.5 %	-	96.3	78	46.8

By observing the results above, we can conclude:

- For all cases, the mean and maximum values of indoor temperatures of rooms located in the ground floor are lower than the same values for the rooms located in the upper floor. These results confirm the previous observations from the graphs.

- The mean indoor temperatures of the rooms located in ground floor are close to the values of mean external temperatures. However, in the upper floor, mean temperatures of the rooms are from 0.8ºC to 1.3ºC above the mean external values. The exception occurs in the House 3 where the mean indoor temperatures are 1.8ºC (ground floor) and 2.6ºC (upper floor) higher than the mean outdoor temperature.

- All rooms in House 1 and the study-room in House 3 showed the lowest values of mean temperature swing. However, in general, the mean values of indoor temperature swings did not present much difference between the houses with higher thermal inertia and House 2 (medium thermal inertia). It can be explained by the fact that all occupants have the custom of keeping the windows open during daytime. Moreover, House 4 showed higher temperature swing due to the low mass in the envelope.

- The reduction in the indoor maximum temperature below the outdoors' maximum ($Tmax_{Out} – Tmax_{In}$), in the hottest day, was higher in the rooms located in the ground floor. The living room in House 1 showed a reduction of 3.8°C below the outdoors' maximum while that in House 2 was 3.5°C. The rooms located in upper floor achieved a reduction of 3.5°C (TV room) and 2.5°C (study-room) in House 1 and 2.6°C (bedroom) in House 2. The wooden house (number 4) showed temperature reductions about 2.9 °C and 2.1°C below the external maximum (ground floor and upper floor, respectively). The dinning room in House 3 showed no peak temperature reduction below the outdoor maximum while the study-room, located in the ground floor, presented a reduction of 1.6°C below the outdoors' peak.

- To measure the performance of the indoor thermal behaviour, the percentage of temperatures above the comfort limit[1], taken as 29ºC, was used. From these results the best performance was in houses 1 and 2, followed by the study-room in house 3. The dining room in house 3, despite of the higher thermal inertia in the external walls, has the same level of performance of the house with wooden walls.

- A major effect of the thermal mass is to reduce the internal temperature swing. To identify this effect on each building, the ratio of the internal and the external temperature swings ($Swing_{Out}/Swing_{In}$) was calculated. A ratio value of 1 would indicate that the effect of the building mass on the temperature swing is zero. From the results, House 1 showed a higher reduction on indoor temperature swing, which indicates a major effect of the thermal mass. The dining room in House 3 and both

[1] The comfort limit of 29°C is discussed in the section 6.2.

rooms in House 4 showed smaller ratio values, which denotes a small effect of the thermal mass of the envelope.

To conclude the statistical analysis, the frequency of temperatures was calculated and the distribution of temperatures can be visualised in the following graphs.

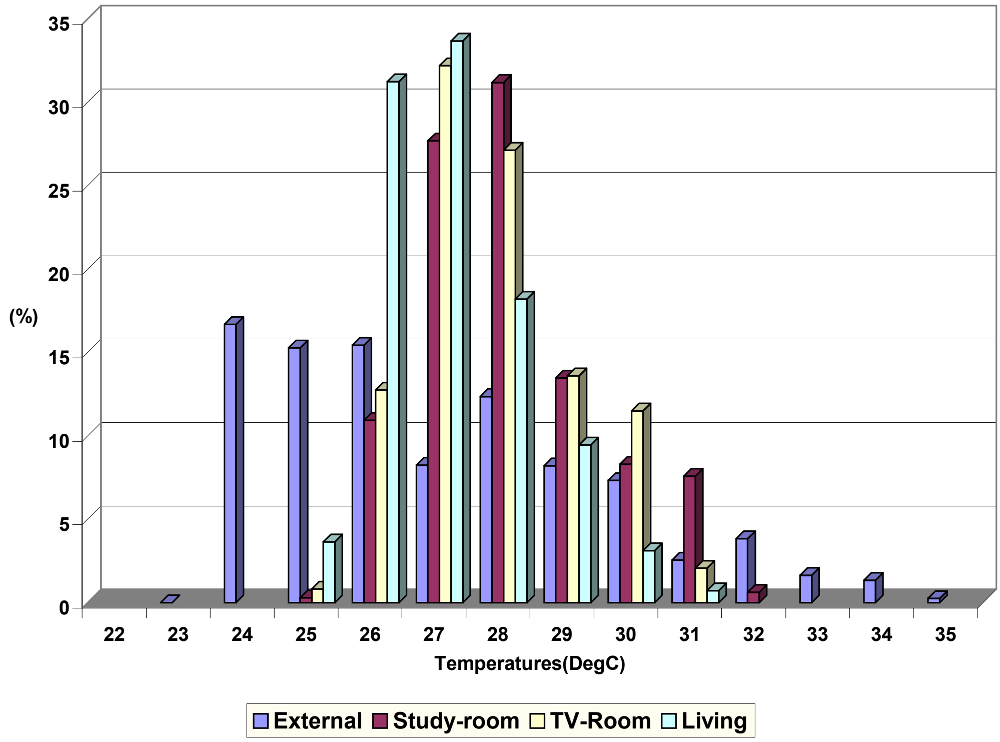


Figure 4.19: Frequency of temperatures – House 1 – period: 14/02 to 28/02.

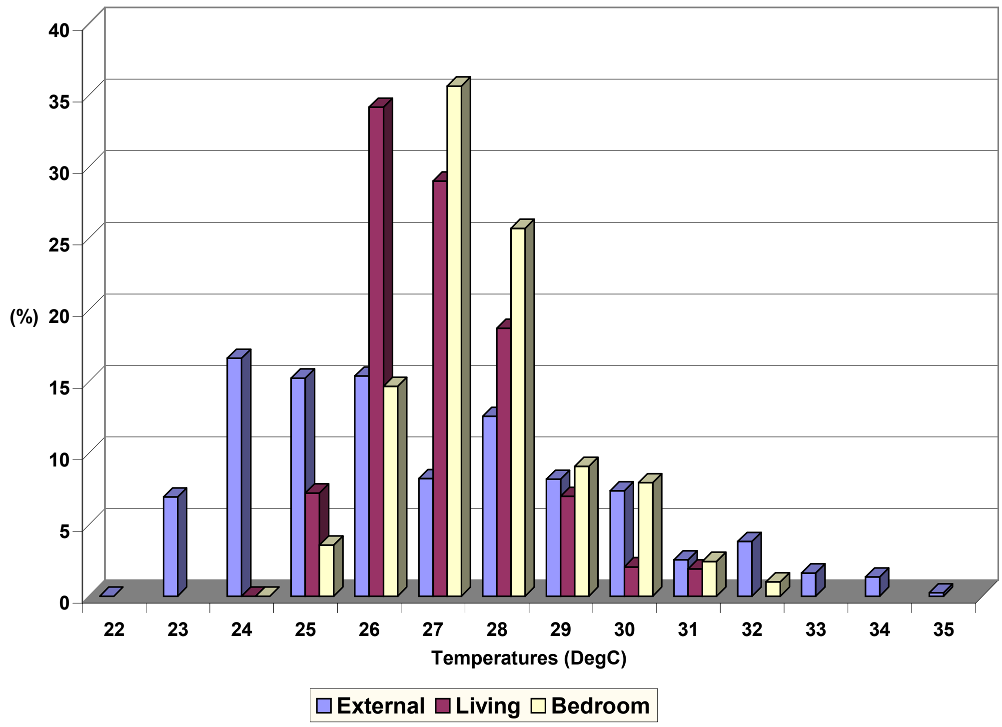


Figure 4.20: Frequency of temperatures – House 2 – period: 14/02 to 28/02.

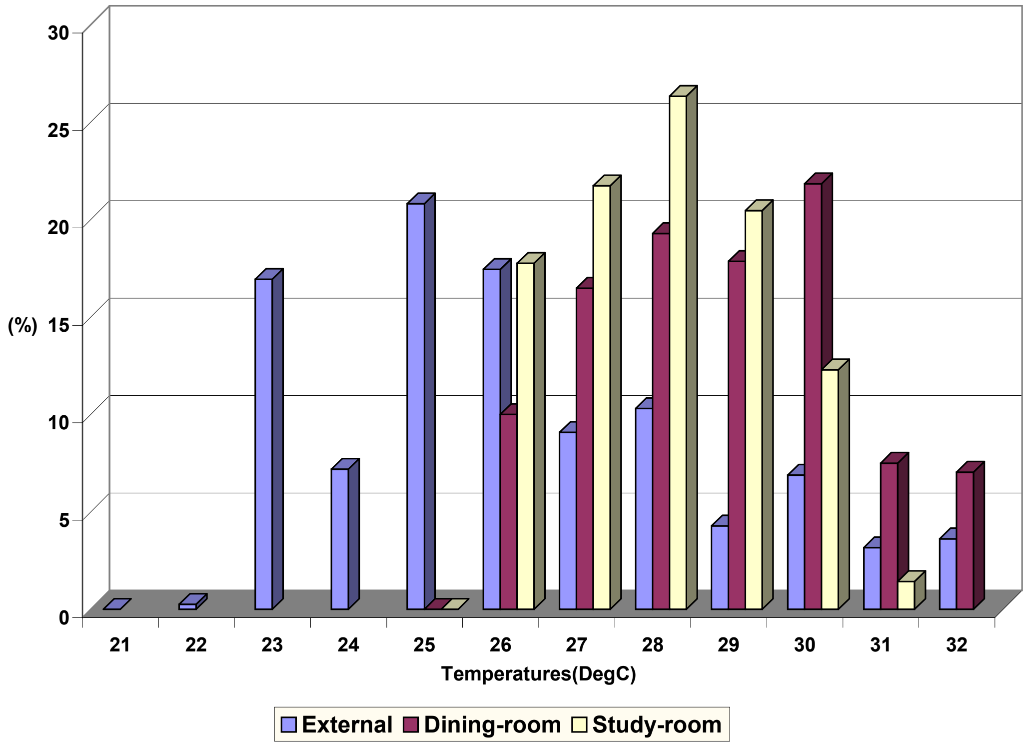


Figure 4.21: Frequency of temperatures – House 3 – period: 15/02 to 28/02.

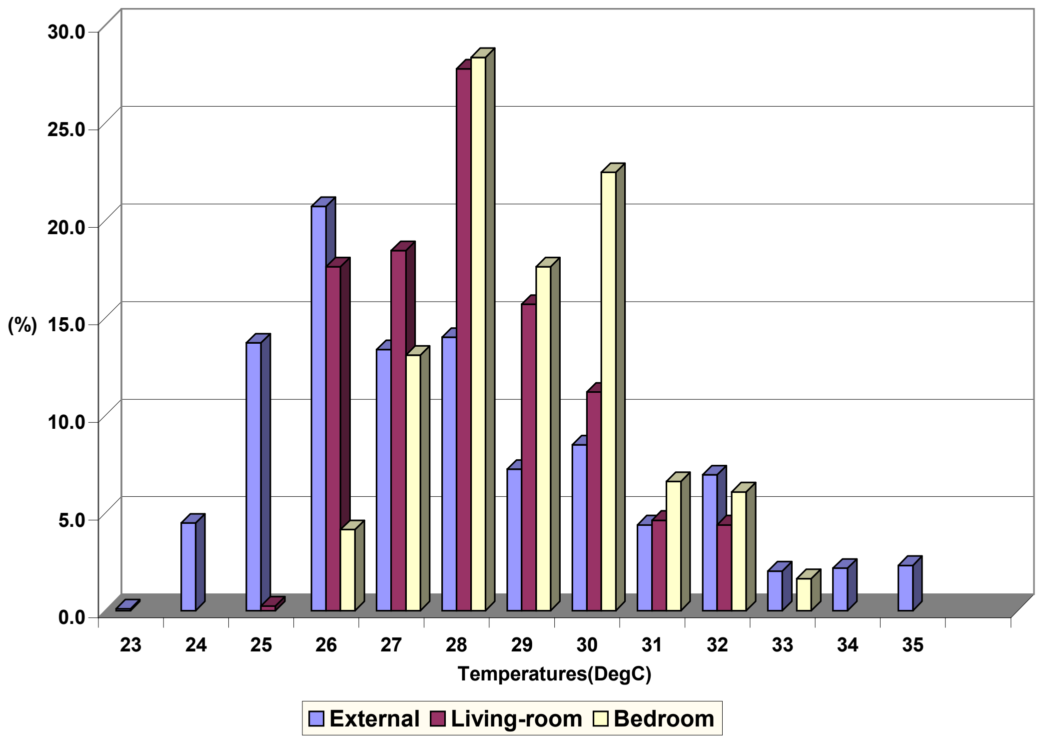


Figure 4.22: Frequency of temperatures - House 4 – period: 14/02 to 28/02.

In House 1 (figure 4.19), for the room located in the ground floor, higher frequencies of temperatures of 26°C and 27°C were obtained, while the rooms located in the upper floor showed higher frequencies of temperatures of 27°C and 28°C. The same happens in House 2 (figure 4.20).

In House 3 (figure 4.21), both rooms showed higher frequencies of temperatures in the range of 27°C and 29°C. In the study room the most frequent temperature is 28°C, while in the dining room, the highest frequency is for 30°C.

In House 4 (figure 4.22), both rooms showed the highest frequency of temperature of 28°C, although the room located in the upper floor also showed high frequency of 30°C.

4.6.2. Solar Access Analysis:

From the observations above, it was decided to evaluate the solar access of the rooms with worst thermal performance in the houses of higher thermal inertia. The study-room's opening in House 1 and the dining room's opening in House 3 were evaluated regard the possible solar access in the rooms in summer time. Shadow masks for these openings were drawn over a solar chart, using TownScope 2.0 software (1998), providing a "fish eye view" of the room. The shadows were evaluated for two points in both rooms: P1, which is located 1m from the window and P2, located at the centre of the room. Figure 4.23 shows the plans of the rooms with the position of the reference points.

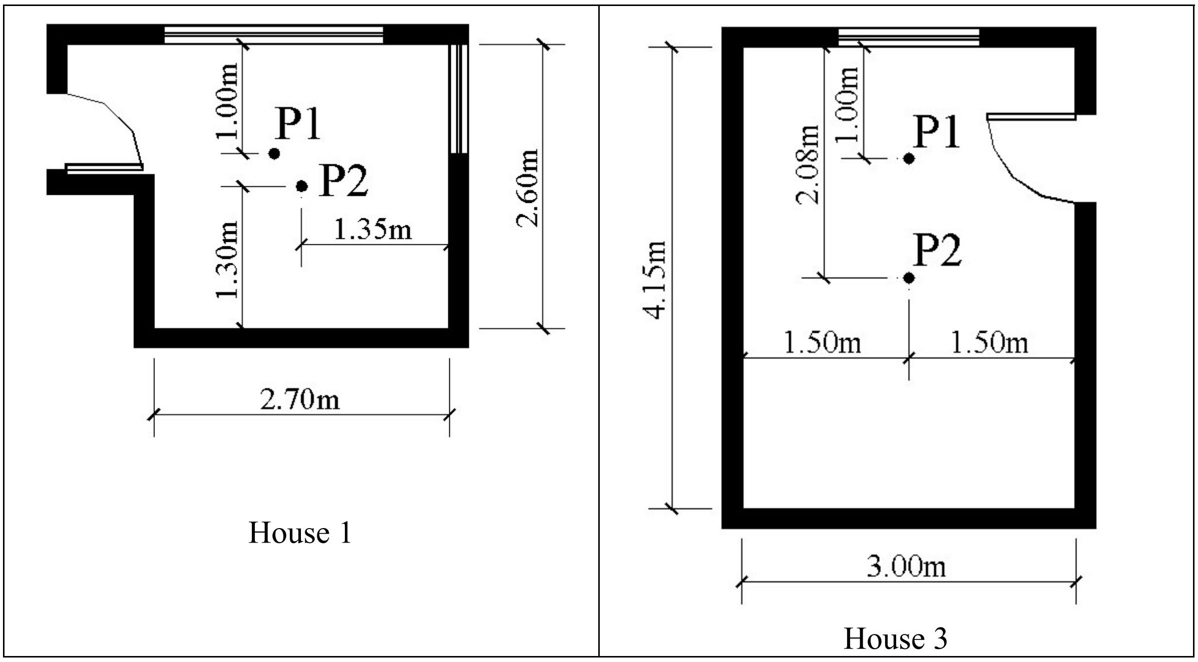


Figure 4.23: Plans of the evaluated rooms showing the position of the reference points.

The figures below show the results. The solar chart on left shows the shadow mask considering the point located about 1 m from the window (P1). The one on the right shows the result for the point located in the centre of the room (P2). The points were considered at a height of 1 m above the floor.

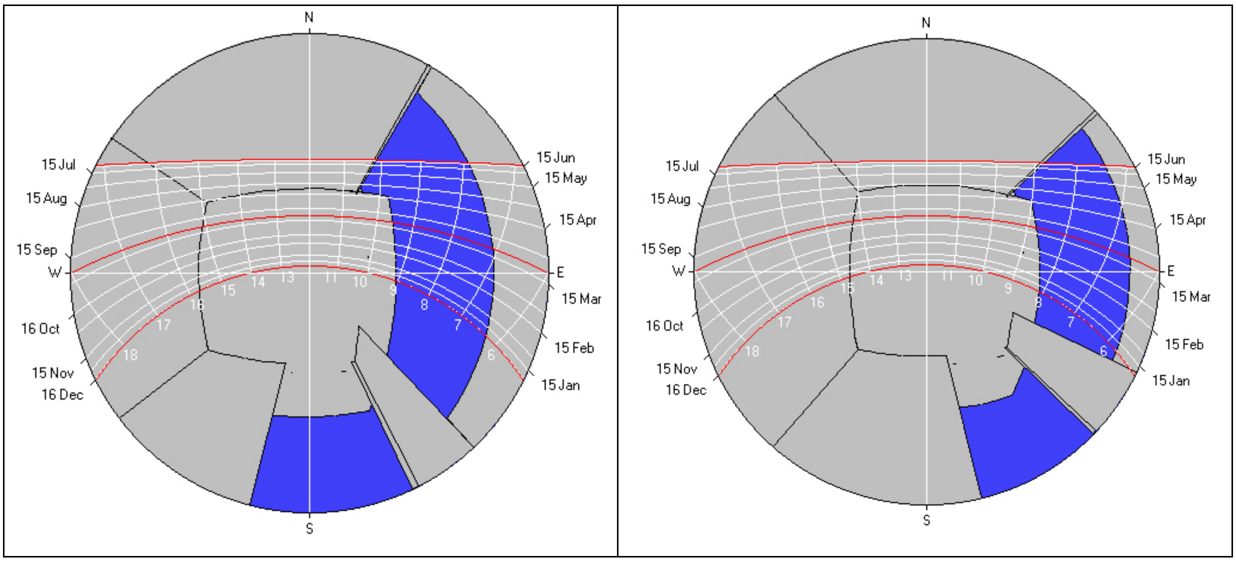


Figure 4.24: Solar access evaluation for the study-room's opening of House 1.

The study-room of House 1 showed the worst thermal performance compared to the other rooms in the same house – 15.8% of temperatures are above 29ºC. This room has a window area of 2.4 m^2 (window to floor ratio of approximately 32%). The window is East orientation and only an overhang of 60 cm protects it. In that situation, the solar radiation penetrates in the ambient in the morning period, as shown by the shadow masks.

In the solar chart on the left (figure 4.24), with the point of reference located about 1m from the window, the surface receives solar radiation from 6:30h to 9h approximately, during summer time. For the second case, when a central point is analysed, the surface receives solar radiation until 8 h approximately.

The second opening showed in the figure is a door-window, which gives access to a balcony. This opening has South orientation therefore it does not receive solar radiation during all year.

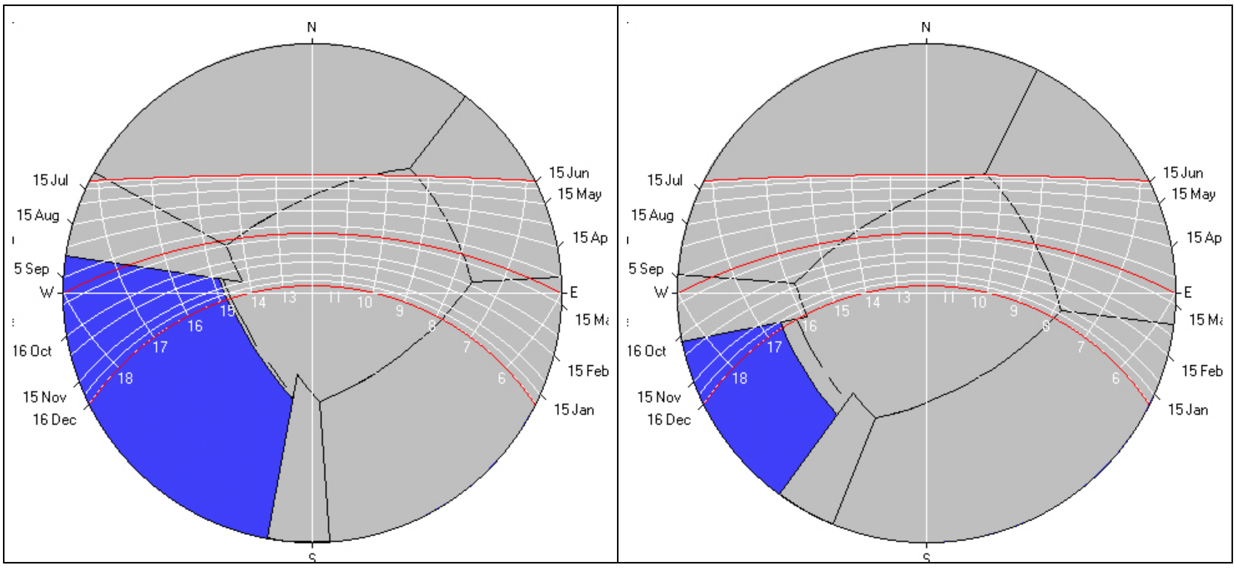


Figure 4.25: Solar access evaluation for the dining room's opening of House 3.

The dining room of House 3 showed the worst thermal performance compared to all study cases, except the bedroom in house 4. The percentage of temperatures that exceeds 29ºC in the dining room is 35.4%. The window of this ambient has Southwest orientation and an area of 2.0 m^2 (window to floor ratio of 16%). An overhang of about 30cm protects it and there is a transparent curtain internally.

The solar chart on the left (point located about 1 m from the window) shows that the surface receives solar radiation from 15h to 18h approximately, during the summer months. For the point located in the centre of the ambient (chart on the right), the surface receives solar radiation from 16:30h in December and January and from 18 h in February (see figure 4.25).

4.7. Conclusions:

The results of monitoring were evaluated through profile of internal temperatures and humidity, statistical values such as mean, maximum and minimum as well as frequency of temperatures above 29ºC. Besides this, a solar access evaluation was performed to the openings of the rooms with worst thermal performance.

Some of conclusions are summarised below:

- All residences showed higher internal temperatures in the rooms located in the upper floor. Some hypotheses arise from this result: the influence of the heat transmitted through the roof or temperature stratification.

- The higher thermal inertia of houses 1 and 3 (stone walls) helps to decrease the variation of internal temperature (providing smaller amplitude), but when the external temperatures go down, the interior remains warm, due to the heat stored in the mass.
- The houses of higher thermal inertia did not show the best internal condition all the time. It can be explained by the custom of keeping doors and windows open during daytime, which damages the inertia effectiveness as the internal temperature increases due to warm air that comes in.
- The solar access analysis showed the influence of the size and orientation of the openings and the necessity of adequate shading devices in the performance of the ambient. According to Balcomb (1983), especially in a sunny day, the rate of energy inflow at the point receiving solar radiation (an area approximately the size of the window), is much greater than most masonry materials can accommodate for very long. Thus, most of the energy will be redistributed by convection and infrared radiation.
- There is a potential for using night ventilation as the external temperatures fall to 22ºC during the night.

From the field studies results, certain considerations for applying thermal inertia in the climate of southern Brazil emerge, such as:

- The role of the roof system, e.g. the thermal capacity of the ceiling and the use of insulation or radiant barrier in the roof: just for applying higher thermal inertia in the walls does not guarantee better performance for the house. Higher thermal inertia ceiling and the use of insulation or radiant barrier should be considered to reduce the heat coming from the roof.
- Size of openings and adequate shadow: window / floor area ratio should be considered carefully and the shadow should be assured especially in cases when the opening is located in a problematic orientation such as East, West, Southwest or Northwest. The high inertia of the surface of the construction components (walls, floors) which receives direct solar radiation will keep the heat for longer if it is not dissipated by ventilation.
- Night ventilation: the nocturnal ventilation should be taken into account to guarantee the dissipation of the heat that is stored in the structure. The architectonic design

should consider openings for night ventilation taking into account the security and protection against insects.

- The effect of allowing daytime ventilation on the performance of higher thermal inertia buildings as it takes indoor conditions close to outdoors' climate.

It can be highlighted that the differences in results between the four houses can be caused by some other factors, such as different architectonic layout, orientation of the rooms and location of the residences. Nevertheless, here, the results were considered taking into account only the differences in terms of inertia.

The aspects above will be further investigated through simulation studies in the chapters 6 and 7.

Chapter 5. Building Modelling and Calibration:

5.1. Introduction:

This chapter describes the development of the calibration phase of the TAS program. The results of measurements from fieldwork are compared with thermal simulations using TAS thermal simulation tool (TAS v.8.4). House 1 was chosen to be modelled because of its higher thermal inertia characteristics. The construction details of House 1 were input in the program as well as a weather file for Florianópolis.

5.2. Brief Description of Building Thermal Analysis Program – TAS:

TAS is the Building Thermal Analysis Program used in this research for the Analytical Studies, including the calibration phase. TAS is a software tool, which simulates the thermal performance of buildings, and the main applications of this program are in assessment of environmental performance, natural ventilation analysis, prediction of energy consumption, plant sizing, analysis of energy conservation options and energy targeting. This software is linked to the 3D –TAS, a 3D modeller and together these two programs go by the name of Tas Building Designer.

The following summary about the simulation principles was taken from TAS theory manual:

"The fundamental approach adopted by Tas is dynamic simulation. This technique traces the thermal state of the building through a series of hourly snapshots, providing the user with a detailed picture of the way the building will perform, not only under extreme design conditions, but also throughout a typical year. This approach allows the influences of the numerous thermal processes occurring in the building, their timing, location and interaction, to be properly accounted for."

The heat transfer mechanisms are considered as follow, accordingly to TAS theory manual:

"Time-varying conduction heat transfer and heat storage in the building fabric is modelled in Tas using the normal co-ordinate method with a time-step of 1 hour. The basis of the method is a description of the thermal state of the wall in terms of a set of normal co-ordinate variables. These variables, which define a decomposition of the temperature and flux distributions in the wall in terms of eigenfunctions, are updated at each time increment, and are used, in combination with recent input data, to calculate all output quantities. The method thus possesses elements in common with the two most widely used of existing methods for the analysis of wall heat flows, combining an economical state-

representation resembling that employed by finite difference methods with fast and accurate techniques borrowed from response factor theory.”

Convection at building surfaces is treated using a combination of empirical and theoretical relationship relating convective heat flow to temperature difference, surface orientation and, in the case of external convection, wind speed. The internal convection is dependent on the temperature difference between the room air and surface temperatures, it means that h_c varies from hour to hour.

Advection is the transfer of heat via the bodily movement of the air. In TAS air flow rates may either be specified in advance or calculated by the program. Prescribed air flow rates may be specified under three headings: Infiltration, Ventilation and Air Movement. TAS will calculate air flow rates by natural ventilation in Aperture Air Flow given data on the characteristics of apertures.

TAS solves the zone heat balance for setting up equations representing the individual energy balances for the air and each of the surrounding surfaces. These equations are then combined with further equations and the whole set of equations is solved simultaneously to generate air temperatures, surface temperatures and room loads. This procedure is repeated for each hour of the simulation. As described in the manual:

"*The matrix solution procedure assumes linearity. In reality, due to the dependence of convection coefficients on temperature difference, the system of equations is non-linear. For this reason, the matrix solution is repeated iteratively until the assumed convection coefficients are consistent with the calculated temperature differences. Convergence is deemed to have been achieved when no surface temperature varies by more than 0.2K from one iteration to the next. After the heat balance has been obtained for each zone, the whole procedure is repeated in an iterative process which ensures that inter-zone connections (via conduction and advection) are correctly accounted for.*"

The main Input characteristics of the software are described as follow:

a) Zone Names and Groups: This facility allows the user to name zones and to define groups of zones for data editing and output viewing.

b) Schedules: It may be used to specify the timing of building element substitution and the timing of aperture opening.

c) Constructions Details: This option gives access to the facilities concerned with the specification of the building's geometry and material composition, together with the characteristics of air flow apertures. These facilities are *Building Elements*, *Aperture Types, Feature Shading*, among others regarding building geometry.

- The *Building Elements* table defines a set of construction types used in the building.
- *Aperture Types* is concerned with specifying data for the simulation of **natural ventilation**.

An aperture is an opening in a wall or floor through which air may flow. Examples of apertures are windows, doors, louvres and floor openings such as stairwells. Each aperture has an area, a mean altitude, an orientation and a plan hydraulic diameter derived from 3D_Tas geometric model. The apertures properties can be specified in this option, such as: time-varying *aperture factor* (openable proportion), aperture schedule **(**times at which apertures of the given type are open) and whether apertures for the given building element are in a sheltered position (if the aperture is exposed to the wind pressure or not). The *aperture factor* is a number, in the range (0,1), which specify the area of the aperture as a fraction of the area of the surface it is associated with.

Aperture air flows are calculated by TAS using a model, which takes account of the pressure flow characteristics of the apertures, wind pressure and stack effect, and any prescribed air flows. The flow equations are solved iteratively. At each time step, wind pressures are calculated for all exposed apertures. Then, at each iteration step, air densities in all zones are calculated from the zones temperatures, and these are used (together with wind pressure if appropriate) to calculated stack pressure gradients for both sides of each aperture. The balance takes into account any air flow prescribed in the Air movement facility. The flow equations are solved using a gradient-based method to yield zone pressures and flow rates in both directions through each aperture. These flows are then fed back to the TAS thermal analysis where they are used to generate updated zone temperatures (both air and mean radiant). The heat and moisture transfers due to aperture air flows are treated in the same way as those for prescribed air flows.

- *Feature Shading* allows the user to define simple *Shading Types* in terms of side-fins and overhangs. A *shading type* may be assigned to any building element, and will apply to all exposed surfaces of that building element type.

d) Internal Conditions: This option deals with the specification of environmental control; *infiltration* and *ventilation* rates and *incidental gains* schedules.

- The *environmental control* deals with all plant control settings, such as temperature and humidity control and plant schedules and installed capacities. This is used when the building is air-conditioned.

- *Incidental gains* are internal heat gains from occupancy and equipment.

- The term *infiltration* is used in TAS to describe the user-specified exchange of air between a building zone and the exterior by **natural ventilation**. Infiltration carries both sensible and latent heat into or out of the zone. Infiltration rates for each zone may be specified and scheduled to vary with time, by setting air change rates in Internal Conditions. These air change rates are converted to air mass flow rates. During the simulation, the sensible heat gain due to infiltration into a zone is modelled as:

$$Q^{inf} = m^{inf} C_p (T_o^{air} - T^{air}) \quad (5.1)$$

where

m^{inf} is the infiltration air mass flow rate

C_p is the specific heat capacity of air at constant pressure

T_o^{air} is the outside air temperature

T^{air} is the zone air temperature

- There is an option to specify mechanical *ventilation* rate for a zone in addition to the infiltration. The ventilation is assumed to be drawn into the zone direct from outside, and its effect on the zone sensible and latent balance is modelled by the equation:

$$Q^{vent} = m^{vent} C_p (T_o^{air} - T^{air}) \quad (5.2)$$

where

m^{vent} is the ventilation air mass flow rate

e) Preconditioning: It is recommended that every simulation should include a preconditioning period of 10 days or more to assure that the effect of the initial condition has became negligible at the start of the period of interest. The required period of preconditioning will vary with building type and internal conditions.

The Zone Temperatures Outputs include: Air temperature, Mean Radiant temperature (MRT), Resultant temperature (calculated as the mean of air temperature and mean radiant temperature) and Surface temperature.

5.3. Weather Data Preparation and First Calibration of the Model:

5.3.1. Weather Data

The weather file used in TAS consists of a group of parameters relating to the weather site and hourly values of seven climate variables: Global Radiation, Diffuse Radiation, Cloud Cover, Dry-bulb Temperature, Relative Humidity, Wind Speed and Wind Direction.

As TAS thermal simulation tool does not have any Brazilian weather data, it was necessary to create a new weather file with all climatic data for Florianópolis. In view of the difficulties in obtaining climatic data, especially solar data for Brazilian cities, it was decided to create a weather file for part of the period correspondent to the fieldwork only.

To create the new weather file, solar data for the specific period (January and February 2001) was then obtained from LabSolar (Solar Energy Laboratory – department of Mechanical Engineering at Federal University of Santa Catarina – Brazil). Unfortunately, solar data for February of that year was only available from 1st to 22nd. LabSolar also provided outdoor air temperature and humidity data for the period, however these data were incomplete.

It was decided to use the external measurements of temperature and humidity of House 1 to compose the weather file with the aim of diminishing the climatic differentiation within the urban scale (since both data from Labsolar were incomplete and the station is located in a different site). The remaining variables such as cloud cover, wind speed and wind direction were filled using data from TRY file available for some cities of Brazil (Goulart, 1998), including Florianópolis. This TRY file does not contain any solar data. The discontinuity existent in relative humidity data from the field experiment due to some problem with the instrument was completed with relative humidity obtained from Labsolar. The weather file created for Florianópolis includes the period from 22nd of January to 22nd of February.

5.3.2. Model

A model representing the House 1 from the fieldwork, which has higher thermal inertia characteristiscs was input in TAS. Some new materials were introduced in the Materials Database to be able to better represent the Brazilian materials used in the house. The thermophysical properties of the materials introduced were obtained from ABNT (1998).

The figure 5.1 shows the Model in a perspective view with a shadow display for the day 42nd (February, 11), 16 pm.

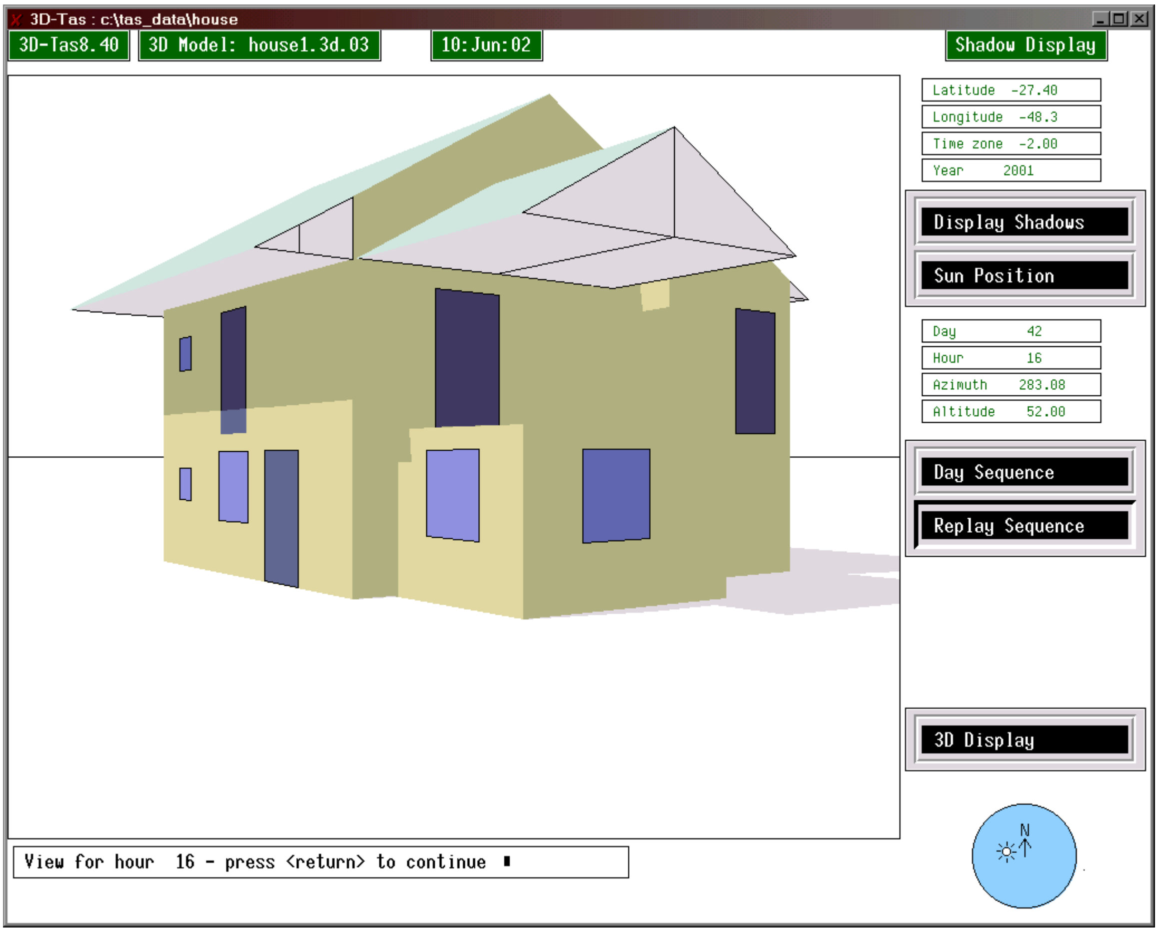


Figure 5.1 – Model representing House 1.

Considerations in the Model:

a) Feature Shading – Overhangs were considered in all orientations according to the real building.

b) Opening Schedules – The model is naturally ventilated and the times when the windows are open or closed were considered according to the regular routine of the occupants. In the reality, these times can vary a little from one day to another.

Schedule	Open	Closed
a (openings of Ground floor)	9 – 18 h	1 – 8 h and 19 – 24 h
b (openings of upper floor)	9 – 16 h	1 – 8 h and 17 – 24 h

c) Zones – All rooms of the residence were considered as a different zone to take into account the thermal exchanges between rooms. However, the interest in the results was concentrated only in three zones: Zone 1 – Living room, Zone 4 – TV room and Zone 5 –

Study-room. These zones correspond to rooms that were monitored in the fieldwork. The figure 5.2 shows the plans for both floors and the monitored rooms are highlighted.

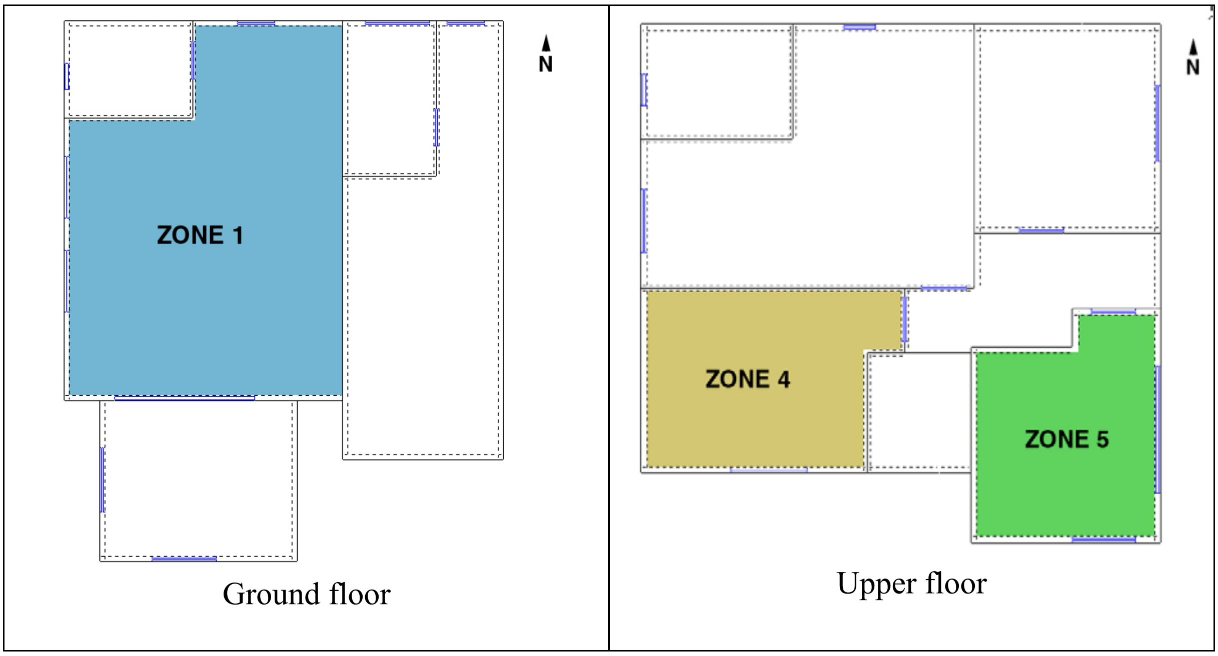


Figure 5.2 – Plans of the model showing the monitored rooms.

d) Internal Conditions – The values for occupancy and equipment gains are based in ASHRAE Fundamentals (2001): Sensible heat gain per sedentary occupant is assumed to be 67W. In single-family houses, a sensible load of 470 W should be considered for appliances divided between the kitchen and laundry areas.

In the model, the gains from equipments are considered only in zone 1 (living room) because the kitchen area is part of the living (open plan kitchen). Equipment gains are also considered in the service area (laundry).

The default value of 0.5ach is considered for air infiltration.

e) Aperture Features – The openable proportion of the windows were taken as 50% and initially the model was considered not sheltered from the wind. All internal doors were considered open to allow air circulation and thermal exchanges between zones.

5.3.3. Results:

The model was simulated for the period from 11th to 22nd February, considering that solar data were available up to 22nd and allowing twenty days as preconditioning days.

The graphs below show the first simulation for zones 1, 4 and 5, and results are compared to the measured data in the fieldwork.

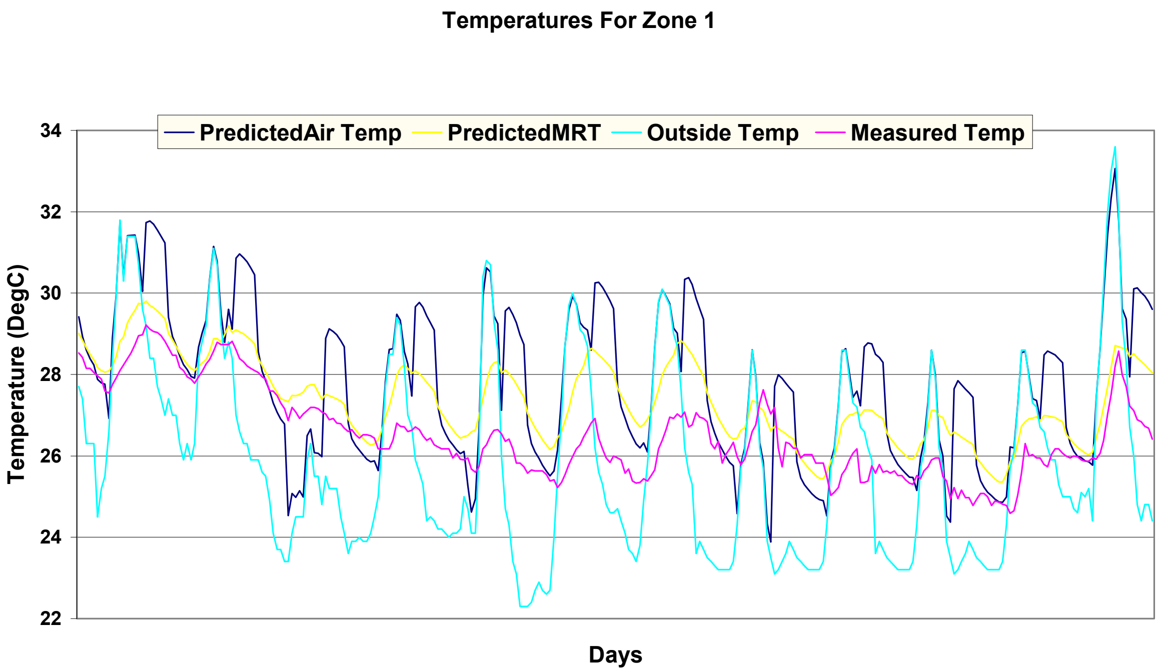


Figure 5.3 – Results of first simulation for Zone 1 (living room).

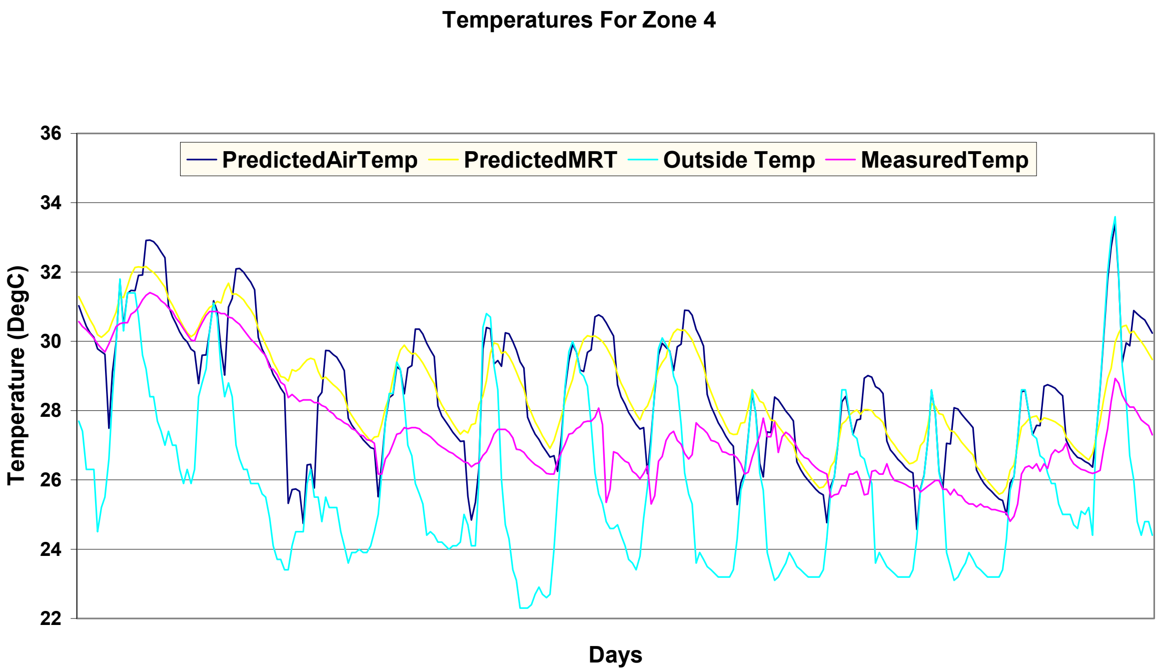


Figure 5.4 – Results of first simulation for Zone 4 (TV room).

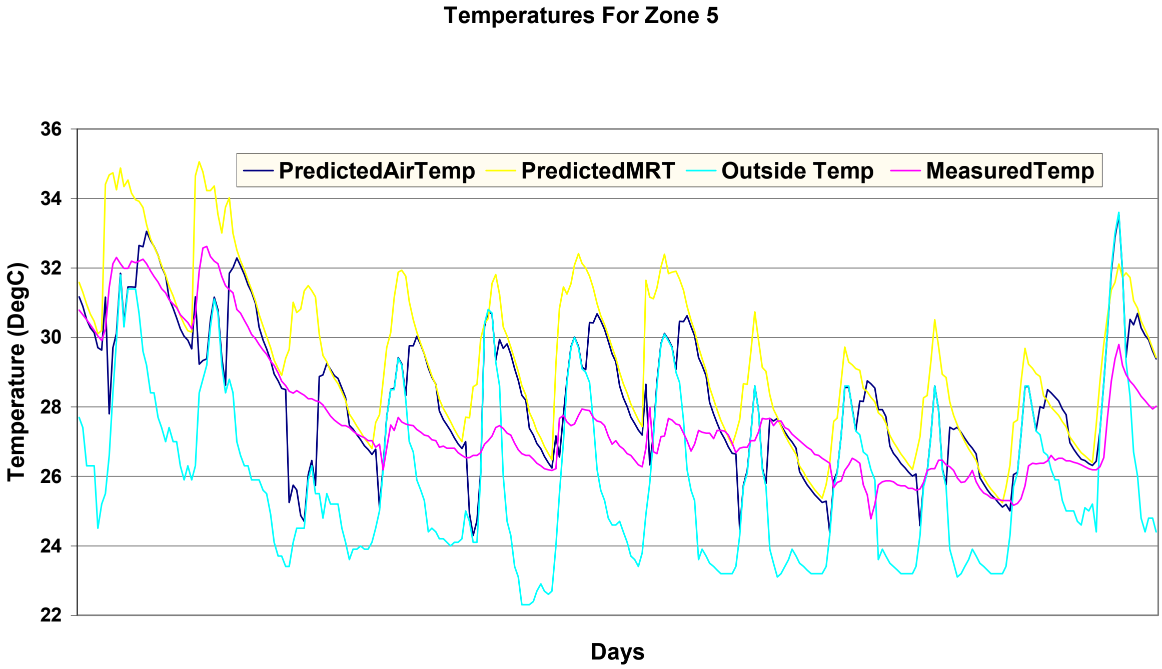


Figure 5.5 – Results of first simulation for Zone 5 (study-room).

It can be observed that the air temperature (dark blue line) follows the outside temperature when the windows are open, which results in a different profile far from the measured temperature (pink line). On the other hand, the mean radiant temperature (MRT) (yellow line) has a distribution similar to the measured one, although the results are overestimated. The mean radiant temperature (MRT) calculated by TAS takes account of the diffuse solar radiation flux, which an occupant of the zone would experience and which would contribute to the occupant's perception of radiant temperature. The instruments used for measuring the internal conditions of rooms probably register rather the combination of radiant and air temperature than air temperature only.

There are large differences between measured and predicted data. The results for Zone 1 (living room) that is located in the ground floor had a better agreement with the measurements than Zone 4 and Zone 5 – rooms located in the upper floor. The worst result was in Zone 5, which is a study-room located in the east orientation.

5.4. Sensitivity Analysis:

The previous results of calibration were not satisfactory as the predicted temperatures are overestimated. Some of those differences may be due to the uncertainty in input data and the difficulty to precisely replicate reality. It is necessary to determine the sensitivity to the key uncertainties such as: climate, geometry and zoning, constructions and attributes, occupancy characteristics, airflow and control (Robinson, 2003).

In order to get a better agreement between the simulated and measured values and evaluate the sensitivity of TAS thermal simulation tool, a series of further simulations was performed. Some modifications were implemented to the model and the results were compared to the previous simulation's results and against the collected experimental data.

The following parameters have been investigated:

- Air infiltration values;
- Solar absorptance of internal surfaces;
- Aperture features, such as open proportion of the windows and wind pressure coefficient;
- Opening schedules: windows closed 24 hours;
- Shading feature of the window;
- Internal gains;
- Thermal Inertia of the walls;
- Number of preconditioning days.

New simulations were performed by varying the specified parameters and keeping the rest as they were previously. The main observations from the results are summarized below:

a) Air Infiltration: the value of air infiltration was increased from 0.5ach (default) to 1.0ach in all zones. Results demonstrated that some peaks of air temperature decreased slightly when compared to the previous simulation. Although the difference was not significant, the new predicted air temperature approximated a little more of the measured one. The value of 1.0ach of air infiltration seems to better represent the reality. (see Internal Conditions in section 5.2 to a description of how infiltration is modelled by TAS).

b) Solar Absorptance of the walls: The value of internal solar absorptance was reduced to the minimum value in the range of solar absorptance of the granite material (from 0.55 to 0.45). This modification had little influence, even so, the minimum value was adopted as some peak of predicted air temperature and mean radiant temperature get closer to the measured peak values.

c) Aperture Features: The wind pressure on a building facade depends in a complicated way on the speed and direction of the wind, the geometry of the building and any nearby obstruction. TAS bases its analysis on the concept of a wind pressure coefficient. The wind pressure coefficient for a particular aperture is defined in terms of the wind speed at the building reference height. The wind pressure on the aperture is assumed to vary as the square of this wind speed. The TAS interface allows the user to specify a time-varying aperture factor (openable proportion), which is a number (between 0 and 1), specifying the area of the aperture as a fraction of the area of the surface it is associated with. In addiction, there is an option to indicate if the aperture is sheltered from the wind or not. In order to verify the influence of the wind speed and the wind pressure coefficient in the predicted indoor air temperature, the following modifications were implemented: the apertures were considered *sheltered* from the wind, which means that the model does not consider wind pressure coefficient in the bulk air simulation and no wind speed is taken into account; the *openable proportion* of the windows was reduced from 0.5 (50%) to 0.25 (25%).

The main difference between *sheltered* and *no sheltered* condition is in the airflow *In* and *Out* of the zones. When the model is *no sheltered*, the results take into consideration the wind pressure and wind speed. On the windward side of the building, the wind pressure coefficients are usually positive and their values tend to increase with height. Hence, if the model is *no sheltered,* Zone 5 has a higher inflow through the window (which is facing the prevailing wind direction), while the window in Zone 4 works as an extractor (all the inflow comes from the circulation). On the other hand, when the model is considered *sheltered*, there is a balanced air circulation between the zones. Sheltered condition has the effect of treating the apertures as though they were on the leeward side of the building and thus they are not subject to the wind pressures experienced by exposed apertures. (see Apertures Types in section 5.2 to a description of how TAS treats the aperture air flows)

These modifications did not improve significantly the general results. The Mean Radiant temperature was almost the same as before. Nevertheless, when the model was considered *sheltered* and with 25% of openable proportion, the peak of Air Temperature decreased up to 2°C in the hottest days and the predicted minimum temperatures came closer to the measured data. It was decided to adopt these two latter conditions in the model.

d) Opening schedules: In order to evaluate the influence of the external air temperature coming in through the windows on the internal air temperature, the opening schedule was changed and all the openings were considered closed all times.

In the previous simulation, (windows open during the day), the curve of the predicted air temperature is coincident with the external temperature in the times when the windows are open. When the model is simulated considering the windows closed all times, the shape of the curve of internal Air Temperature does not follow the external one.

Most of results for the predicted Mean Radiant Temperature showed almost no difference compared to that of the simulation with the windows open daytime. However, when the external temperature goes down, the simulation with windows closed all times showed higher values of Air Temperature and Mean Radiant Temperature. The predicted internal temperatures remain warm for longer even when the external climate is cooler. It happens because the heat stored in the structure is not dissipated since there is no ventilation through the windows. In this case, the minimum values of both Air Temperature and MRT were, in most of the days, coincident with the minimum measured values.

Moreover, in the simulation with the windows closed, the results for some days showed better agreement with the measurements than the results with windows open daytime. It happened in all three monitored zones. It means that, probably in these dates, the openings of the house were kept closed all day.

e) Shading feature: It was observed that the worst agreement between the predicted and the measured data always occurred in Zone 5. The high solar gain due to the large window of that zone, probably, had direct influence on the internal predicted temperatures, especially on the mean radiant temperature.

In order to achieve a better agreement between the simulated and measured data, a new shading feature was considered in the window of Zone 5. An external shade of solar transmittance equal a 0.34[1] was assigned to the clear glass to simulate a possible solar obstruction by trees or buildings nearby.

The results showed that this modification did not have much influence on air temperature profile when compared to the previous simulation. However, the influence on mean radiant temperature was very significant. The new predicted mean radiant temperature came closer to the measured data and, in some cases, resulted practically the same. It has confirmed the influence of the solar gain through the window on internal conditions of that zone.

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[1] Corresponds to the solar transmittance of an external shading device such as a translucent awning or canopy.

f) Internal gains: In the first assumption the internal gains were distributed in a more simplified way. The gains from occupancy and equipment in the monitored rooms were considered starting both at 8 a.m. and finishing at 6 p.m. (for equipment) and at 12 p.m. (for occupancy). This distribution can have overestimated the internal heat gain and, consequently, increased the predicted temperatures.

   A new arrangement was implemented, which combines internal heat gains with appropriate time-variance. This modification decreased the internal heat gain as, for example, the gains from equipment in Zone 1 (living-room with a open kitchen) was only considered taking two hours (by midday), which is more according to the reality. Also, the value of gains from occupancy was decreased, considering that the house was not occupied all the time.

   The effect of this modification was significant on the internal conditions as the new predicted temperatures came closer to the measured data.

g) Thermal Inertia of the walls: The influence of the thermal inertia was investigated through the construction characteristics of the walls. The aim was to find out if the model was well reproduced in terms of thermal inertia.

   In the new simulation, the width of the wall was changed from 20cm to 30cm and the density of the granite was increased.

   With these modifications the agreement between the predicted and measured data improved. However, when the external temperature goes down, the predicted air temperature remains higher due to the heat stored in the structure, which is kept for longer. As in general the agreement between the data has improved, the width of the wall is now considered 30 cm and the granite density value adopted is 2700 kg/m^3.

   Also, this analysis showed that the position of the instrument is an important issue. The registered values could have been affected by the radiant temperature of the structure rather than air temperature, whilst in TAS, the zone temperature is calculated by balancing heat gain and losses at a single central air point.

h) Number of preconditioning days: As the required period of preconditioning will vary with building type and internal conditions, a reduced interval was tested to investigate the sensitivity of the model to this parameter. The number of preconditioning days was decreased to 10.

   In this case, this modification did not have influence on the results and the number of preconditioning days can be assumed as the minimum value (10 days) only to assure that the effect of the initial condition has became negligible at the start of the period of interest.

5.5. Final Calibration:

The conclusions from the sensitivity analysis led to a new simulation taking into consideration the results highlighted above.

The first three graphs show the results considering the opening schedule that represents the normal routine of the house (windows open daytime). The second set of graph show the predicted temperatures obtained considering windows closed 24h.

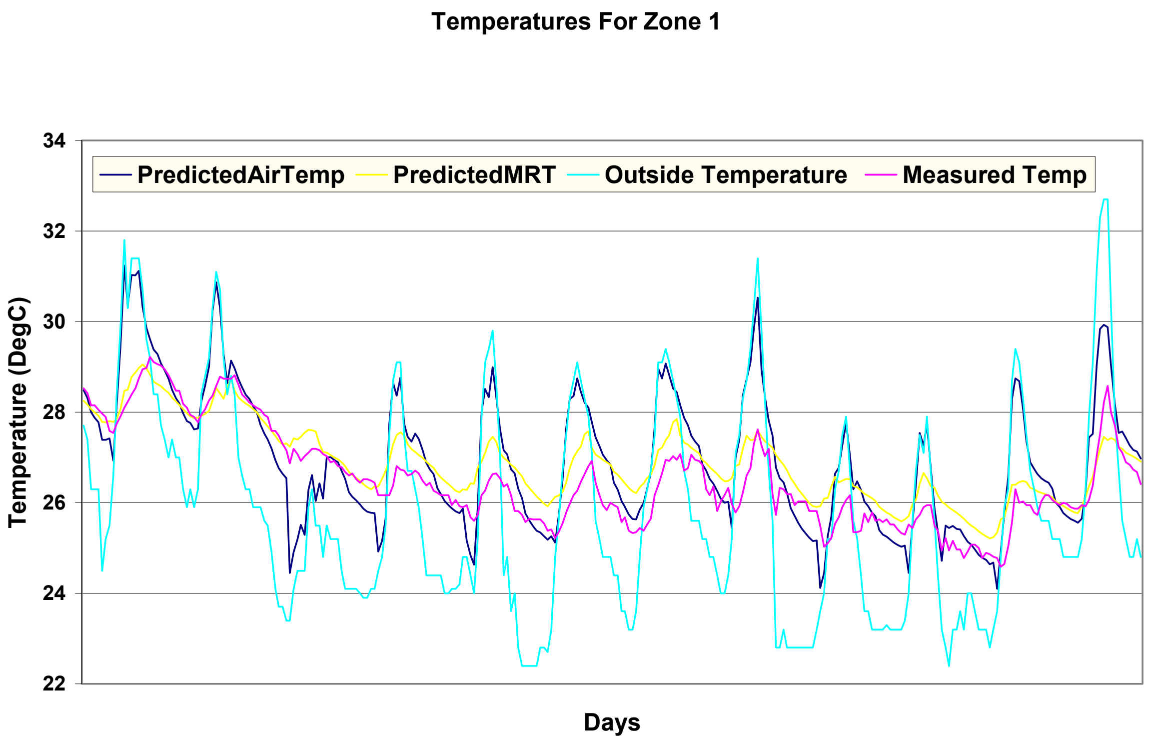


Figure 5.6 - Final calibration results - Zone 1 (living room).

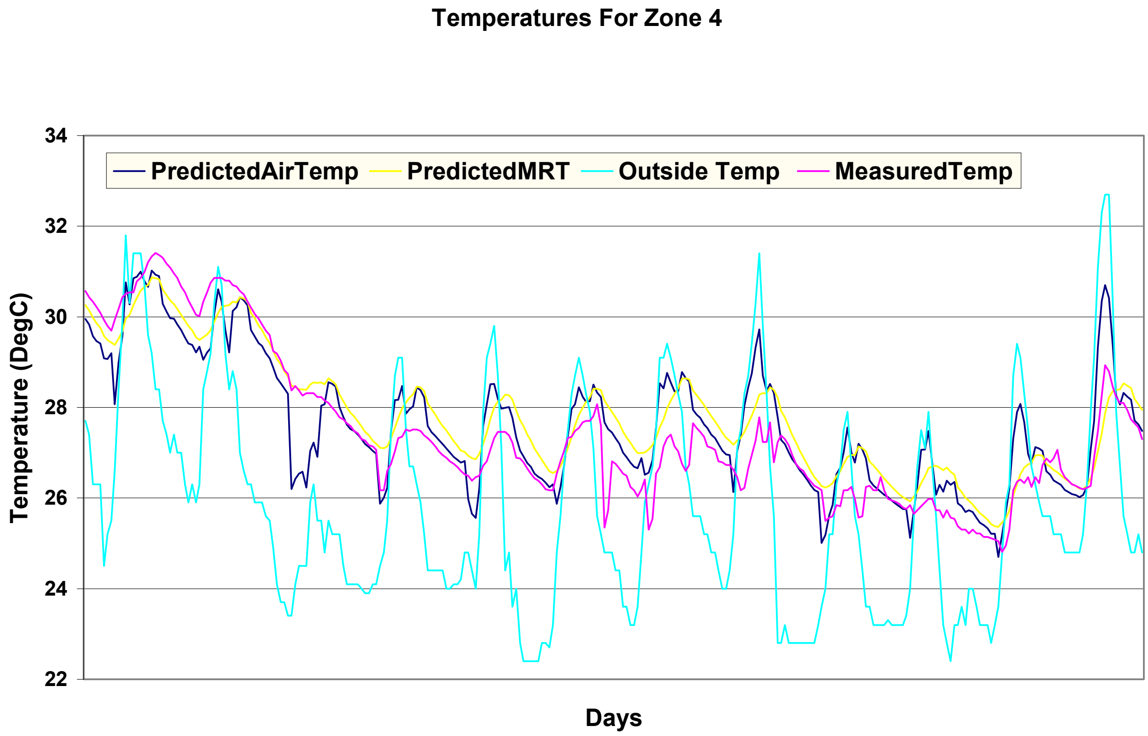


Figure 5.7 - Final calibration results - Zone 4 (TV room).

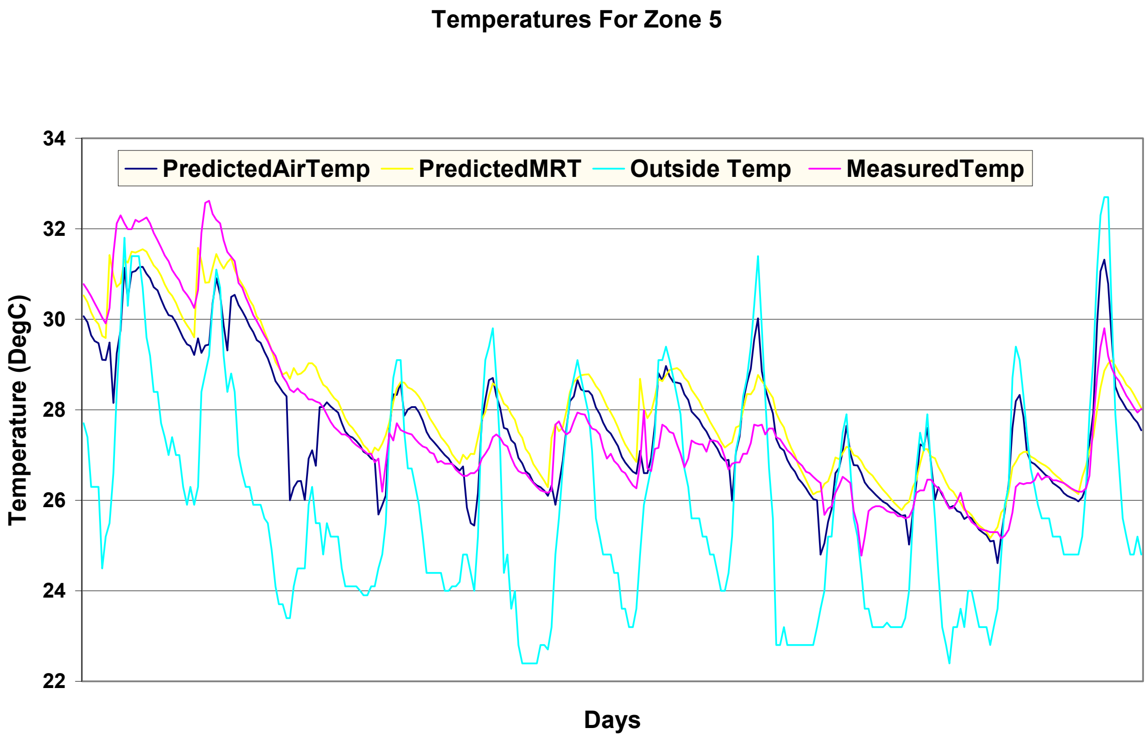


Figure 5.8 - Final calibration results - Zone 5 (Study-room).

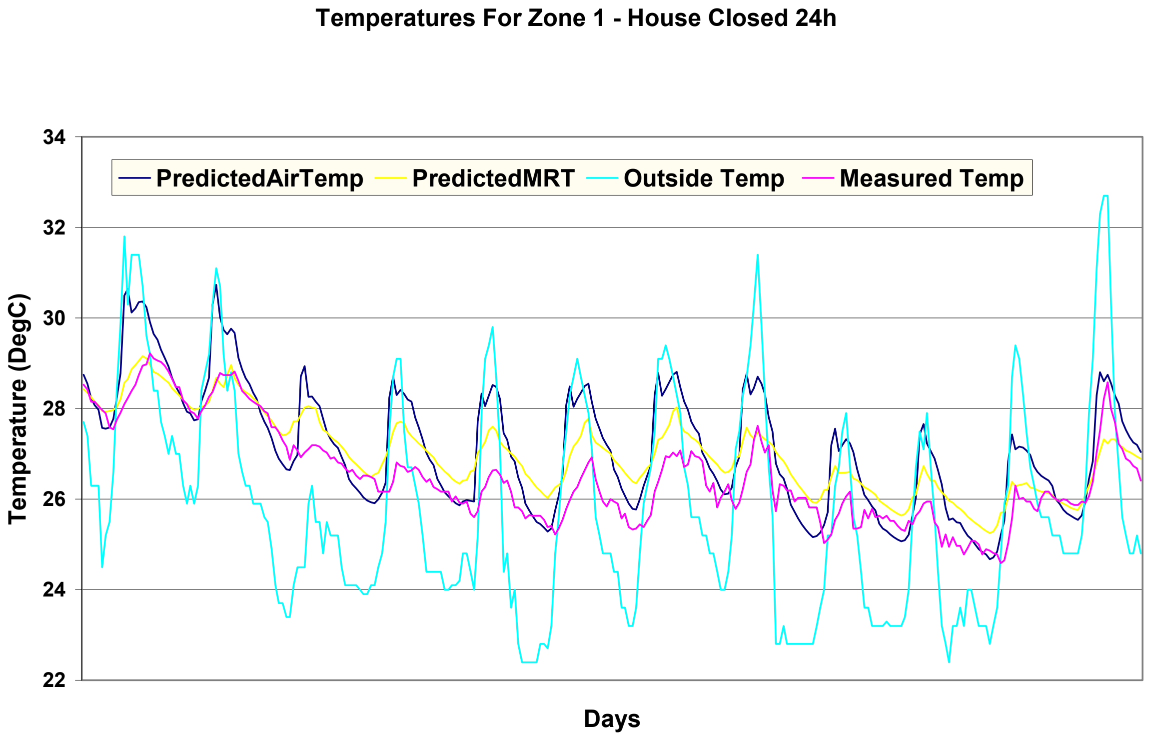


Figure 5.9 - Final calibration results with windows closed 24h- Zone 1 (living room).

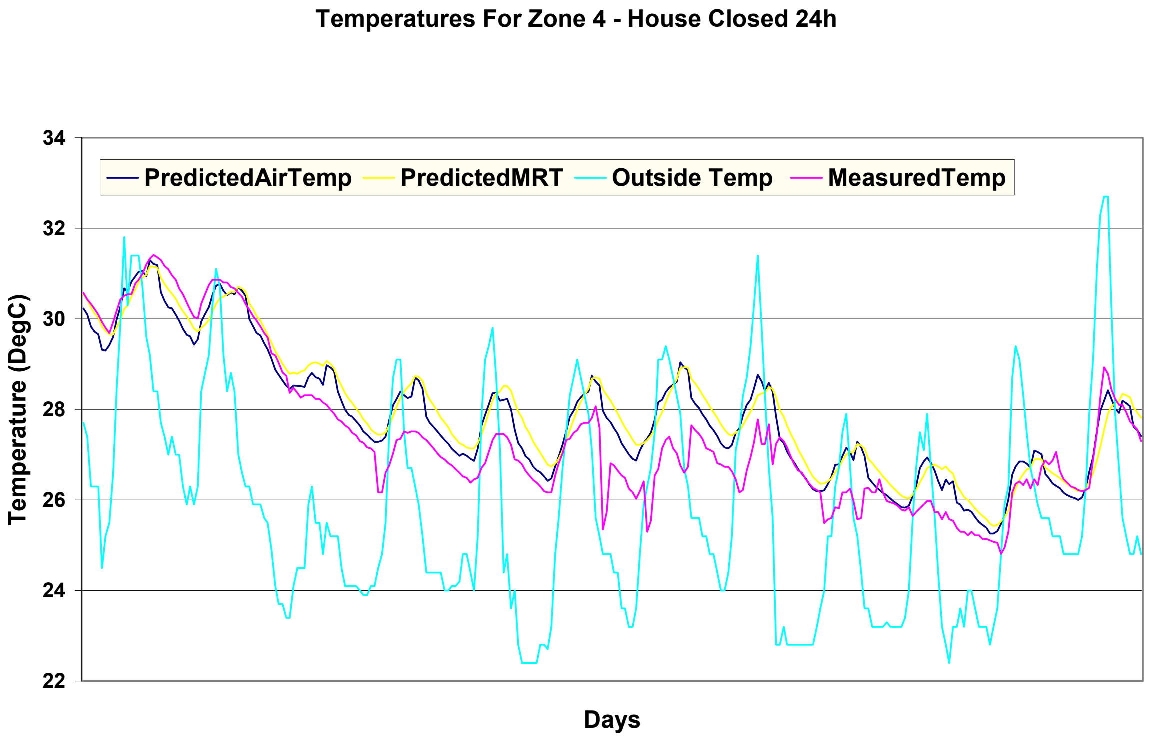


Figure 5.10 - Final calibration results with windows closed 24h- Zone 4 (TV-room).

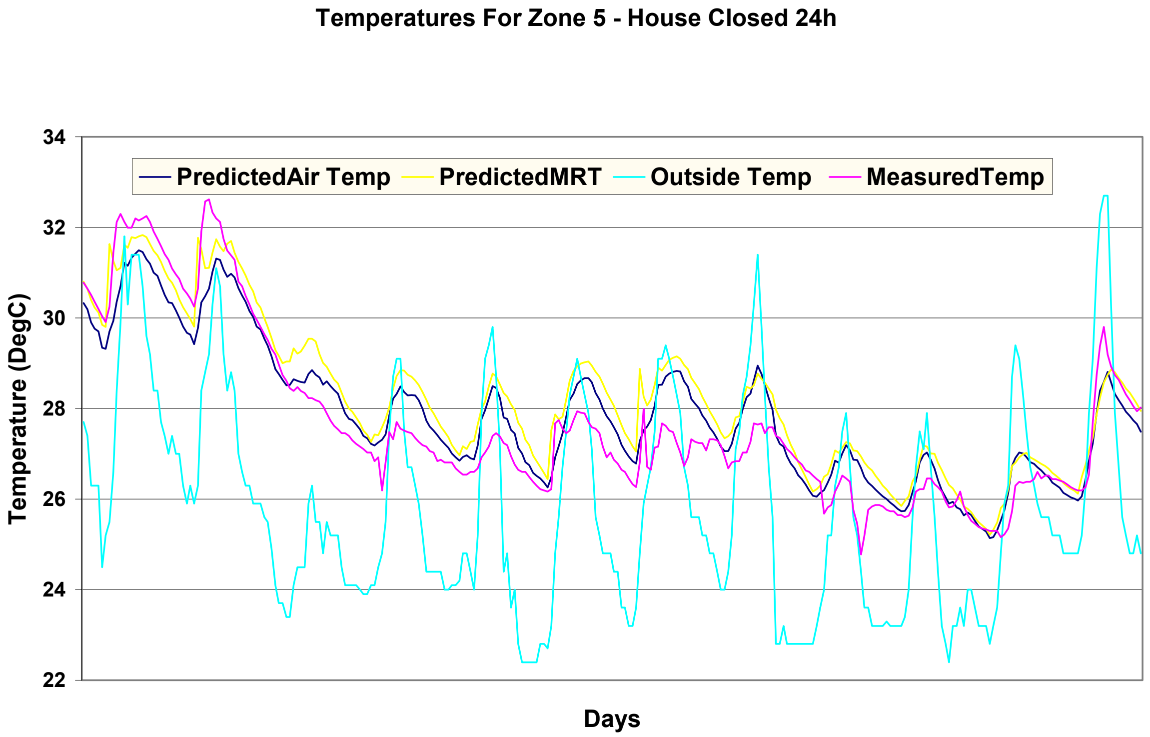


Figure 5.11 - Final calibration results with windows closed 24h- Zone 5 (Study-room).

As shown, the achieved agreement between the collected experimental data and predicted results is variable. There are days when the measurements and simulated results are close and days in which the differences between the two data are more evident. The results showed that, in general, there is an overestimation of the model when compared with the measurements for the same period.

According to (Allard, 1998), the reasons for such differences between the measured and the simulated data can be multiple:

a) Differences in climatic data: the house reproduced by the model is located in a low-density area with a particular microclimate (trees and sea nearby), which is impossible to be taken into consideration in the simulation program. Besides this, weather parameters such as wind speed, wind direction and cloud cover used in this weather file are from a TRY file (Test Reference Year), which is a year different from when the field work was carried out.

b) Uncertainty in input data: wind pressure coefficients, thermal mass, and building occupancy, especially the window use (open and closed times).

c) Measurement errors: the accuracy of the instruments used in the monitoring is about 0.5 to 0.7 K. The location where the instruments were installed can also have affected the results.

The Air Temperature predicted by TAS should be used to compare with the measured one, as the manufacturer claims that the instruments record air temperatures. However, looking at the results, the predicted Air Temperature seems to have a direct relation to the outside air, as the curve of the simulated air temperature follows the external air temperature curve when the windows are open. It can be explained by the form that zone air temperature is calculated by TAS. Zone air heat balance combines heat gain from infiltration, ventilation, air movement, casual gains, plant and surface convection. The sensible heat gain due to infiltration and ventilation is calculated taking into account the outside temperature (see equations 5.1 and 5.2).

Sensitivity analysis has shown that, sometimes, the Mean Radiant Temperature (MRT) seems to have more agreement with the measured results. TAS calculates the MRT as a weighted average of the zone's surface temperatures, modified by the effects of radiant gains (incidental gains and the diffuse component of solar gain). Besides this, TAS assumes that the air in a zone is well mixed and therefore representable by a single zone air temperature.

Consequently, during the fieldwork, care is needed to place the logger in a position that is representative of the room temperature and it is important to isolate the loggers away from the structure, to ensure that the temperatures recorded are air temperatures and not temperatures of the structure. This can be difficult because criteria such as security of the instrument can lead to a choice that can distort the data collected. It is highlighted by Longobardi (2000), as his results show that the temperature recorded by the loggers is a resultant temperature, comprising some part radiant temperature and some part air temperature.

In this specific fieldwork, for security reasons, the instruments were placed on lightweight shelves, attempting to locate the sensor as far as possible from the walls. However, when comparing to the predicted temperatures by TAS, the placement of the instruments can have affected some results as the temperature recorded seems to be a Resultant Temperature or sometimes a MRT rather than Air Temperature.

In addition, the ups and downs of the curve representing the measured data show that, possibly, the open /close times of the windows occurred in different hours of the schedule adopted. The opening schedule considering windows open daytime represents the average behaviour of the occupants. Moreover, sometimes the measurements can be representing the house with windows closed all day. As one can see in the graphs showing the simulation with the windows closed 24h, the curve representing the air temperature presents, in some days, better correlation with the measurements. Also, assumptions were made concerning the internal gains. That profile is different if the inhabitants are at home or if everyone leaves house during the day.

In order to examine the deviations between the measured data and the simulated results, the Mean Bias Error (MBE) and the Root Mean Square Error (RMSE) were calculated. MBE indicates the mean difference of the predicted values from the measured values, whereas RMSE is a measure of deviation of the simulated values around the measured data. The equations are shown below:

$$MBE = \sum (Yi - Xi) / N$$

$$RMSE = \{\sum (Yi - Xi)^2 / N\}^{1/2}$$

Where: Yi = Predicted value

Xi = Measured value

N = Number of observations

The differences between the predicted temperatures (Air Temperature, MRT and Resultant) and the measured indoor temperatures were calculated for the three zones for both situations: windows open daytime (usual routine of the house) and windows closed 24h.

Table 5.1 – Differences between predicted and measured data for the simulation considering windows open daytime.

	Predicted AirTemp – Measured			Predicted MRT – Measured			PredictedResultant – Measured		
Zone	MBE	RMSE	MaxDif	MBE	RMSE	MaxDif	MBE	RMSE	MaxDif
Living	0.44	1.06	3.1	0.35	0.55	1.3	0.40	0.70	1.7
TVroom	0.19	0.82	2.3	0.36	0.68	2.8	0.27	0.69	2.6
Study-room	-0.05	0.93	2.4	0.36	0.72	2.1	0.16	0.73	2.0

Table 5.2 – Differences between predicted and measured data for the simulation considering windows closed 24h.

	Predicted AirTemp – Measured			Predicted MRT – Measured			PredictedResultant – Measured		
Zone	MBE	RMSE	MaxDif	MBE	RMSE	MaxDif	MBE	RMSE	MaxDif
Living	0.60	0.98	2.5	0.48	0.65	1.3	0.55	0.76	1.7
TVroom	0.40	0.71	2.6	0.53	0.81	3.1	0.46	0.74	2.8
Study-room	0.18	0.69	2.0	0.53	0.83	2.2	0.35	0.73	2.0

Values of mean difference (MBE) between measured and simulated temperatures show that, sometimes, the measured results are closer to the simulated Air Temperature and sometimes, closer to the Mean Radiant Temperature.

In the case with the windows open during daytime (table 5.1), the maximum difference obtained between the measured and simulated results was 2.8°C (TV room) if the MRT is considered. When the simulated Air Temperature is considered, the maximum difference was 3.1°C (Living-room). However, when the Resultant temperature is evaluated, the maximum difference between the data obtained in the Living-room was the smallest among the zones (1.7°C).

Study-room's measurements showed best agreement with the Resultant Temperature, as the mean difference between the data was 0.16°C, although the corresponding RMSE was higher (0.73°C). The negative value of MBE obtained in that room when simulated Air Temperature is considered means that, in the average, the values of measured temperatures are higher than the predicted one.

The mean difference between MRT and measured temperatures were similar in all three rooms with the MBE of about 0.36°C.

When the windows are closed 24h (table 5.2), measured values in the Living room had a better agreement with the simulated MRT (MBE = 0.48°C), whereas the measurement in the Study-room was closer to the simulated Air Temperature (MBE= 0.18°C). In this case, the maximum differences obtained between the measured and predicted result were both in TV room: 2.6 °C when Air temperature is considered and 3.1°C when MRT is considered.

It can be observed that when the Resultant temperature is examined, the mean differences (MBE) are higher when the windows are closed for all zones. It means that the simulation considering the windows open during daytime is closer to the actual behaviour of the occupants, at least for most of the days during the fieldwork.

5.6. Conclusions:

The sensitivity analysis showed that the predicted temperatures were affected mainly by the distribution of internal heat gains and by solar gain coming through the window in Zone 5.

The evaluation of thermal inertia of the walls showed that the position of the instrument is an important issue as the sensor could have been registering the radiant temperature of the structure rather than air temperature.

The fact of considering the model sheltered from the wind and the reduction of openable proportion of the openings did not improve significantly the general results. However, in the hottest days, peaks of Air Temperature have decreased and get closer to the measurements.

The simulation considering the opening schedule showed that, sometimes, the measurements can be representing the thermal performance of the house with the windows closed 24h as, in some days, the predicted temperatures were closer to the measured temperature than the results with windows open daytime.

The increasing of the shading feature had a major effect in zone 5, due to the considerable glazing area facing East in that room (window to floor ratio of 32%). Due to the placement of the instruments near the wall, the measured temperature in that zone has been affected by the temperatures of the structure, whereas the predicted temperatures has been affected by diffuse solar radiation flux throughout the glazing surface.

The calculated mean differences between measured and predicted temperatures showed that, sometimes, the measured results are closer to the predicted Air Temperature and sometimes, they are closer to the predicted Mean Radiant Temperature. These results showed that the temperature recorded by the loggers is a Resultant Temperature rather than air temperature only. Based on that, the Resultant Temperature predicted by TAS can be considered to represent the room temperature as it is calculated as the average of Air Temperature and Mean Radiant Temperature.

Higher values of MBE for the predicted Resultant temperature with windows closed 24h have confirmed that the house had the windows open during daytime in most of the days of the fieldwork. Therefore the daytime opening schedule is representative and it will be adopted in the Base-case.

Differences between the measured and the predicted values have reinforced the uncertainty in input data when one is trying to reproduce the thermal behaviour of a building using a simulation tool. Despite of the calibration of the model did not have total agreement with the measurements in the fieldwork, the sensitivity analysis has shown the main parameters affecting the simulations results. Moreover, this difference is not a problem if the purpose of simulation is to get values of relative validity, e.g., in parametric studies or for comparative evaluation of design alternatives.

The calibration process has given background to the next stage, in which parametric variations will be performed and compared with a base-case. Tables from TAS showing the main input data (aperture types, building elements and internal conditions) can be seen in Appendix A2. This final Input Data represents the Base-case.

Chapter 6. Parametric Studies:

6.1. Introduction:

Conclusions from fieldwork and literature review led to some aspects, which should be taken into account when using higher thermal inertia in buildings in hot/humid climates. Such aspects include the level of thermal inertia of the walls; the influence of the roof/ceiling construction; the potential of night ventilation; window size and shading.

The aim of the parametric studies is to determine the extend to which this features should be used to improve the performance of a building with higher thermal inertia.

This chapter describes the parametric analyses, which were performed using TAS Building Thermal Analysis Program (see section 5.1) and the obtained results of the parametric variations.

The analyses considered in the model are the following:

a) Night ventilation (mechanical and natural);

b) Influence of the size of windows and the use of shading devices;

c) Influence of the roof system: two different levels of thermal inertia of the ceiling/roof and the presence of radiant barrier or insulation;

d) Influence of different levels of thermal inertia in the walls.

e) Model Improved with different levels of thermal inertia in the walls

To accomplish the parametric studies, a Base-Case is considered to comparisons, which is the model from the calibration stage. The model represents the house with higher thermal inertia among the four studied houses in the fieldwork and reproduces the case-study zones as built. Internal Conditions, Occupancy Pattern and all the elements considered in the Base-case are reproducing the real situation and the normal routine of the building: daytime ventilation; no shading in the window.

In most of the cases, only two zones are studied: Zone 1, located in the ground floor and Zone 5, which is located in the upper floor. These two zones were chosen because they represent two extreme conditions of the model and in a way, they indicate the limits of the thermal inertia performance:

Zone 1 is well protected from solar gains, has greater internal surface area and showed best performance according to the fieldwork. In the other hand, Zone 5 has a large window allowing solar penetration and showed the worst performance between the two studied zones located in the upper floor. In addition, it receives the influence of the heat coming through the roof. The details of the respective Surface Geometry are:

Table 6.1 – Surface Geometry of the Zones.

	Int. Volume (m^3)	Int. Floor Area (m^2)	Total Int.Wall Area (m^2)	Window/floor ratio (%)
Zone 1	67.4	29.6	41.51	4.7
Zone 5	17.4	7.6	23.0	31.6

Parametric variations are carried out to find causes of increasing or diminishing of thermal inertia performance when compared to the base-case. The results of variations provide, then, answers to improve the performance of a higher thermal inertia building.

All simulations are performed considering the internal doors open, to allow the air flowing throughout the building.

The parametric variations are described in more details below:

a) Night Ventilation:

Two conditions are evaluated:

By *Natural Means*: i. e. through the building's openings - windows are open between 23:00 and 7:00 and closed in the rest of the times. Two situations were considered:

- Natural nocturnal ventilation, with 25% of open proportion of windows;
- Natural nocturnal ventilation, with 50% of open proportion of windows.

Using both *Mechanical and Natural Means*: supply air is made through mechanical means, while openings assist the outflow of the air to avoid the over-pressurization of the building. In this case, 25% of open proportion of the windows was considered to allow the outflow air. Three levels of forced ventilation were studied:

- 10 air changes per hour;
- 20 air changes per hour;
- 30 air changes per hour.

b) Window:

The main source of heat gain in Zone 5 is, probably, the large window facing East. In this case, only the window of that zone of the Base-case is examined as follows:

Window to floor area ratio: The Base-case has a window / floor ratio of approximately 32%. Two smaller proportions were also examined and compared to the base-case:

- 20% window / floor ratio;
- 10% window / floor ratio.

Solar Protection: Three different levels of solar protection were studied:

- No solar protection: clear glass (3 mm) and an overhang (roof) of 0.90 m.

- External Shading Device: clear glass and a *brise soleil* ($\propto$ = 49.08°), providing shading from 9:10h a.m., since the window has East orientation.

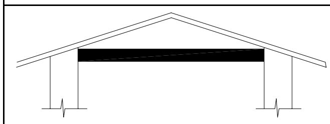
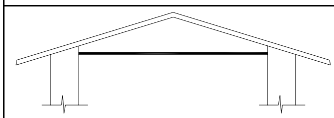
- External Venetian Blind or Shutter: clear glass plus an external blind (Solar Transmittance = 0.07). This shading device is assigned to the glass, so the open proportion of the window is assumed not to have shutter (TAS limitation).

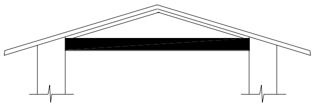
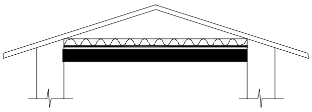
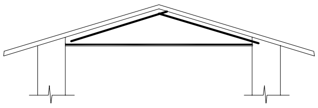
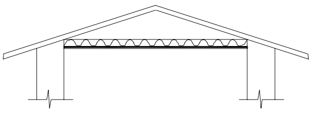
c) Different Levels of Thermal Inertia in the Roof System:

In the roof system evaluation, two different levels of thermal inertia were analysed: 10cm concrete slab ceiling and timber ceiling, both under clay tile roof. Besides this, the performance of the roof system was also tested by adding thermal insulation and radiant barrier in both: concrete slab and timber ceiling. Table 6.2 shows the different ceiling/roof configurations and their respective heat capacities and U-values. The variations are as follows:

- Horizontal Concrete slab ceiling under sloped clay tile roof: **Base-Case**
- Horizontal Timber ceiling under sloped clay tile roof;
- Horizontal Concrete slab ceiling, radiant barrier (emissivity = 0.05) under sloped clay tile roof;
- Horizontal Concrete slab ceiling, insulation (conductivity = 0.04 W/m K) under sloped clay tile roof;
- Horizontal Timber ceiling, radiant barrier (emissivity = 0.05) under sloped clay tile roof;
- Horizontal Timber ceiling, insulation (conductivity = 0.04 W/m K) under sloped clay tile roof.

Table 6.2 – Roof configurations, Heat Capacities and U-values.

Roof configuration	Description	HC_T [kJ/(m^2.K)]	U [W/(m^2.K)]
	Sloped clay tile roof Horizontal concrete slab ceiling (10 cm thick)	113	1.92
	Sloped clay tile roof Horizontal timber ceiling	32	2.00

Roof configuration	Description	HC_T [kJ/(m^2.K)]	U [W/(m^2.K)]
	Sloped clay tile roof Radiant barrier Horizontal concrete slab ceiling (10 cm thick)	113	1.08
	Sloped clay tile roof Insulation Horizontal concrete slab ceiling (10 cm thick)	115	0.33
	Sloped clay tile roof Radiant barrier Horizontal timber ceiling	32	1.11
	Sloped clay tile roof Insulation Horizontal timber ceiling	34	0.62

d) Different Levels of Thermal Inertia in the Walls:

Walls of lower thermal inertia than the Base-case are evaluated:

- Granite Block walls, which corresponds to the Base-Case;
- Double Brick wall;
- Single Brick wall;

The table 6.3 shows the walls configurations, their respective heat capacities and U-values. The Occupancy, Use Pattern (daytime ventilation) and Internal Gains are considered the same as in the base-case; only the walls of the model are changed. The objective of this analysis was to verify the influence of different walls on the thermal behaviour when no design strategy is applied, i.e. no night ventilation; no shading and no improvement in the roof system.

Table 6.3 – Wall configurations, Heat Capacities and U-values.

Wall configuration	Characteristics of the Elements			**HC_T [kJ/(m^2.K)]**	**U [W/(m^2.K)]**
	ρ (kg/m3)	**λ (W/(m.K))**	**c (kJ/(kg.K))**		
Type: **Granite Block**					
Granite	2700	2.9	0.84	680	3.63
Total Width = 30 cm					
Type: **Single Brick**					
Brick	1300	0.9	0.92	206	3.14
Plaster both sides	2000	1.15	1.0		
Total Width = 14 cm					
Type: **Double Brick**					
Brick 1	1600	0.9	0.92	312	2.42
Brick 2	1300	0.9	0.92		
Plaster inside	2000	1.15	1.0		
Total Width = 22 cm					

e) Model Improved: Best performances from variations ***a*** to ***c*** are implemented to the model. They comprise: 10 ach night ventilation (no daytime ventilation), 20% window to floor ratio and use of the external blind in the window of zone 5, and finally, concrete slab ceiling and radiant barrier under the tile roof. The new model is, then, evaluated, considering the Brick Walls and Granite Block Walls.

6.2. Assessment of Comfort Improvement:

Even if the comparison between the results and the base-case provides some important information about the efficiency of the studied parameters, more accurate analysis of the total impact of the techniques on occupancy conditions is required and parametric results must be translated into comfort indices. Many theories can be used to characterise the feeling of thermal comfort.

Human thermal comfort is dependent on four environmental variables: air temperature, humidity, air movement and radiation; and on two personal variables: metabolic rate (activity) and clothing. There are others contributing factors for the thermal comfort such as: food and drink, acclimatisation, body shape, subcutaneous fat and age.

Air temperature is the most important environmental factor. It will determine the convective heat dissipation, together with any air movement. There is an agreement between most of researches that at or near comfort conditions the best measure of thermal sensation is the air (dry bulb) temperature, within very wide limits of humidity (Docherty and Szokolay, 1999). Also, the thermal sensation of a sedentary person is strongly influenced by the temperature variation. According to Evans (2000), the temperature variation is considered to be more important for comfort than wind, humidity and radiation under many situations in and around buildings. Evidently, high level of humidity combined with high ambient temperatures reduces the upper limit of the comfort zone, as the evaporative capacity of the air is diminished and sensible transpiration and skin moisture increase. However, in a typical warm humid climate, the average outdoor temperature range is in order of 7 to 10°K. Evans (2000) gives the following example: when the temperature varies from 23 to 30°C, the minimum relative humidity is about 65%, which coincides with the maximum temperature. At midday, the effect of the high absolute humidity changes the upper comfort limit by 1.5K. The effect of humidity is much less than the effect of 7°K temperature variation through the day.

The climatic condition described above is typical for summer in Florianópolis climate (see section 4.2): the average range of daily temperature is about 8°K and during summer months, the temperature can vary from 21 to 29°C (average values of minimum and maximum).

Moreover, when establishing comfort limits, clothing and activity levels should also be considered as variables and not constants. The incorporation of clothing and activities as variables is an essential part of the adaptive process of thermal regulation. Unless in formal situations, when dress restrictions may reduce acceptable temperature ranges or upper limits of the comfort zone.

Evidently, as thermal comfort is a subjective sensation, only air temperature can not be enough to evaluate thermal comfort, but it is the most important variable to determine comfort. Based on that, the temperature is used in this thesis as a parameter of comparison of the zone's thermal performance. The performance criterion adopted is the number of hours that zone temperature exceeds certain temperature-base.

The temperature limits chosen in this work are two: 27°C, which is the upper limit of comfort zone considered for temperate climate countries and 29°C, which is the upper limit of the comfort zone for warm climate countries, considering the acclimatisation of people to hot humid conditions and from living in unconditioned buildings. These values of upper temperature limits are suggested by Givoni (1992) for acceptable conditions under still air.

In an early study, Szokolay (1981) also suggests a higher upper limit of temperature being acceptable in residential buildings: "*In the domestic situation, or where clothing* *need not be more than shorts and short-sleeved shirts, the upper comfort limit of 30°C is probably realistic*".

To validate the chosen upper limit of 29°C, this value was tested by the two main thermal comfort theories: the predicted mean vote (PMV) and the adaptive model.

The adaptive approach is based on empirical observation of the results from field surveys of thermal comfort and includes in some way the variations in outdoor climate for determining thermal preferences indoors. It assumes an adaptive principle: "*If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort*" (Nicol, 2001).

The expression used here to represent this theory and the comfort temperature was taken from de Dear and Brager (2002), based in Auliciems (1981) correlation:

$T_{conf} = 0.31T_{a,out} + 17.8$

Where $T_{a,out}$ is the mean outdoor dry bulb temperature of the month.

Instead of the monthly mean of the outdoor temperature, in this case, the mean of temperature corresponding to the hottest day of the studied period will be considered. The reason for that is to cover for the worst possible condition.

The hottest day of the period has a mean temperature of 29.7°C, so, the resultant T_{conf} according to the above expression is equal to 27°C. According to the adaptive theory, the comfort zone can be taken as ± 2.0°C about the neutrality point, hence, the upper limit, in this case, is 29°C.

The PMV theory (developed by Fanger, 1970) represents the 'predicted mean vote' (on the thermal sensation scale) of a large population of people exposed to a certain controlled environment.

To test the upper limit of temperature using the PMV theory, the software PEM (v1.2b, 1997) was used to make the calculations and the following conditions were considered: The radiant temperature was considered the same as air temperature (29°C) and relative humidity between 50 and 80%. The metabolic rate is assumed to be between 0.7 and 1.0 met, indicating sedentary or light activity as in residences and the air movement is taken as 0.1 m/s (still air). Moreover, very light summer clothes were assumed to be worn (Clo between 0 and 0.5).

As a result, PMV values of 0.3 and 0.9 were found, with corresponding PPD of 6.4 and 22.5%, respectively. The latter situation corresponds to 80% of relative humidity, which is the mean value for that climate. However, if higher air movement is provided indoors (0.5 m/s), the resultant PMV value was zero, with PPD of 5.0%.

According to ISO 7730 an acceptable PPD should be < 10%, which corresponds to a PMV between – 0.5 and + 0.5.

According to both theories, the limit of 29°C is perfectly acceptable in that climate condition and considering the domestic situation.

In the parametric study, the reduction (or increasing) in the number of hours that zone Resultant Temperature is above both limits (27 and 29°C) due to variations is calculated and compared to the Base-case. The Resultant Temperature is defined as the average of air temperature and mean radiant temperature.

The period assessed in the parametric studies comprehends 22 days (from 1st to 22nd February – summer period), which corresponds to the total solar data obtained from LabSolar (see section 5.3) and allowing ten days as preconditioning days. Hence, the total number of hours of the period evaluated corresponds to 528 hours.

6.3. Parametric Variations Results:

6.3.1. Night Ventilation:

The results given in table 6.4 shows that there is a gradually reduction in the number of hours above 27°C as the amount of provided night ventilation increases. These vary from 13.3% to 22.2% for natural ventilation and 30 ach mechanical ventilation, respectively, when compared to the base-case.

Table 6.4 – Number of hours above 27°C and 29°C and reductions regarding the base-case when night ventilation is applied – zone 1.

Zone 1	Resultant Temperature			
	Nº of hours above 27°C	Reduction (%)	Nº of hours above 29°C	Reduction (%)
Base-Case	293	-	56	-
Nat. Vent. (25%)	254	13.3	49	12.5
Nat. Vent. (50%)	246	16.0	45	19.6
Mech. Vent. 10ach	243	17.1	44	21.4
Mech. Vent. 20ach	234	20.1	44	21.4
Mech. Vent. 30ach	228	22.2	44	21.4

However, there is no reduction from 10 ach when the limit of 29°C is considered and the decrease varies between 12.5% (for natural ventilation) and 21.4% (for 10 ach).

It also can be seen that temperatures are above 27°C for about half of the time of the evaluated period (which corresponds to 528 hours), even when applying night ventilation.

Table 6.5 – Number of hours above 27°C and 29°C and reductions regarding the base-case when night ventilation is applied – zone 5.

Zone 5	**Resultant Temperature**			
	Nº of hours above 27°C	Reduction (%)	Nº of hours above 29°C	Reduction (%)
Base-Case	416	-	196	-
Nat. Vent. (25%)	376	9.6	164	16.3
Nat. Vent. (50%)	357	14.2	150	23.5
Mech. Vent. 10ach	353	15.1	147	25
Mech. Vent. 20ach	342	17.8	139	29
Mech. Vent. 30ach	337	19	132	32.6

As given in table 6.5, the higher the amount of night ventilation rate in zone 5, better the thermal condition in both limits, although the reductions above 29°C are more significant. Also, the number of hours above both limits is higher in this zone, compared to zone 1. For the base temperature of 27°C, the achieved reduction of the overheating hours due to nigh ventilation varies between 9.6% and 19%, while for 29°C, the reduction is between 16.3% and 32.6%.

6.3.2. Window Size and Shading:

In this analysis, the predicted Air temperature and Mean Radiant temperature are also shown. The aim was to demonstrate the different effect of the glazing area on the different temperatures. Results for the limit of 27°C are not shown for the window to floor ratio analysis as the obtained reductions were insignificant. This analysis was undertaken only in Zone 5, which has a large window allowing solar gain.

6.3.2.1. Window to floor area ratio

Table 6.6 – Number of hours above 29°C and reductions when the window / floor ratio is decreased.

Window/ Floor Area Ratio	**Air Temp.**		**Resultant Temp.**		**Mean Radiant Temp.**	
	Freq. above 29°C	Reduction %	Freq. above 29°C	Reduction %	Freq. above 29°C	Reduction %
Base-case 32%	159	-	196	-	248	-
20%	147	7.5	186	5.1	221	10.9
10%	147	7.5	182	7.1	216	12.9

The influence of the window size is more evident on the Mean Radiant temperature, since the decrease in the window to floor ratio from 30% to 10% provides reduction of the overheating hours between 10.9% and 12.9%, respectively (table 6.6). In the other hand, the reduction for the Air temperature was only 7.5% and there is no reduction in the overheating hours when the window/floor ratio varies from 20% to 10%. The reduction in the numbers of hours above 29°C for the Resultant temperature varies from 5.1% to 7.1 % for 20% and 10% window/floor ratio respectively.

6.3.2.2. Solar Protection

Table 6.7 –Number of hours above 27°C and reductions when a shading device is applied.

Shading Device	**Air Temp.**		**Resultant Temp.**		**Mean Radiant Temp.**	
	Freq. above 27°C	Reduction %	Freq. above 27°C	Reduction %	Freq. above 27°C	Reduction %
No protection	362	-	408	-	440	-
Brise Soleil	348	3.9	391	4.2	431	2
Venetian Blind	335	7.5	349	14.5	361	17.9

As seen in table 6.7, the use of a *brise soleil* provides an insignificant reduction in the number of hours that temperature exceeds 27°C (4.2% for the resultant temperature). The external shutter or Venetian blind provides better results, although the impact is greater on the Mean Radiant temperature of the room, reaching 17.9% of reduction compared to not to have shading device. The reduction achieved for the Resultant temperature when using a Venetian blind is 14.5%.

Table 6.8 –Number of hours above 29°C and reductions when a shading device is applied.

Shading Device	**Air Temp.**		**Resultant Temp.**		**Mean Radiant Temp.**	
	Freq. above 29°C	Reduction %	Freq. above 29°C	Reduction %	Freq. above 29°C	Reduction %
No protection	152	-	203	-	249	-
Brise Soleil	145	4.6	176	13.3	215	13.6
Venetian Blind	132	13.2	141	30.5	140	43.8

The external Venetian Blind is the shading device more efficient in the reduction of amount of hours above 29°C as shown in table 6.8. The decreasing is, again, more evident in the Mean Radiant temperature, achieving 43.8% compared to the situation when the window has no solar protection. The amount of Resultant temperature above 29°C has a reduction of 30.5% regarding to no solar protection condition.

6.3.2.3. Daylight Analysis

A daylight level analysis was performed for this zone for the different window sizes (32%, 20% and 10% of window to floor ratio) with clear glass and with an external blind (solar transmittance of 0.07). The objective of this evaluation is to verify if there is acceptable daylight level in the room even with the window size reduction and the use of shading. The study was carried out using Ecotect Lighting Analysis (Ecotect v.5.0). The sky model was set to overcast (worst case scenario) and the Daylight Factor inside the zone was calculated for Florianópolis's latitude, to which the "design sky" corresponds to 10000 lux. Daylight factor treats the illuminance that occurs at a point inside a room as a fraction of the simultaneous illuminance on an unobstructed horizontal plane outdoors.

The complete results of this analysis, including the figures can be seen in the Appendix A3. The grade was placed at a high of 0.70 m from the floor and the different colours represent the different ranges of daylight factor, denoted as a percentage of the design sky value. For instance, a daylight factor of 2% corresponds to an illuminance level of 200 lux (0.02 x 10000).

The values given in the table 6.9 correspond to the illuminance at a point in the middle of the zone. There are variations around the room, in some cases, as shown by the different colours in the grade (see figures in the appendix).

Table 6.9 – Illuminance levels inside the room, considering different window sizes and the use of a blind.

Window Size (with clear glass)	Illuminance lux	Window Shading (clear glass + blind)	Illuminance lux
32 %	1500	32 %	1300
20 %	1100	20 %	900
10 %	600	10 %	480

The acceptable level of illuminance depends on the activity that will be performed in the room, for instance, for reading purposes, an illuminance of 300 to 500 lux is acceptable and for design or drawing tasks, the satisfactory level should be about 1000 lux, according to NBR 5413 (ABNT,1991). As the evaluated zone is a study-room, where sometimes design tasks are performed, the acceptable level should be between 900 to 1000 lux.

From the table 6.9, one can see that the smallest window allows an illuminance level in the room adequate for reading purposes, but not for design tasks, while the large window allows excessive illuminance level. The size corresponding to the window to floor rate of 20% permits a range of suitable illuminance level in the room, even with the use of an external blind.

The use of the blind provides a more homogeneous distribution of the illuminance level in the zone for all sizes of windows.

It must be noted that the design sky used for the calculations considers an overcast sky and the results will be different for conditions with clear blue sky. In this case, an excessive level of illuminance can cause discomfort from glare inside the room and the occupant should consider the use of an additional device such as an internal blind or a curtain.

6.3.3. Different Levels of Thermal Inertia in the Roof System:

In this case, Zone 4, also located in the upper floor, is included in the evaluation. The reason for that is to add a different situation in the analysis, since the thermal performance of Zone 5 is greatly influenced by the glazing surface facing East.

Despite of being located in the ground floor, the results for Zone 1 are also shown with the aim of revealing the impact of the upper ceiling configuration and the presence of insulation or radiant barrier in the roof on the zones located in the lower level.

The Base-case has a horizontal concrete slab ceiling. See table 6.2 for the description of the characteristics of the different roof configurations.

Table 6.10 – Number of hours above 27°C and 29°C and reductions when different roof configurations are applied – zone 1.

Zone 1 (Ground floor)	**Resultant Temperature**			
	Number of hours above 27°C	Reduction (R) or Increasing (I) (%)	Number of hours above 29°C	Reduction (R) or Increasing (I) (%)
Concrete slab (base-case)	265	-	40	-
Timber ceiling	278	4.9 (I)	53	32.5 (I)
Concrete slab + radiant barrier	255	3.8 (R)	34	15 (R)
Concrete slab + insulation	268	1.1 (I)	47	17.5 (I)
Timber + insulation	273	3.0 (I)	41	2.5 (I)
Timber + radiant barrier	273	3.0 (I)	44	10 (I)

Table 6.10 shows that the influence of the thermal capacity of the roof on Zone 1, which is located in the ground floor, is higher when the limit of 29°C is taken into account. The use of timber in the upper ceiling provides the worst performance for this zone, always

increasing the amount of hours above the base temperatures, when compared to the use of a concrete slab ceiling. The timber ceiling is not enough to obstruct or absorb the amount of heat generate by the exposition of the roof to solar radiation. That heat gain reaches the lower levels of the building, causing the increasing in the overheating hours. The use of insulation on a timber ceiling provides a lesser increasing in the overheating hours (above 29°C) for this Zone than using a radiant barrier.

The achieved reduction in the number of hours above the base temperatures due to the use of radiant barrier on a concrete slab (upper ceiling) varies between 3.8% (for 27°C) and 15% (for 29°C). However, it seems that, for the ground floor, the addition of insulation on the concrete slab ceiling causes an increasing in the number of hours above both specified limits of temperatures.

The explanation for this fact is that insulation material has a higher thermal resistance and a poor transmittance. Consequently, a higher insulated roof does not allow enough night cooling by conduction or by long wave radiation, keeping the heat inside and increasing the indoor temperature.

Table 6.11 – Number of hours above 27°C and 29°C and reductions when different roof configurations are applied – zone 4.

Zone 4 (Upper floor)	**Resultant Temperature**			
	Number of hours above 27°C	Reduction (R) or Increasing (I) (%)	Number of hours above 29°C	Reduction (R) or Increasing (I) (%)
Concrete slab (base-case)	363	-	124	-
Timber ceiling	372	2.5 (I)	145	16.9 (I)
Concrete slab + radiant barrier	330	9.1(R)	94	24.2 (R)
Concrete slab + insulation	345	4.9(R)	105	15.3 (R)
Timber + insulation	347	4.4 (R)	98	20.9 (R)
Timber + radiant barrier	351	3.3 (R)	105	15.3 (R)

In Zone 4, which is located in the upper floor, there is also an increasing in the number of hours above both limits when a timber ceiling is used instead of a concrete slab ceiling only (see table 6.11). When employing insulation on the timber ceiling better thermal response is achieved (for the limit of 29°C) in this Zone than the application of a radiant barrier in a timber-ceiling roof. The reductions achieved are 20.9 % (insulation) and 15.3% (radiant barrier).

In this case, the use of insulation in conjunction with concrete slab in the upper ceiling shows reduction in the overheating hours compared to the results of a concrete slab only. The corresponding decreases are 4.9% (for 27°C) and 15.3% (for 29°C). Nevertheless, higher reductions are achieved when a radiant barrier is applied on the concrete ceiling – 9.1% and 24.2%, respectively.

Table 6.12 – Number of hours above 27°C and 29°C and reductions when different roof configurations are applied – zone 5.

Zone 5 (Upper floor)	**Resultant Temperature**			
	Number of hours above 27°C	Reduction (R) or Increasing (I) (%)	Number of hours above 29°C	Reduction (R) or Increasing (I) (%)
Concrete slab (base-case)	368	-	152	-
Timber ceiling	364	1.1 (R)	170	11.8 (I)
Concrete slab + radiant barrier	345	6.2 (R)	123	19.1 (R)
Concrete slab + insulation	360	2.2 (R)	136	10.5 (R)
Timber + insulation	362	1.6 (R)	134	11.8 (R)
Timber + radiant barrier	362	1.6 (R)	135	11.2 (R)

As given in table 6.12, the mean difference for this zone, also located in the upper floor, is that there is a slightly reduction (1.1%) in the number of hours above 27°C when a timber ceiling is used instead of a concrete slab. Probably, the explanation for this result counts on the fact that the presence of a large window facing East has more influence on the heat gain of that room than the configuration of the roof itself and the lighter material of the ceiling provides rapid dissipation of the heat, during the night. However, for the base temperature of 29°C, there is an increasing of the overheating hours due to the use of a timber ceiling of 11.8%. In this case, applying insulation or a radiant barrier on a timber ceiling provides similar reductions: 11.8% (insulation) and 11.2% (radiant barrier).

The use of a radiant barrier on a concrete slab has, again, the best performance, achieving reduction in the number of hours above both limits: 6.2% (for 27°C) and 19.1% (for 29°C) when compared to the use of a concrete slab only. The use of insulation on the concrete slab also presents reductions: 2.2% and 10.5%, respectively, but it has a lesser effect than a radiant barrier. The reflective strategy uses larger air spaces faced with foil on one or both sides. The metal foil, which is usually aluminium, is both a poor emitter and a poor absorber (good reflector) of thermal radiation, reducing significantly the heat flow through the roof in hot climates. As discussed before, adding insulation in these climates may be a disadvantage, as the insulation material would hold the heat inside, which was demonstrated by the results of Zone 1.

Despite of both zones being located in the upper floor, the reductions achieved for Zone 5 due to the use of insulation or radiant barrier are smaller compared to the results for Zone 4. That happens due to the greater solar heat gain coming through the window into Zone 5.

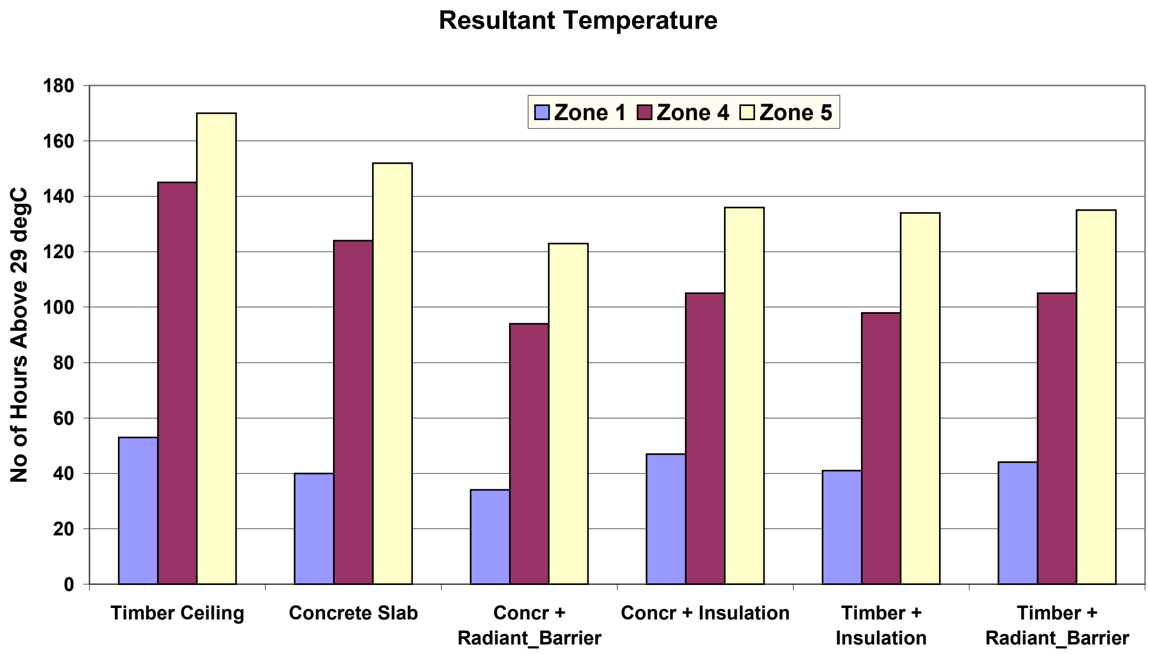


Figure 6.1 – Number of hours that resultant temperatures are above 29°C for different configurations of the roof in the 3 zones studied.

The figure 6.1 shows the frequency of temperatures above 29°C obtained in the three zones, using the different roof configurations. The use of radiant barrier on a concrete slab ceiling provides the smallest number of hours which indoor temperature exceeds 29°C for the three zones, while the use of only a timber ceiling provides the worst thermal performance.

The use of insulation material on a concrete slab also improves the thermal performance for both zones of the upper floor compared to the concrete slab ceiling without any insulation, however, it causes an increasing in the overheating hours for the zone located in the lower level.

Applying insulation or a radiant barrier on a timber ceiling provides similar thermal performances to a concrete slab with insulation. However, when a timber ceiling is used, slightly better thermal response is achieved with insulation instead of a radiant barrier.

6.3.4. Different Levels of Thermal Inertia in the Walls:

Single and Double Brick walls were evaluated and compared to the Base-case, which represents the house with Granite Block walls. See table 6.3 for the characterisation of the different walls.

Table 6.13 – Number of hours above 27°C and 29°C and reductions when different thermal capacities walls are applied – zone 1.

Zone 1	Resultant Temperature			
	Nº of hours above 27°C	Reduction (R) or Increasing (I) (%)	Nº of hours above 29°C	Reduction (R) or Increasing (I) (%)
Granite Block Wall	265	-	40	-
Double Brick Wall	277	4.5 (I)	55	37.5 (I)
Single Brick Wall	181	31.7 (R)	50	25 (I)

The table 6.13 shows that for the base temperature of 29°C there is always an increasing of the overheating hours when Brick walls are considered. The Single Brick wall provided an increasing of 25% of the hours, while the Double Brick wall presented an increasing of 37.5% in the overheating hours. However, for the base temperature of 27°C, the Single Brick wall showed a significant reduction (31.7%) in the overheating hours compared to the Granite Block wall, while the Double Brick wall showed an increasing of 4.5%.

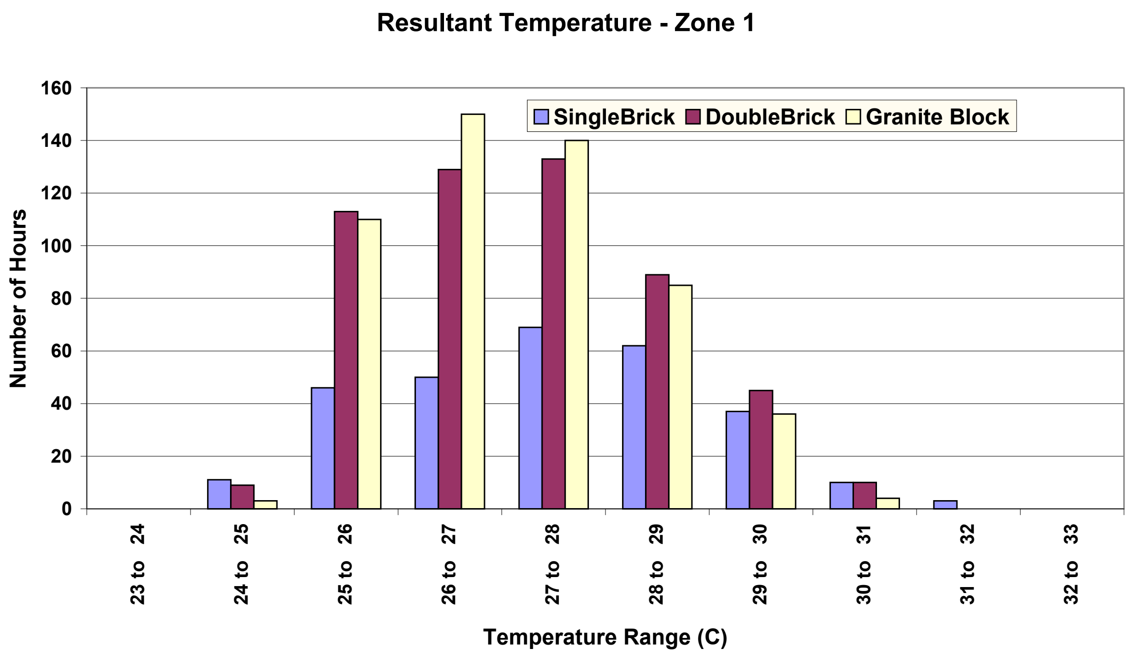


Figure 6.2 – Frequency of resultant temperatures in different ranges for different walls types - zone 1.

The figure 6.2 shows the frequency of different ranges of indoor temperatures for the three studied walls for Zone 1.The use of Single brick wall presented smaller values of frequency in the most of the ranges of temperatures. In the other hand, the use of Granite block wall reduces the number of hours in the higher extremes temperature range, starting from 29°C.

Table 6.14 – Number of hours above 27°C and 29°C and reductions when different thermal capacities walls are applied – zone 5.

Zone 5	**Resultant Temperature**			
	Nº of hours above 27°C	Reduction (R) or Increasing (I) (%)	Nº of hours above 29°C	Reduction (R) or Increasing (I) (%)
Granite Block Wall	368	-	152	-
Double Brick Wall	375	1.9 (I)	187	23 (I)
Single Brick Wall	223	39.4 (R)	146	3.9 (R)

For Zone 5 (table 6.14), the Single Brick wall presented a reduction in the numbers of hours above both limits, compared to the Granite Block wall, although the significant reduction happened for the base temperature of 27°C (39.4%). There is an increasing of the overheating hours due to the use of Double brick wall, corresponding to 1.9% (for 27°C) and 23% (for 29°C).

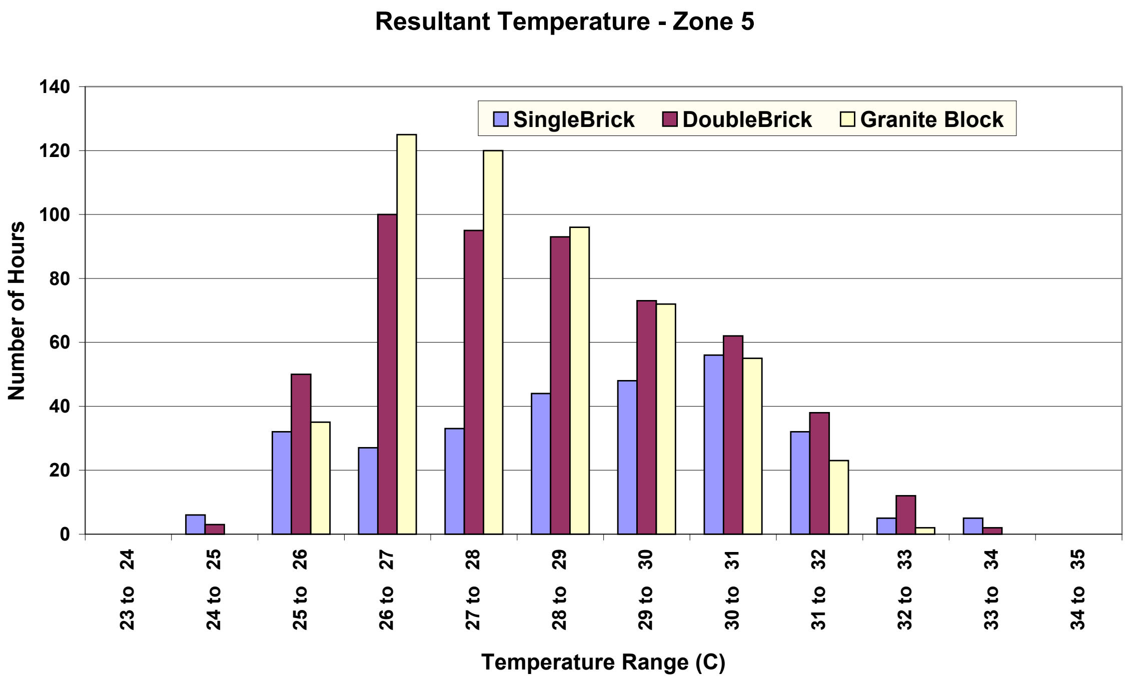


Figure 6.3 – Frequency of resultant temperatures in different ranges for different walls types – zone 5.

The figure 6.3 shows, again, that the use of Granite block wall reduces the number of hours in the higher extremes temperature range, in this case, starting from 30°C, while Single brick walls present smaller frequency of temperature for lower ranges.

6.3.5. Model Improved:

The best combination of all simulations above was implemented to the model, being called **Model Improved**, and new evaluation was carried out considering the three types of walls. The new modifications include: 10 ach forced night ventilation (without daytime ventilation); 20% window to floor ratio[1] and use of an external blind in zone 5; and concrete slab ceiling with radiant barrier under the roof. The results were compared to the Base-case.

The main objective of this analysis was to examine if the higher thermal inertia building achieves better thermal performance when certain measures are taken into account.

Table 6.15 – Number of hours above 27°C and 29°C and reductions for different thermal capacities walls when the model is improved – zone 1.

Zone 1	**Resultant Temperature**			
	Nº of hours above 27°C	Reduction (R) or Increasing (I) (%)	Nº of hours above 29°C	Reduction (R) or Increasing (I) (%)
Granite Block Wall –Base-case	265	-	40	-
Granite Block Wall – Improved	221	16.6 (R)	32	20 (R)
Double Brick Wall – Improved	223	15.8 (R)	47	17.5 (I)
Single Brick Wall – Improved	212	20 (R)	49	22.5 (I)

The table 6.15 gives the results for Zone 1, and shows that for the base temperature of 27°C, there were reductions of the overheating hours in the improved model for the three types of walls. The Single Brick wall – model improved – achieved higher reduction – 20% of the hours against 16.6% of reduction due to the Granite Block wall. In this case, the Double Brick wall had the smallest decreasing in the overheating hours (15.8%).

However, for 29°C, the reduction achieved due to Granite Block wall –model improved – was 20%, while there was an increasing of the overheating hours for both Double and Single Brick wall compared to the Base-case, 17.5% (for Double brick) and 22.5% (for Single brick).

[1] Although 10% of window to floor ratio showed slightly lower value of frequency of temperature above 29°C, the ratio of 20% was chosen as it permits a range of suitable illuminance level in the room, even when associated to an external blind.

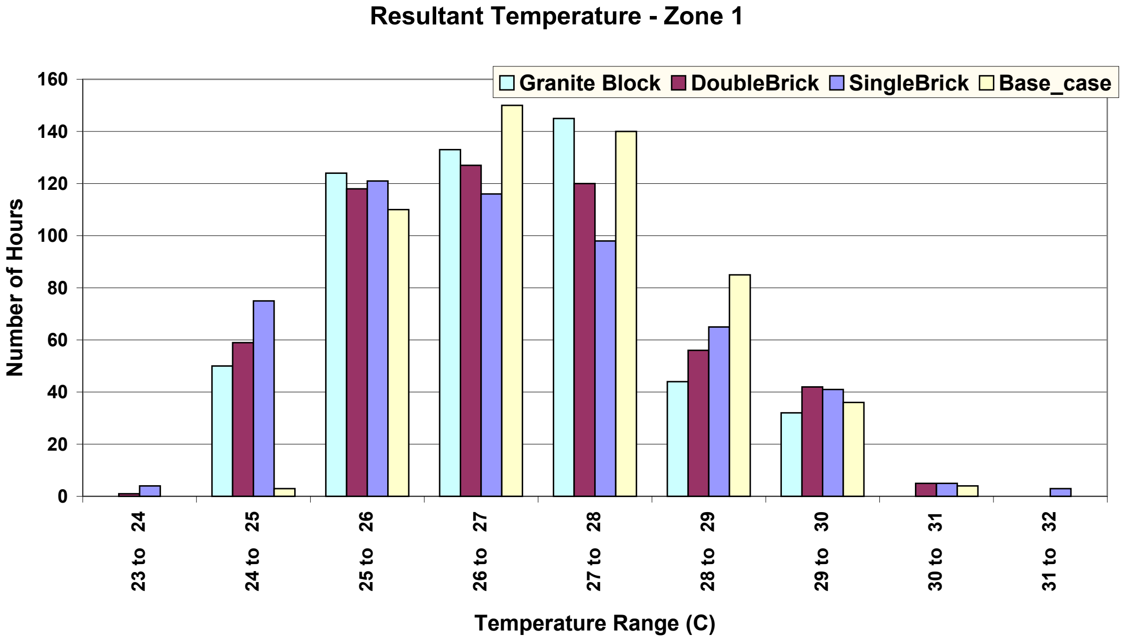


Figure 6.4 – Frequency of resultant temperatures in different ranges for different walls types - zone 1.

The graph of frequency of temperatures (fig.6.4) shows that the Granite Block wall – Model Improved reduces the number of hours in the higher extremes temperature range, in this case starting from 28°C, compared to all other walls and the base-case. Also, the model improved for the three types of wall increases the amount of temperatures in the lower range of 24 to 25°C, which are within the comfort range. In this case, the Double brick wall has better performance than the Single brick for the higher extremes as well.

Table 6.16 – Number of hours above 27°C and 29°C and reductions for different thermal capacities walls when the model is improved – zone 5.

Zone 5	Resultant Temperature			
	Nº of hours above 27°C	Reduction (R) or Increasing (I) (%)	Nº of hours above 29°C	Reduction (R) or Increasing (I) (%)
Granite Block Wall –Base-case	368	-	152	-
Granite Block Wall – Improved	271	26.4 (R)	73	52 (R)
Double Brick Wall – Improved	281	23.6 (R)	99	34.9 (R)
Single Brick Wall – Improved	264	28.3 (R)	100	34.2 (R)

In Zone 5, there were always reductions of the overheating hours for all types of wall with the improved model compared to the Base-case (table 6.16).

For the base temperature of 27°C, the Granite Block wall and the Single Brick achieved similar reductions – 26.4% and 28.3%, respectively. Double brick, in this case, provided a reduction of 23.6% compared to the Base-case.

However, when the limit of 29°C is considered, the reduction of the overheating hours due to Granite Block wall is the highest and significant, achieving 52% of the hours. In this case, the Double and Single Brick walls provided almost the same reduction in the overheating hours – 34.9% and 34.2%, respectively.

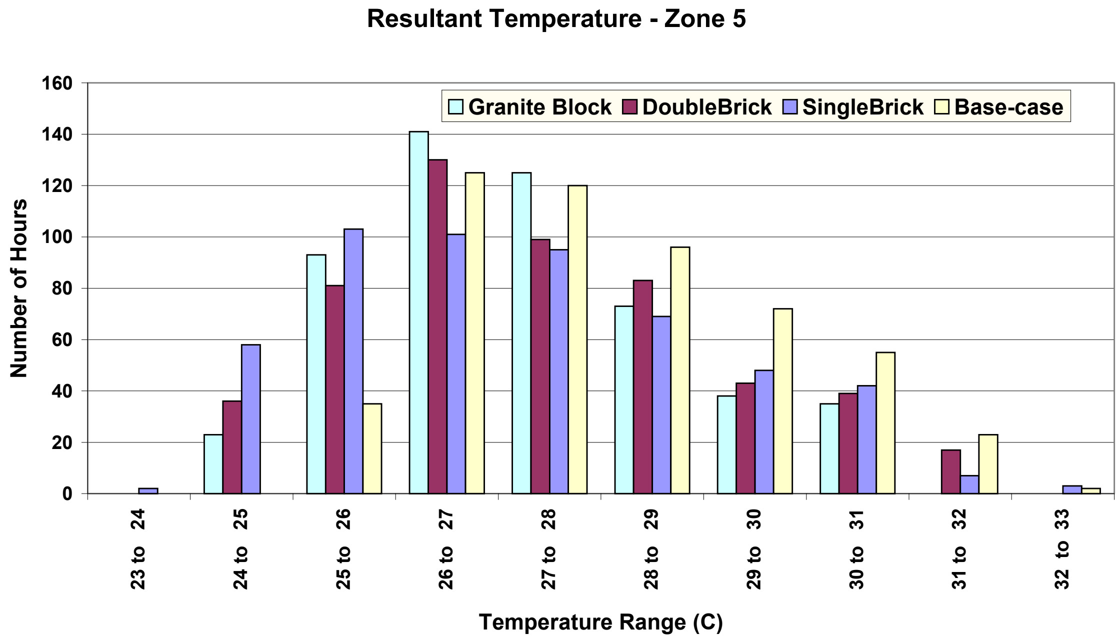


Figure 6.5 – Frequency of resultant temperatures in different ranges for different walls types - zone 5.

Results showed in the figure 6.5 confirmed that the use of Granite Block wall – model improved – provides higher frequency of temperatures in lower ranges when compared to the Base-case (same type of wall) and reduces the number of hours in the peak values compared to all studied walls.

The improvements that were applied in the model had a major effect in Zone 5, where the reduction in the window area and the use of an external Venetian blind were implemented. As the Zone 1 is located in the ground floor and it is well protected from solar gain, the main improvement, which this zone took advantage was the night ventilation.

6.4. Indoor Air Humidity Analysis:

It is well known that thermal comfort implies thermal equilibrium of the body, and hence depends on both air temperature and humidity content. Givoni (1992) points out that studies dealing with the acclimatization to high level of humidity are unknown. In this case, a higher air speed is the most used solution to high humidity. Szokolay (1999) quotes that " *The limits of comfort with respect to humidity conditions is by no means settled. In* *the past these were defined in terms of relative humidity, eg 20% and 80%. Some workers now suggest that the upper limits should be set in terms of wet bulb temperature, eg 18°C WBT for winter and 20°C WBT for summer. In 1974 ASHRAE adopted the limits in terms of vapour pressure: 0.65 and 1.9 kPa (originally 5 mm and 14 mm Hg), which correspond to approximately 4 and 12 g/kg moisture content*."

In addition, cooling depends on evaporation of moisture from the skin. The hypothesis that skin humidity in itself could be a cause of discomfort was tested by Toftum et al (1998), where a model was developed that predicts the percentage of persons dissatisfied due to humid skin as a function of the relative humidity of the skin. The model was used to specify upper limits for indoor air humidity required to avoid discomfort caused by skin humidity. The model predicts that the relative air humidity may be close to 100% without causing much discomfort from humid skin among thermally neutral persons performing sedentary work.

In this study, all the performed analyses have expressed their results in terms of indoor temperature only (see section 6.2 for a discussion of the relationship between comfort and temperature). To illustrate the thermal conditions of the building looking at the level of humidity, the relative humidity was calculated for the Base-case and Model Improved (Granite Block walls) and compared to the external values. The following table gives values of the average of the minimum, the average of the maximum and the mean relative humidity for the period of 22 days.

Table 6.17 – Relative Humidity levels for both zones and outdoors.

RH - **Zone 1**	External	Base-Case	Model Improved
Aver. Min. (%)	65.6	66.3	69
Mean (%)	84.5	79.8	82.2
Aver. Max. (%)	96.7	89.1	94.2
RH – **Zone 5**	External	Base-Case	Model Improved
Aver. Min. (%)	65.6	65.3	69.8
Mean (%)	84.5	76.7	80.8
Aver. Max. (%)	96.7	85.2	92

The Base-case results showed lower levels of relative humidity than the Model Improved for both zones (table 6.17). The possible explanation for this fact is that higher values of relative humidity of the air occur during the night when outdoor temperatures are lower. The air at lower temperature reaches the saturation point at lower moisture content. On the other hand, higher air temperature "holds" higher amount of moisture in the ambient, hence, the saturation point is reached at higher level of humidity. So, as the Base-case has the windows open during daytime and closed night-time, the indoor temperatures are higher than outdoors at night and the level of humidity keeps lower. Also, the average of minimum values of humidity (occurred during daytime) for the Base-case is close to the average minimum of external humidity, as indoor temperatures are close to outdoor temperatures during the day.

For the same reason, the average of the maximum values of relative humidity for the Model Improved keeps close to the outdoors average maximum (occurred at night), because the windows are open during the night to allow nocturnal ventilation. Hence, the mean value of relative humidity is also higher for the Model Improved.

The results showed that the level of internal humidity is still high in terms of thermal comfort. However, it is the combination of high level of humidity with high ambient temperatures that reduces the upper limit of the comfort zone. But it is the minimum relative humidity (in this case, about 65% from table 6.17), which coincides with the maximum temperature.

This thesis is not addressed to resolve humidity problems. In this case, other systems such as higher ventilation or dehumidification should be implemented. Moreover, in this thesis, only the indoor Resultant Temperature is considered as the criterion for the performance evaluation of the thermal inertia, as temperature is considered the most important environmental variable to measure thermal sensation.

6.5. Discussion and Conclusions:

The performance of thermal inertia was evaluated through the parametric studies, where the following parameters were varied: Night Ventilation, Window Size and Shading, Thermal Inertia of the Roof System and Walls.

The results can be summarised as:

The **nocturnal ventilation** by natural means may be moderate and variable. The average of the night airflow varies over the range from 5.0ach to 8.0ach for Zone 1 with 25% and 50% open proportion, respectively. For Zone 5, the average night airflow varies between 8.0ach (with 25% open proportion) and 16.7ach (with 50% open proportion). These average values were calculated based on the hourly results (provided by TAS) for one day in the middle of the studied period as an example. The mechanical ventilation rates assumed in this analysis were 10 ach, 20 ach and 30 ach.

The thermal performance for both zones did not change dramatically when natural ventilation with 50% of open proportion and 10ach mechanical ventilation were applied.

Also, there was no reduction in the number of hours that temperature exceeds 29°C from 10ach rate in Zone 1.

However, in Zone 5, the higher the airflow rate, the higher the reduction of the overheating hours in both limits, although the reduction was more significant above 29°C.

Moreover, for the base temperature of 29°C, reductions achieved for Zone 5 were higher than for Zone 1. It can be interpreted as the higher the heat gains of a room, the higher the cooling effect of night ventilation, as the relative difference between indoor and outdoor temperature during the night would be greater, although higher rates of night ventilation will be needed in this case.

The results of the **window evaluation** confirmed that the influence of glazing surfaces allowing solar radiation coming into the room is more significant upon the Mean Radiant temperature.

The reduction of the size of the window showed small influence on the internal condition, maximum of 7.1% of reduction in the overheating hours for the Resultant temperature. The use of a shading device provided a more significant reduction in the overheating hours, achieving 13.3% due to the use of a *Brise Soleil* and 30.5% due to the use of an External Venetian blind, for the base temperature of 29°C. It means that, providing appropriate shading in a window leads to a better thermal performance in a room than decreasing its size only. Moreover, if a large window is part of the design requirement and can not be avoided by the designer, the use of adequate summer shading should account for the most of the heat gain.

To illustrate this fact, the daily totals of surface solar gains were assessed and the average for the studied period (22 days) was, then, calculated. Solar Gain is provided by TAS as the sum of the surface solar gains for all the surfaces facing into the zone. For the Base-case (without shading), Zone 5 has an average solar gain of 1110 W, while for the Model Improved (with external blind) the solar gain of this zone falls to approximately 300 W.

A Daylight level analysis was performed to verify if there was acceptable daylight level in the room even with the window size reduction and the use of shading. The analysis showed that the window size to floor rate of 20% provided an appropriate level of illuminance for reading purposes and drawing tasks in the studied room, even applying an external blind.

In the **roof system** evaluation, two different levels of thermal inertia were studied: 10cm concrete slab ceiling and timber ceiling, both under clay tile roof. Although they have similar U-values (see table 6.2), when evaluated under periodic conditions these two systems have different thermal performance. Besides this, the thermal performance of the roof system was also tested by adding thermal insulation and radiant barrier.

The use of timber in the upper ceiling provided the worst performance for Zone 1 (ground floor) and Zone 4 (upper floor), increasing the number of overheating hours. On the other hand, for Zone 5, also located in the upper floor, there is a slightly reduction in the number of hours above 27°C due to the use of timber ceiling compared to the concrete slab ceiling. Possibly, the explanation for this result relies in the fact that when a room has a large window to floor rate allowing greater heat gain, a roof with higher transmittance permits the dissipation of the excess heat during the night. However, for the base temperature of 29°C, there is also an increasing of the overheating hours due to the use of a timber ceiling for that zone. Results showed that the thermal characteristics of a timber ceiling are not enough to obstruct or absorb the amount of heat generated by the exposition of the roof to solar radiation and higher temperatures and it needs to be associated to the use of insulation material or a radiant barrier.

The use of an insulation material in the roof improved the performance of the zones located in the upper floor, however it causes an increasing in the number of hours above both limits (27°C and 29°C) for the zone located in the ground floor.

Nevertheless, the use of a higher thermal inertia ceiling (concrete slab) and the application of radiant barrier in the roof system provided the best performance as it achieved higher reduction in the overheating hours for all evaluated zones, compared to the other configurations.

It is shown that radiant barrier works well in hot climates, in which the roof is exposed to solar radiation the most part of the day. The metal foil, which is usually aluminium, is both a poor emitter and a poor absorber of thermal radiation. Lechner (1991), explains that experiments in Florida have shown that the summer heat gain through the roof can be reduced as much as 40 percent using a radiant barrier. In this research, reductions in the overheating hours can vary from 15% to 24% (for the base of 29°C).

The evaluation of the different **walls system** has shown that:

When solar gain is allowed and no night ventilation applied, the Single Brick wall showed better performance for the limit of 27°C for both zones. As the single brick wall has lower thermal capacity and smaller width, the heat accumulated in the structure is quickly dissipated during the night, when temperatures are lower. When a higher limit is considered (29°C), the reduction achieved by the single brick wall was insignificant for Zone 5 and there was an increasing in the overheating hours for Zone 1.

However, when design strategies are applied and solar gain avoided, the best performance was achieved by the higher thermal inertia wall, especially for the base temperature of 29°C (52% of reduction for Zone 5). For the limit of 29°C, Single brick wall is increasing the overheating hours for Zone 1 and reducing the overheating hours for Zone 5, but in a less effective way, compared to the other walls. It means that, if one does not take into consideration some strategies that help the thermal performance of heavyweight buildings (e.g. shading, night ventilation and radiant barrier in the roof), it does not worth to use higher thermal inertia wall in the building.

Also, results illustrate that higher thermal inertia wall is very effective for reducing peak values of temperatures. It is shown that single brick wall works well until the limit of 27°C. Nevertheless, for higher temperatures, higher thermal inertia wall achieves best performance, especially when solar gain is avoided and night ventilation applied.

In the next chapter, further evaluations are performed through correlation analysis.

Chapter 7. Correlation Analysis:

7.1. Introduction:

The following investigation examines some characteristics aiming to find if there is a tendency line representing a relation between the data. If a correlation exists, the corresponding R^2 can be interpreted as a proportion of the variance of the parameter in y which can be attributed to the variance of the parameter in x. The results allow establishing design guidelines for the application of thermal inertia.

The investigated parameters are:

1) The influence of the window size on the internal conditions through the analyses of **mass area to opening area ratio** and **window to floor ratio**.

2) The effect of **night ventilation** on peak indoor temperature and the relationship with the outdoor temperature daily variation;

3) The influence of increasing **surface area of thermal mass** that is exposed to heat exchange on the internal conditions;

4) The consequence of **daytime ventilation** on internal conditions when thermal inertia and night ventilation are applied.

The analyses were carried out for the same zones that were evaluated in the parametric studies. The two zones were chosen because they represent two extreme conditions of the model and the results illustrate the differences on the performance of thermal inertia in these two different scenarios. Zone 1 is well protected from solar radiation, located in the ground floor, it has large volume and small opening, whilst Zone 5 is located in the upper floor (with the influence of the roof thermal capacity), it has small volume and a large window to floor rate (see section 6.1, table 6.1). The model represents the case-study zones as built regarding building materials and dimensions. The internal conditions also correspond to the normal occupancy of the building. The variations were implemented according to the characteristics that were been studied.

The results were evaluated through frequency of hours that zone temperatures exceeds 29°C. The aim was to look for correlation between the studied parameters and the variation on internal conditions. In the night ventilation analysis, the relationship between the decrease on indoor peak temperature and the outdoor temperature daily variation, when night ventilation is applied, was examined.

The main objective of the present evaluations was to understand the extent to which the parameters involved collaborate in the increasing of thermal inertia performance and, from the results, to establish design guidelines for the application of thermal inertia.

All the equations representing the correlation studies are presented in Appendix A4.

7.2. Window Size:

The following analyses were carried out only in Zone 5, which showed worst thermal performance due to a large window to floor rate (32%), probably the source for most of the heat gain of the room.

7.2.1. Mass to Opening Ratio: the ratio of the total area of internal surfaces to opening area.

The present analysis has investigated the following assumption: *if increasing the surface area of the thermal mass while keeping constant the large window to floor rate, will the additional mass absorb the surplus heat gain coming in through the window?*

To accomplish this evaluation, the original window area was kept constant, while additional surface area was considered by placing internal elements in the room with both surfaces facing the interior. The volume of the room was kept constant. The internal area of mass was been increased in a rate of 2 m^2, each one representing a different mass to opening area ratio. The ratio of 18 m^2 thermal mass / m^2 window corresponds to the original room. A smaller ratio from the original was also considered to verify the behaviour of the data with less mass than the base-case.

The graph 7.1 shows the analysis considering the model without any design measure to improve the thermal performance: no shading in the window (clear glass), roof without radiant barrier and only daytime ventilation by natural means.

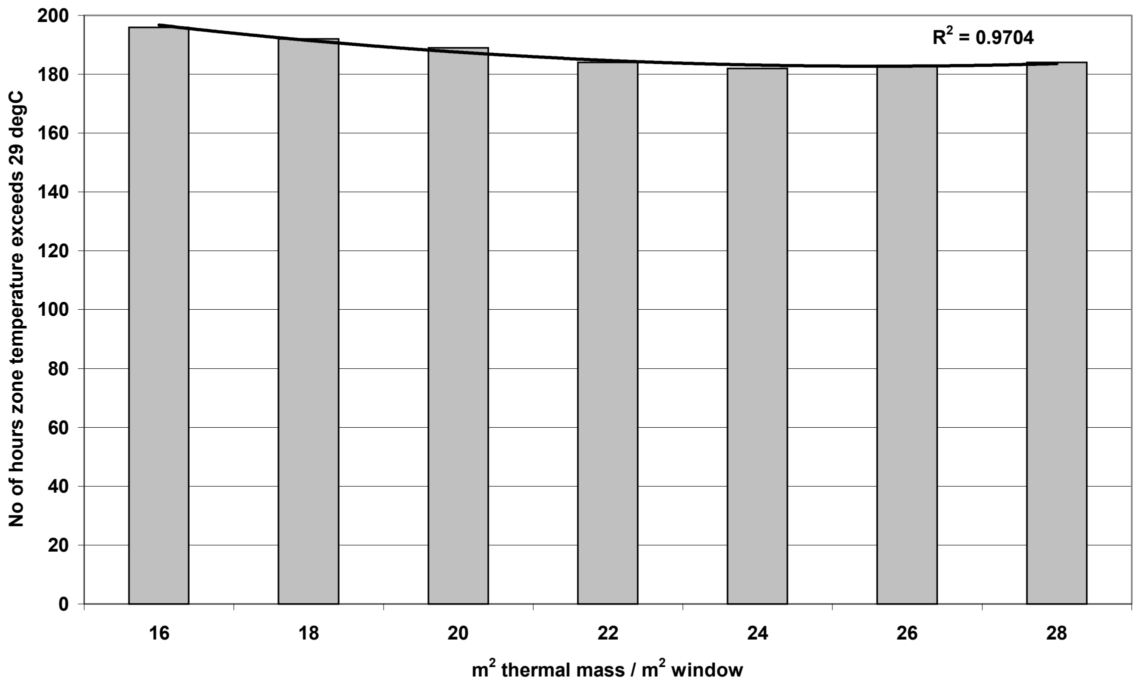


Figure 7.1: Model conditions: daytime ventilation; no shading; without radiant barrier in the roof.

A correlation was found, which is best represented by a polynomial equation (second degree). The correspondent R^2 value between the data is 0.97. The results illustrated in figure 7.1 showed that, in this case, 24 m^2 thermal mass / m^2 window was the amount of area of mass that provided best thermal performance. From that value, increasing the mass to opening area ratio will slightly augment the numbers of hours above 29°C. As in this case, the volume of room is kept constant, probably, higher area of mass will be absorbing the surplus heat, but also higher surface will be releasing heat to the ambient. In addition, the surplus heat is not been dissipated by night ventilation. Further evaluation would be necessary, with different room's volume to establish if there is a limit of area of mass / window area for each situation when higher heat gain is allowed into the room.

A second analysis was carried out, where the best combination of the design measures defined by the results of parametric studies (see section 6.3.5) was applied to the model. They are: a fixed rate of 10 ach of mechanical night ventilation, shading in the window (0.07 solar transmittance) and radiant barrier in the roof. The original window area was kept constant, while the internal area of mass was been increased, same way as before.

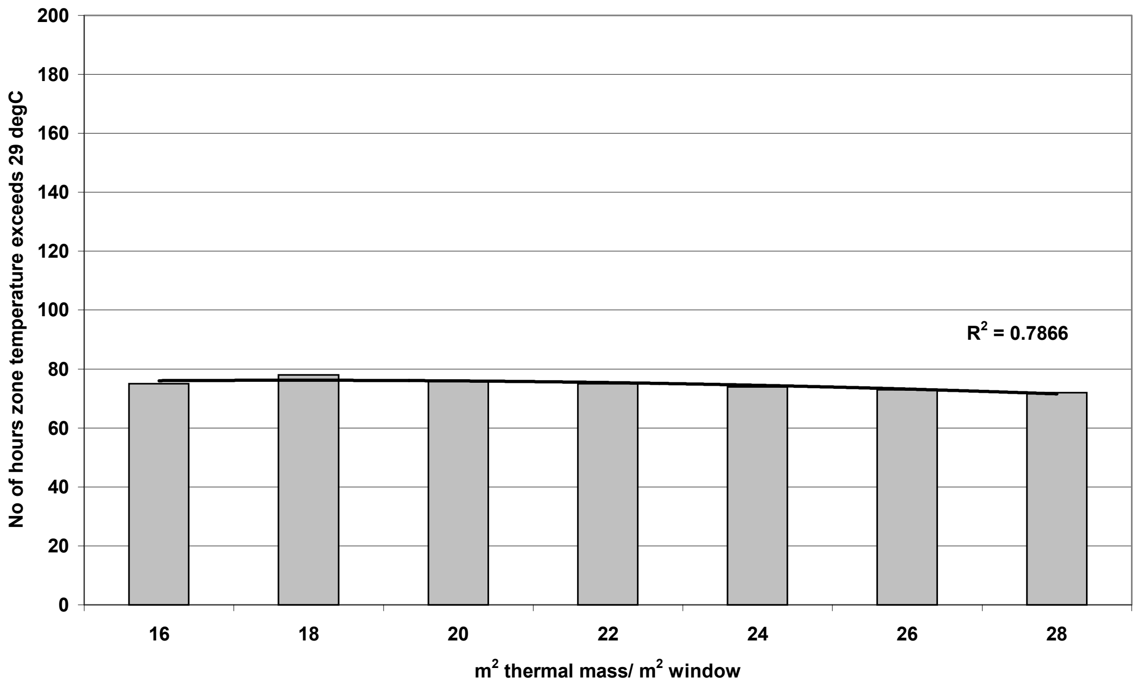


Figure 7.2: Model conditions: night ventilation; shading; radiant barrier in the roof.

As seen in the figure 7.2, the correlation between the data decreases and it is represented by a polynomial equation with R^2 of 0.78. The results demonstrated small variations: between 78 and 72 number of hours that room temperature exceeds 29°C. From 18 m^2 thermal mass /m^2 window, there was a constant, but not significant decrease in the overheating hours as more mass was added:

The main conclusion from analysis above is that when design measures such as shading, night ventilation and radiant barrier in the roof are implemented, the correlation between the data decreases. Also, the improvement is noticeable as the overheating hours decreased when compared to the previous graph. However, increasing the area of mass has not significant effect on the internal conditions, once the right combination of design measures are taken to improve the thermal performance.

The question is, now, how much each of these parameters (night ventilation, shading and radiant barrier) can contribute for the thermal performance, when a large window to floor rate is used in the room and the area of mass is increased.

A third evaluation is carried out, this time the design measures are implemented one by one.

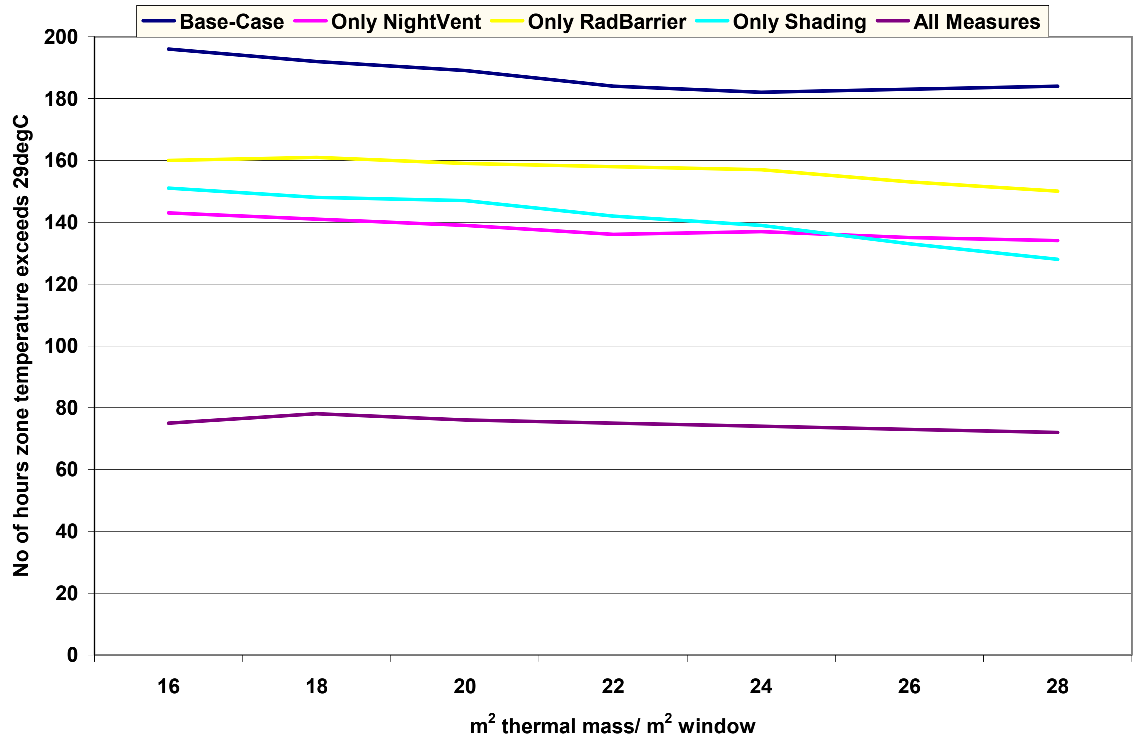


Figure 7.3: The interventions are added one by one.

Night ventilation is the more important design measure when the area of exposed thermal mass increases. It reinforces that higher amount of area of mass is not enough to improve the thermal condition and that the excess of heat gain must be dissipated by night cooling ventilation.

Shading is the second important strategy and becomes the most significant on decreasing the overheating hours from about $24m^2$ thermal mass/m^2 window, as night ventilation is not sufficient to dissipate the excess of heat. As seen in figure 7.1, from that point the overheating hours slightly increases when any design measure is adopted.

7.2.2. Window to Floor Ratio: the ratio of the area of window to the floor area.

The window size topic has already been examined in the section 6.3.2. As seen from the results, the size of the window has influence on the internal condition, although a shading device provides a more significant reduction on the overheating hours.

In this section, the correlation between window to floor rate and the internal conditions was evaluated. The aim was to answer the following questions: *If a large glazing area is a design requirement, which measures should be considered to avoid overheating and which one is more efficient? It is still possible to have a large glazing area without compromising the performance of the thermal inertia?*

The first analysis shows the results for the original model (without considering any design measure to help the performance of thermal inertia). The ratio of the glazed opening to floor area is increased gradually up to 50%, in a rate of 10%. The starting point is zero, which represents no window in the room. The original room has a window to floor ratio of approximately 32%.

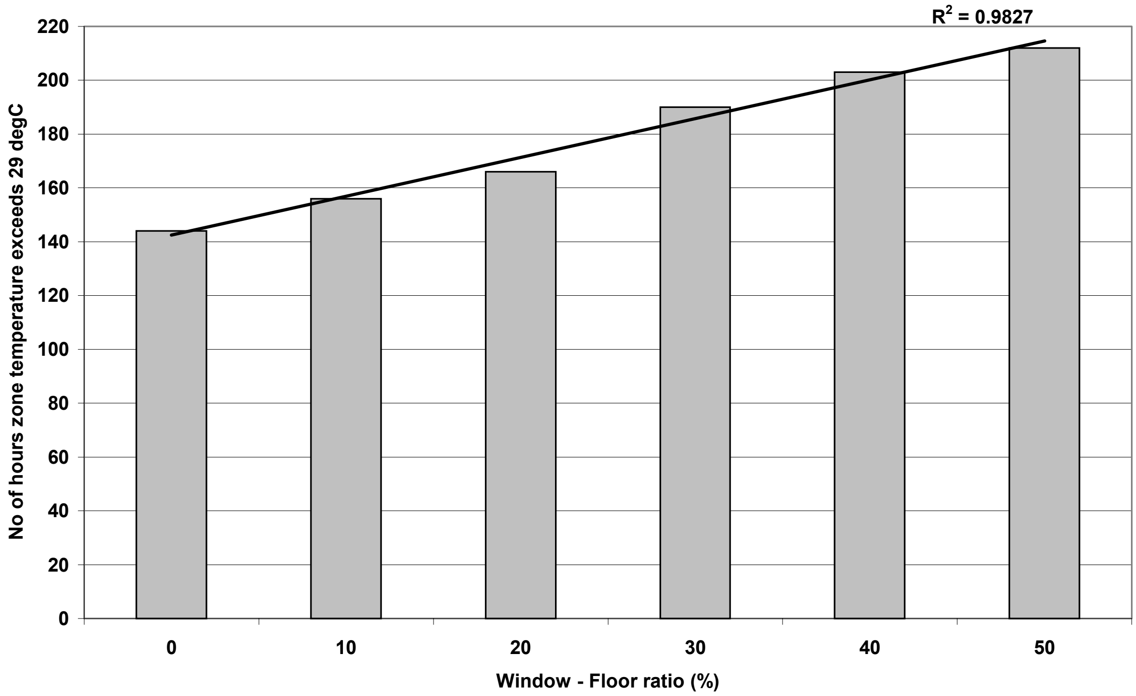


Figure 7.4: Model conditions: daytime ventilation (natural); no shading; without radiant barrier in the roof.

As expected, if any design measure is taken, the increment of the glazing to floor ratio will increase the numbers of hours above 29°C due the solar gain through the window (fig. 7.4). The maximum studied value of window to floor ratio (50%) provides 212 hours above the limit, which represents 40% of the total hours of the studied period.

A linear correlation was found, with the correspondent R^2 value of approximately 0.98.

A second analysis was carried out, in which, again, the design measures (defined from parametric studies) were implemented to the model: a fixed rate of 10 ach of mechanical night ventilation, shading in the window (0.07 solar transmittance) and radiant barrier in the roof. The ratio of the glazed opening to floor area is increased same as before.

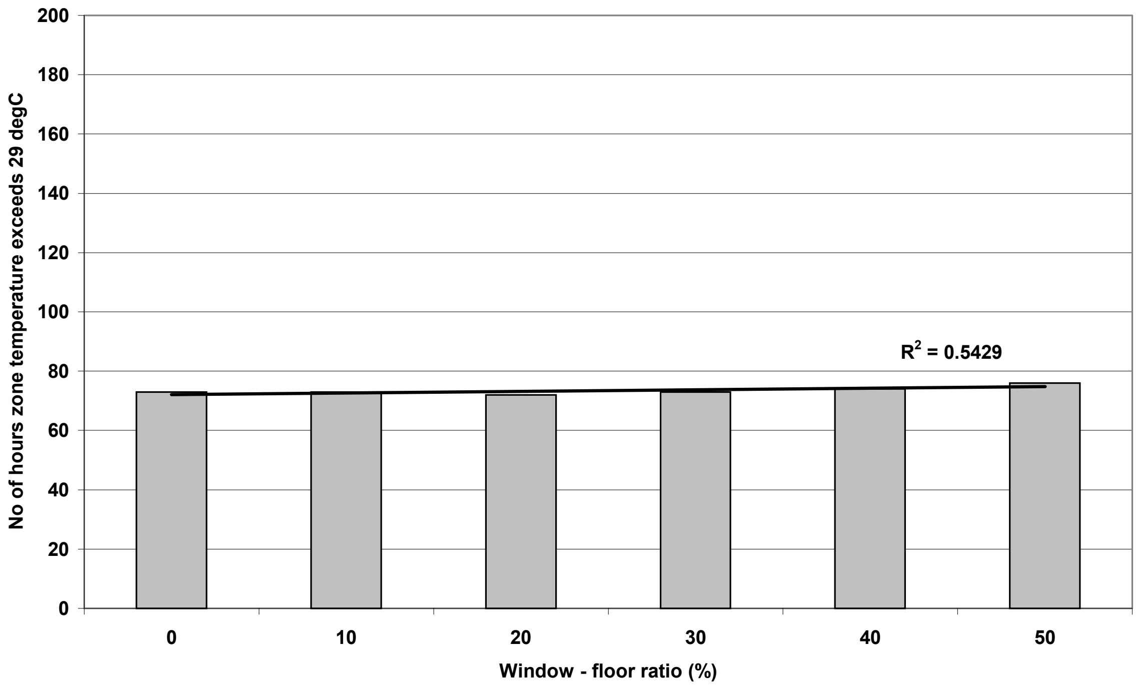


Figure 7.5: Model conditions: night ventilation; shading; radiant barrier in the roof.

This evaluation also demonstrated that, when design measures such as shading, night ventilation and radiant barrier in the roof were used, enlarging the glazing area did not provide significant increasing in the number of hours above 29°C. The number of hours that zone temperature exceeds 29°C were kept between 72 and 76 hours. The correlation found was small, with R^2 of 0.54.

The third evaluation is carried out to find out how much each design measure had contributed to the improvement in the thermal performance, when a large glazed area is a design requirement.

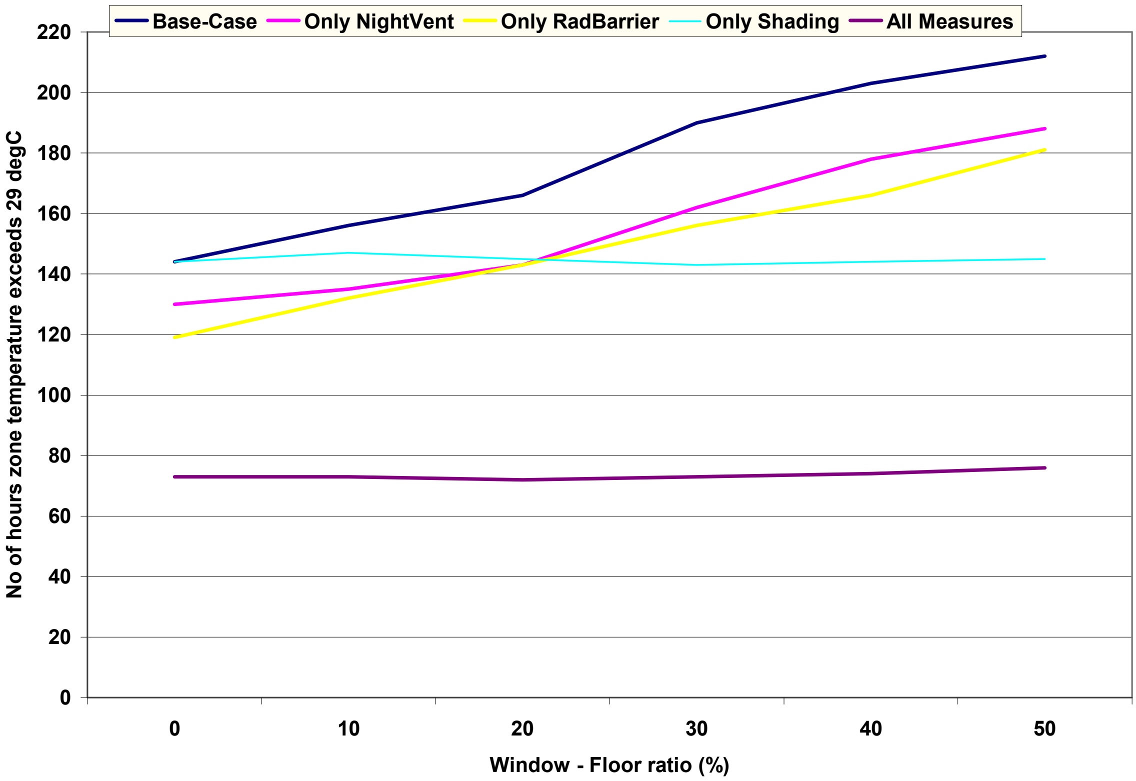


Figure 7.6: The interventions are added one by one.

Shading has not the most significant effect on internal conditions in values of window to floor ratio up to 20%. From that proportion, this design strategy becomes very important on improving the thermal performance of the room.

Also, despite of improving the thermal performance, the use of night ventilation and radiant barrier strategies are not enough to improve the internal conditions as the overheating hours increases with higher proportion of window to floor rate. It is demonstrated by the inclination of the lines representing these strategies. Shading, on the other hand, kept a constant thermal performance, demonstrated by the almost horizontal line representing the results.

7.3. The influence of night ventilation on decreasing the indoor peak temperature:

As seen in chapter 6 (section 6.3.1), night ventilation has an important role in improving the indoor thermal condition. Here, the aim is looking for correlation between the indoor peak temperature reduction and the outdoor daily range of temperature (or temperature swing outside), when night ventilation is applied. Also, to find out how much the performance of thermal inertia is dependent on the outdoor daily range of temperature.

To accomplish these analyses, night ventilation is applied to the original model.

The first analysis comprehends only the effect of night ventilation. The aim was to compare nocturnal ventilation (*natural* -provided only by natural means, and *mechanical* -

rate of 10 ach) with the base-case, which is natural ventilated during daytime (by open windows) and has no night ventilation. The analyses were performed for both case-study zones of the model.

The following graphs show the correlation results for both zones. The x-axis contains the temperature swing outside (TmaxOut – TminOut) for the period studied, while the y-axis includes the reduction of indoor maximum temperature below the outdoor maximum (TmaxOut – TmaxIn).

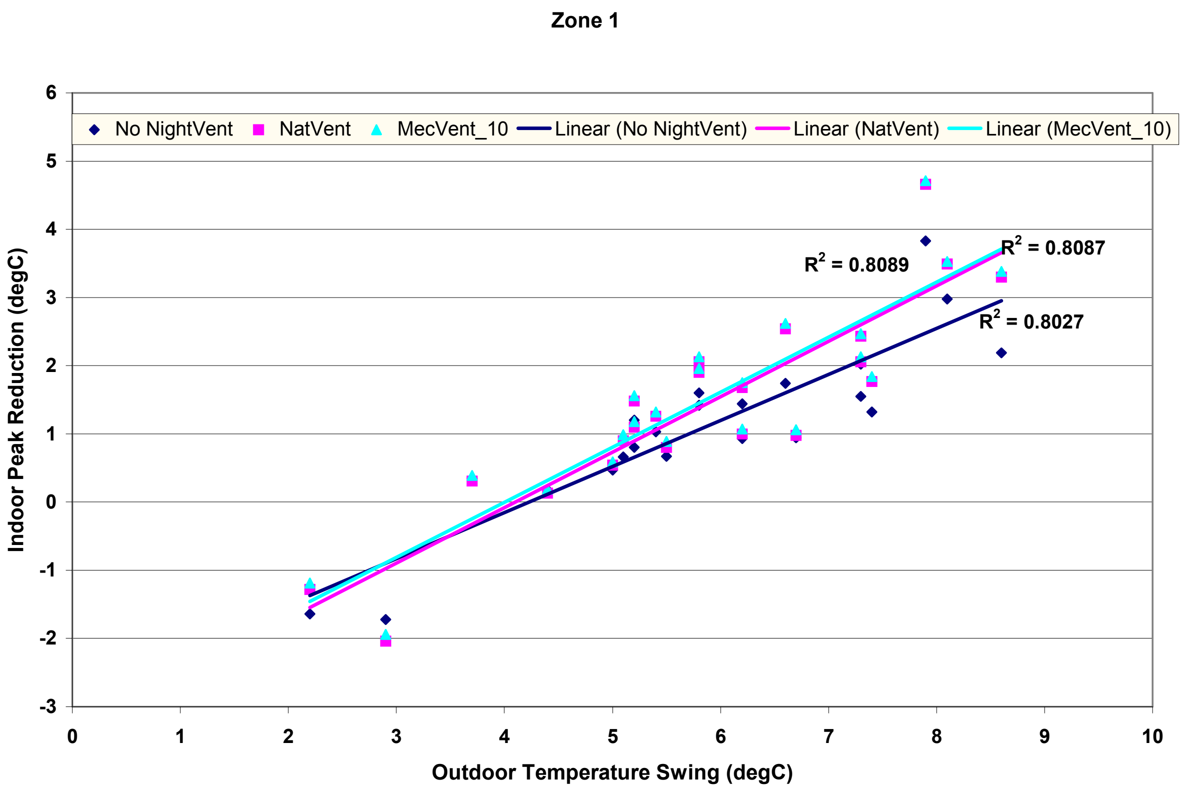


Figure 7.7 – Correlation between indoor peak reduction and outdoor daily range of temperature – Zone 1.

Results for Zone 1 presented good linear correlation between the peak reduction and daily range of temperature for all cases (fig. 7.7). The R^2 values are very similar, resulting 0.8 for the base-case (no night ventilation) and approximately 0.81 for both night-ventilated cases. The distribution of the data of night-ventilated cases was close to that of the base-case, because zone 1 is well protected from solar gain, thus the use of night ventilation provides a no significant improvement on the thermal performance. However, the higher inclination of the lines means that using night ventilation, higher reductions on the peak indoor temperature are achieved. It can be seen that, applying night ventilation, reductions of almost 5°C are likely to be achieved for this zone.

The main observation that needs to be pointed out is that the higher the outdoor temperature swing, the higher the peak reduction on the indoor temperature below the outdoor maximum. Also, it can be observed that when the external temperature swing is very small, there is an increasing in the indoor maximum temperature above the outdoor maximum, resulting the negatives values in the graph. From this result it can be concluded that night ventilation has a major effect on reducing the indoor peak from about 6°C of outdoor temperature swing.

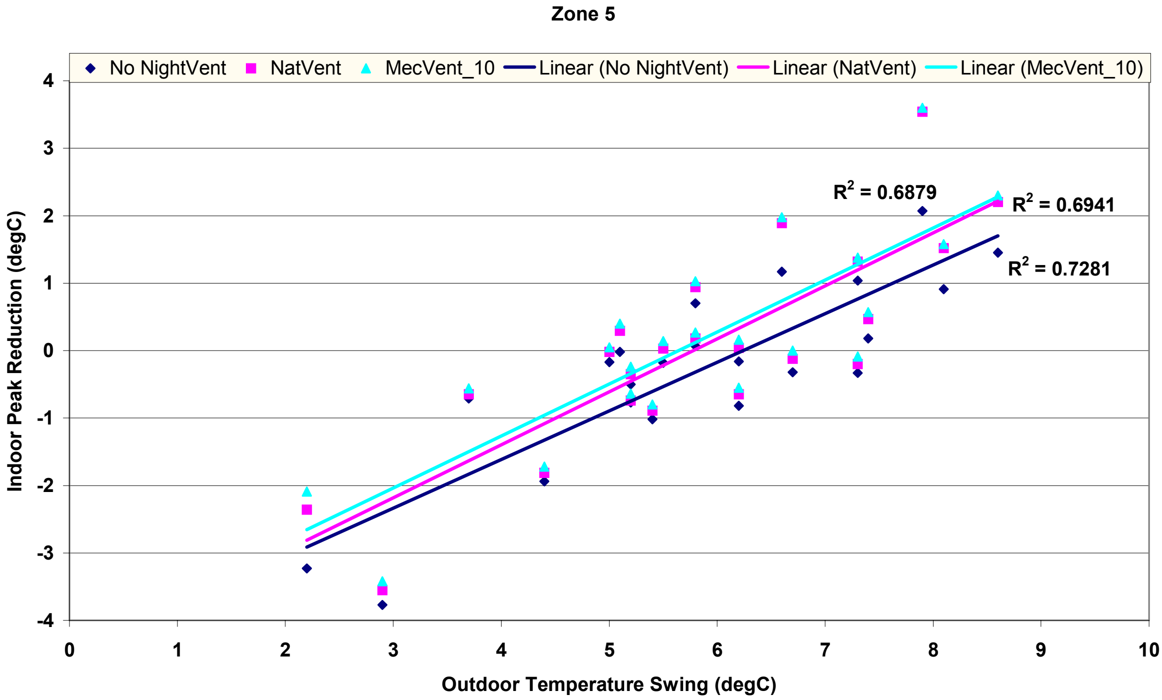


Figure 7.8 – Correlation between indoor peak reduction and outdoor daily range of temperature – zone 5.

Figure 7.8 shows that, in zone 5, slightly higher correlation was found for the base-case (no night ventilation) with correspondent R^2 value about 0.73, while R^2 was approximately 0.69 for both night-ventilated cases.

Although the tendency is the same as for zone 1 (higher the outdoor temperature swing, higher the peak reduction), the correlation between these two variables was smaller in this zone for all cases, demonstrated by the R^2 values obtained. Again, the influence of the large window in the thermal performance of this room is noticeable. In this case, only night ventilation strategy may not improve the zone's thermal performance and other measures needs to be taken.

Moreover, although higher peak reductions were achieved with the use of night ventilation, they were not so significant. Maximum indoor peak reductions were about 3.5 °C below the outdoor maximum temperature (compared to almost 5°C obtained in zone 1).

In addition, when the outdoor temperature swings are smaller, the indoor peak temperature for zone 5 can increase about almost 4 °C above the outdoor maximum (zone 1 showed an increase of 2 °C above the peak outside in this case).

In the next evaluation, the aim was to compare walls of different thermal inertia, when night ventilation is provided (in this case, only a fixed rate of 10 ach). Shading in the window of zone 5 and radiant barrier in the roof were also applied to the model. Double brick and single brick walls were compared to the granite block wall. The graphs show the results for both studied zones.

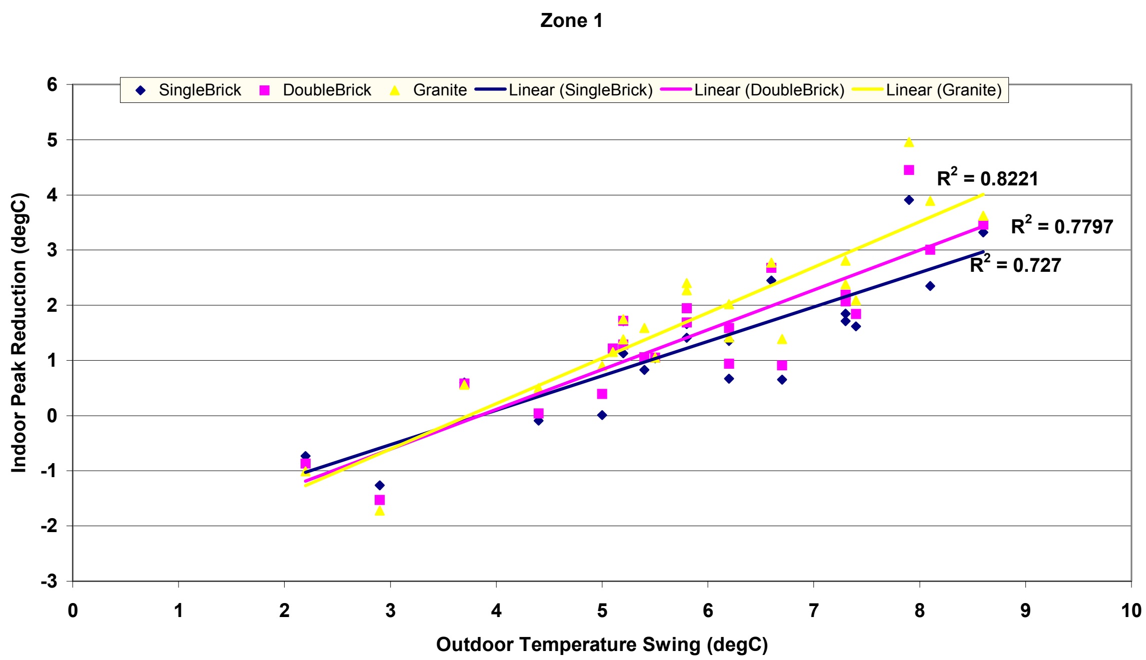


Figure 7.9 – Correlation between indoor peak reduction and outdoor daily range of temperature, model with night ventilation and different walls – zone 1.

For zone 1, the tendency lines, observed in figure 7.9, shows that there was a good linear correlation for all cases, although the model with granite block walls presented higher correlation with R^2 of 0.82. The correspondent R^2 values for brick walls were 0.78 for double brick and 0.73 for single brick.

The main conclusion from this analysis is that the higher the thermal inertia of the model, better the correlation between indoor peak reduction and outdoor daily range of temperature.

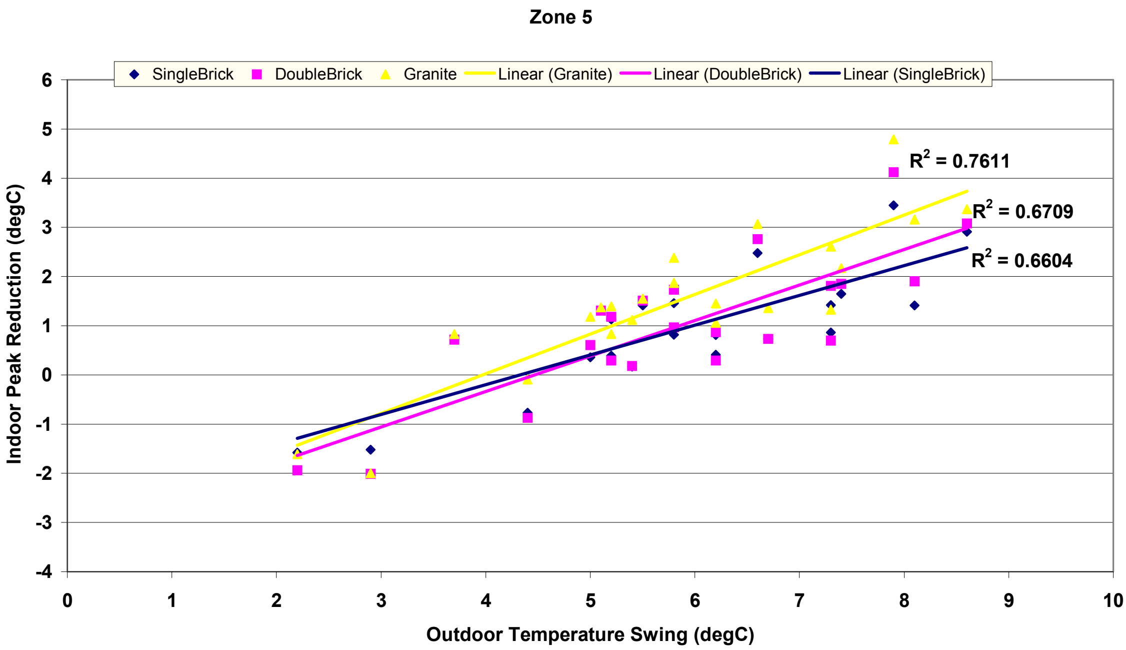


Figure 7.10 – Correlation between indoor peak reduction and outdoor daily range of temperature, model with night ventilation and different walls – zone 5.

Figure 7.10 shows the results for zone 5. Again, higher correlation was found for the model with granite block walls, with R^2 of 0.76. The correspondent R^2 values for brick walls were 0.67 for double brick and 0.66 for single brick. The correlation between indoor peak reduction and outdoor daily range of temperature for zone 5 is good, although still smaller than for zone 1.

Once more, higher the thermal inertia of the walls, higher the correlation between the reduction of the peak temperature inside and the outdoor temperature swing.

The use of shading in the window and radiant barrier in the roof, integrated with night ventilation provided better correlation between the data for the model with higher thermal inertia in this zone, as R^2 value went up from 0.69 (see graph 7.8) to 0.76 (represented here by the yellow line). Also, one can observe that the addition of the design measures to the higher thermal inertia walls model provided higher values of indoor peak reductions reaching almost 5°C below the outdoor maximum temperature when outdoor temperature swings are higher (compared to 2°C obtained with the model night ventilated only). Finally, when the outdoor temperature swings are small, the indoor peak temperature for zone 5 can increase, now, less than 2°C above the outdoor maximum (same as zone 1).

7.4. Exposed Surface of Thermal Inertia:

According to the literature review, the greater the exposed surface of thermal inertia, better the thermal performance of a room, as it is the exposure of internal surfaces to the air that guarantees heat dissipation. Also, lightweight finishing materials work as insulation, so covered surfaces should not be considered for thermal storage purposes.

This analysis was carried out to find out the relationship of the exposed area of thermal mass on the indoor temperatures.

To accomplish this analysis, part of the internal surfaces of the room were covered using lightweight finishing material, such as carpet on the floor, cork board on the walls (to simulate walls with pictures, tapestries, etc) and acoustic panels on the ceiling. Different proportions were evaluated. The proportions were calculated according to the covered area, as a percentage of the total internal surface area. Zero percent of covered surface means all surfaces of thermal mass are exposed and corresponds to the original model, while one hundred percent of covered surface means all internal surfaces are assigned with lightweight finishing material.

First, analyses in the original model were carried out, e.g. without any design measure to improve the thermal performance: no shading, roof without radiant barrier and daytime ventilation by natural means (no night ventilation). The following graphs illustrate the results for both studied zones. They show the correlation between the percentage of covered surface and numbers of hours that zone temperatures are above 29°C.

The results for zone 1 (fig. 7.11) show that there is no tendency line in this case and the distribution of the data is more depending on the covering location than on the increasing of the covered proportion. It is demonstrated by a poor linear relation with R^2 value of 0.34. The variation in the overheating hours does not depend on the amount of the covered surfaces, however the model with all surfaces exposed showed better performance than the most of the covered surfaces proportions. The exception was the percentage of 40%, correspondent in this case to have all internal surfaces of the walls covered by lightweight finishing material, which worked as an insulation. A possible explanation for this fact is that, as this zone is well protected from solar radiation and it is located in the ground floor (no heat coming from the roof), the lightweight material added to the walls has improved the thermal performance of the room. However, one needs to take into account that once the room has its internal gains increased, the surface of the walls will not be able to absorb the excess of the heat due to the insulation property of the lightweight finishing material.

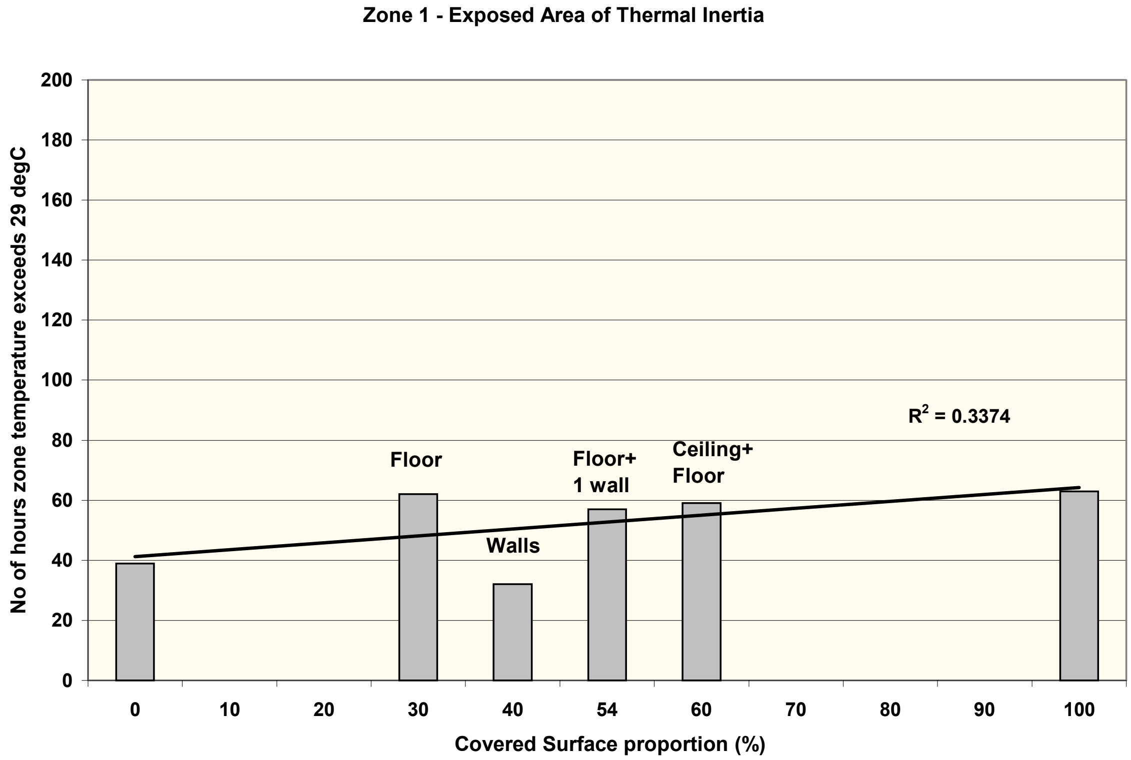


Figure 7.11: Model conditions: daytime ventilation; no shading; without radiant barrier in the roof – Zone 1.

Moreover, adding carpet to the floor seems to have worsened the internal conditions as demonstrated by the results that correspond to proportions of covered surfaces including the floor.

Figure 7.12 shows that a good correlation was found between the variables in zone 5, which is represented by a linear regression with the correspondent R^2 value of approximately 0.81. Here, the greater the covered area, higher the number of hours that room temperature exceeds 29°C. There was again an exception, which, in this case, corresponds to the covered area of the floor and ceiling (44% proportion). The performance of this model was practically the same as the model without any lightweight finishing material. A possible explanation for this fact is that adding a false ceiling to the original concrete slab has increased the property of insulation of the roof, improving the thermal performance of this zone (located in the upper floor, thus subject to the heat coming through the roof).

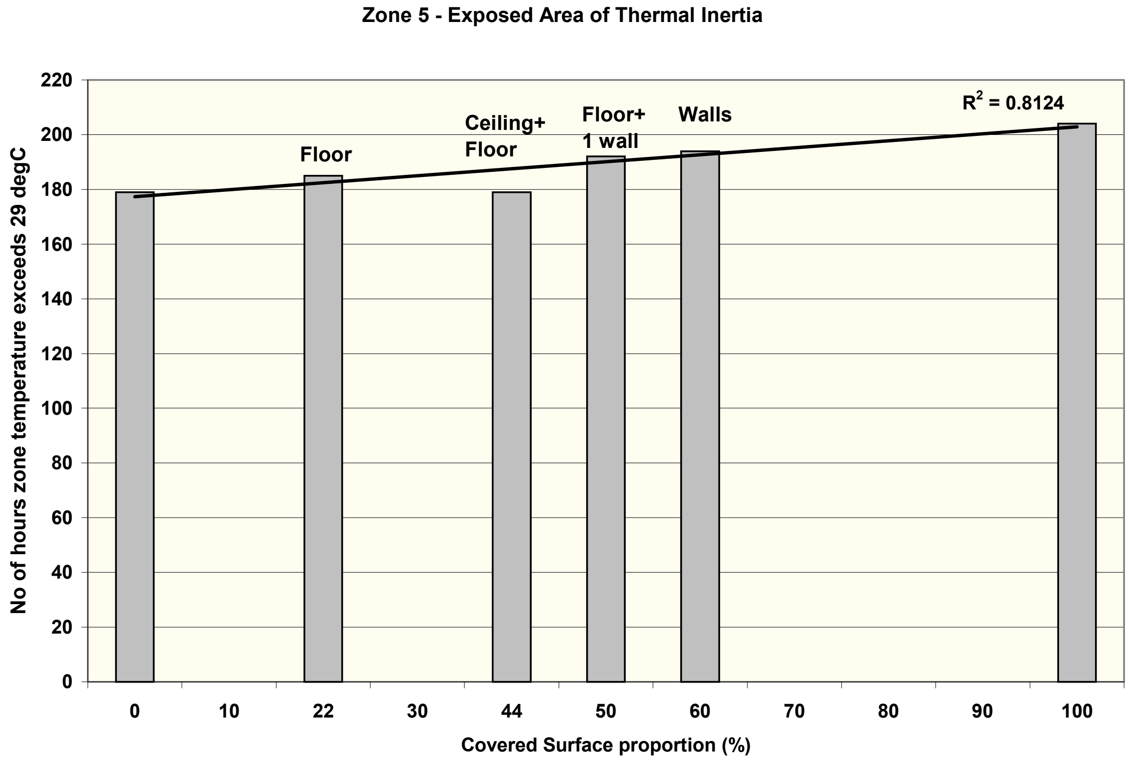


Figure 7.12: Model conditions: daytime ventilation; no shading; without radiant barrier in the roof – Zone 5.

As this room has a large window allowing solar gain, the main conclusion from results above was that exposed surface of thermal mass seems to have more influence where solar gains are greater due to large openings.

To confirm this hypothesis, a second analysis was carried out, where design measures such as shading in the window, a fixed rate of 10 ach of night ventilation and radiant barrier in the roof are applied to the model to improve the thermal performance.

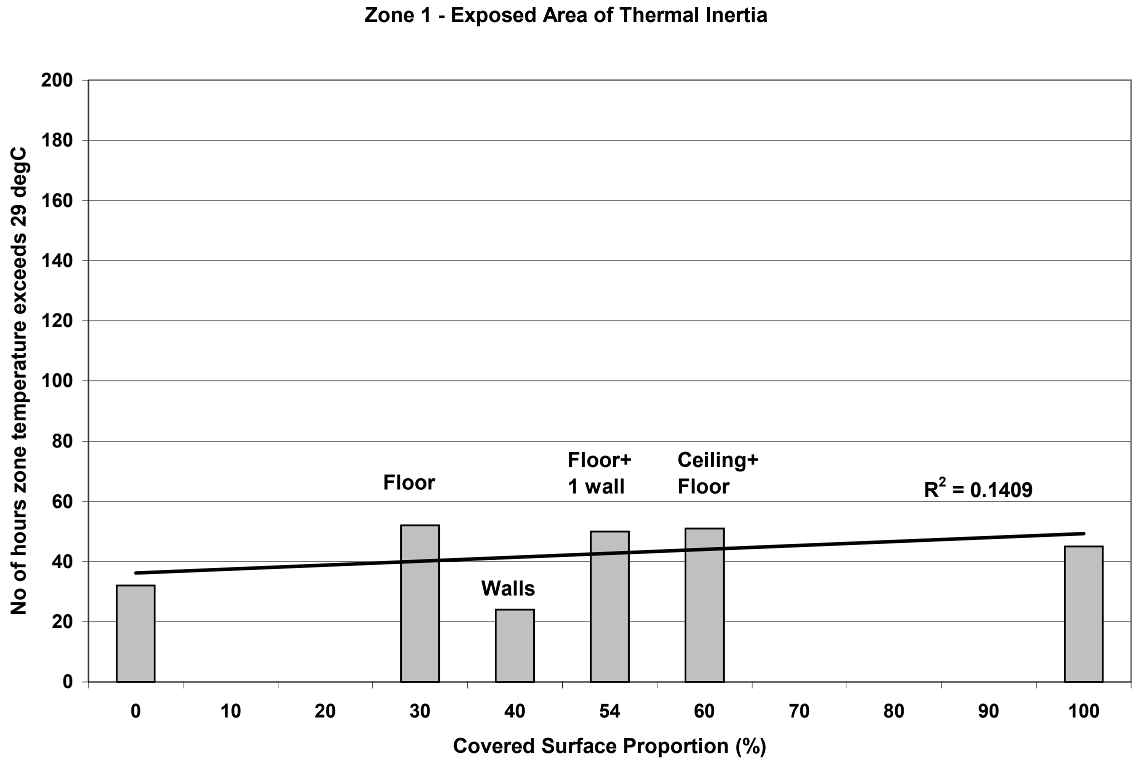


Figure 7.13: Model conditions: night ventilation; shading; radiant barrier in the roof - Zone 1.

The internal condition of zone 1 still did not present correlation with covered surface proportion as given in figure 7.13. There is no tendency line representing the data and the linear relation is poor with R^2 value of 0.14. The distribution of the results were similar as before (see figure 7.11), but in this case the thermal performance was improved with the application of the design measures, as the number of hours above 29°C decreased.

The results for zone 5 (figure 7.14) showed, again, that when design measures such as shading, night ventilation and radiant barrier in the roof were taken, the correlation between the data decreased and, in this case, became insignificant with R^2 of 0.02.

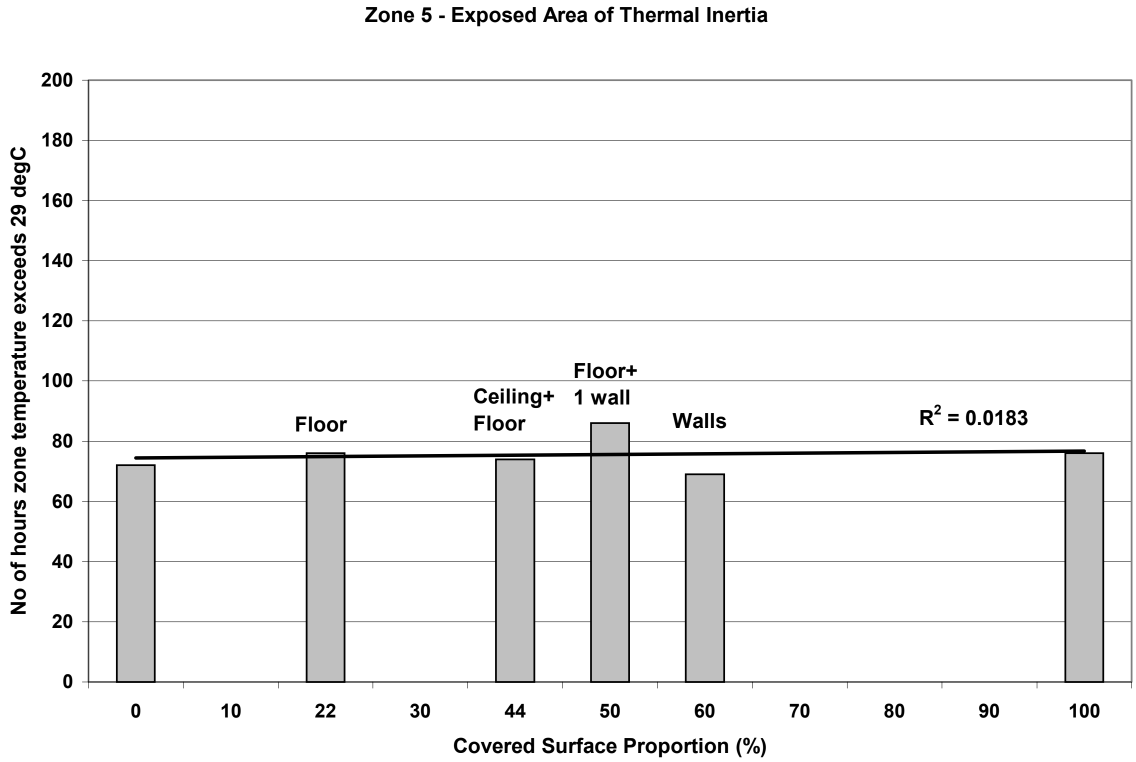


Figure 7.14: Model conditions: night ventilation; shading; radiant barrier in the roof – Zone 5.

Results reinforce that the impact of the design measures was more significant in zone 5. Zone 1 has presented very small correlation already in the analysis without the application of design strategies to improve the thermal performance. That happens because that zone is well protected from solar gains. The zone located in the upper floor, in the other hand, has thermal problems especially because of a large window to floor rate, which is the main source of the heat gain into this room.

When the design measures are applied, the results for zone 5 assume the same characteristics as for zone 1, e.g., adding carpet to the floor has worsened the internal conditions and covering the internal surfaces of the walls has improved the thermal performance even more than having all internal surfaces exposed.

The main conclusion from these analyses is that when solar gain is avoided, the increase of the covered surface proportion had small influence on the internal conditions, which was demonstrated by the small or insignificant correlation result. Therefore, the use of lightweight finishing material covering part of the thermal mass had worsened the thermal performance. The best performance was achieved when all internal surfaces are exposed to heat exchange. The exception happens when the walls were covered because the lightweight finishing worked as insulation. However, this condition may change when internal gains are greater as the covered surfaces will not be able to absorb the excess of heat.

For summer condition, if lightweight finishing can not be avoided, shading is the critical strategy to be considered.

7.5. The influence of daytime opening:

The night ventilation strategy is usually associated with the recommendation of keeping the building closed during the hot daytime hours to avoid bringing the warm outdoor air into the room. Therefore, inhabitants of warm-humid climates have preference for open-air living and this habit can compromise the performance of a building where thermal inertia and night ventilation are properly integrated.

The next analyses assess the influence of daytime ventilation on the performance of thermal inertia when night ventilation is applied to answer the question: *How much does daytime ventilation reduce the performance of thermal inertia?*

The first two graphs show the correlation between the number of hours of daytime ventilation and the number of hours that temperature exceeds 29°C for both studied zones. The model is night ventilated by mechanical means at a rate of 10 ach. Daytime ventilation is provided by natural means using 25% of open proportion of windows. This proportion is the same used in the base-case, which represents the normal routine of the higher thermal inertia house (see item 5.2 – Calibration of the model). The average daytime airflow into the room is 12.1ach for Zone 1 and 4.8ach for Zone 5, both considering 25% open proportion of window. The average values were calculated based on the hourly results for one day in the middle of the studied period as an example (see appendix A5 for hourly values of daytime airflow provided by TAS).

In this first analysis, no other design measure, such as shading in the large window and radiant barrier in the roof, is considered. Zero number of hours of daytime ventilation means that the building is closed during the day. The opening daytimes hours correspond to the hotter period of the day: from 10h to 16h. The number of hours of daytime ventilation is increased gradually from one to seven hours, in a rate of two.

The figure 7.15 shows the results for zone 1. A poor correlation was found represented by linear relation with R^2 value of 0.32. For this zone, increasing the number of hours of daytime ventilation did not cause a significant augment in the numbers of hours above 29°C, denoted by the similar results. In this case, as the zone is well protected from solar gains and has a greater internal volume, the daytime ventilation seems not to interfere in the thermal performance.

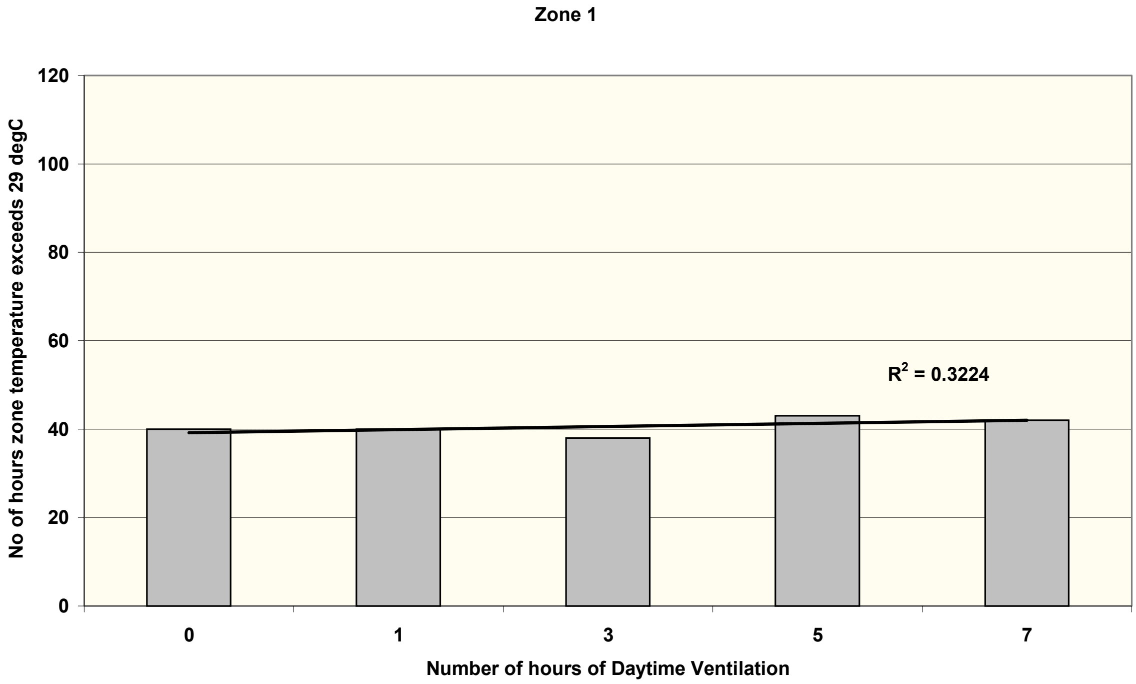


Figure 7.15: The influence of daytime ventilation on the thermal performance – zone 1. Model conditions: night ventilated; no shading; without radiant barrier in the roof.

There was a good linear correlation for zone 5, represented by R^2 value of 0.97 (fig. 7.16). As the number of opening times during the day increases, the number of hours that zone temperature exceeds 29°C also increases. Seven hours of diurnal ventilation can add 11.2% more hours above 29°C compared to no daytime ventilation condition. Once more, the presence of the large window in the room, responsible for the greater heat gain, has influence on the thermal performance and daytime ventilation, in this case, should be avoided.

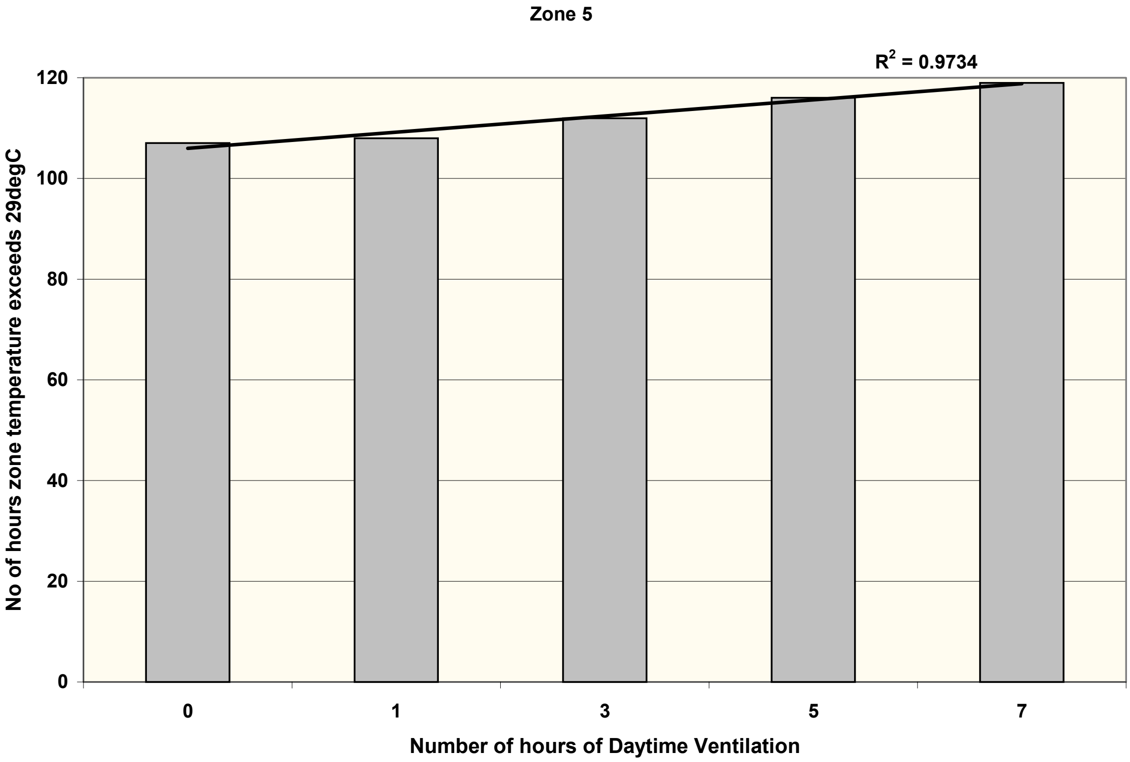


Figure 7.16: The influence of daytime ventilation on the thermal performance – zone 5. Model conditions: night ventilated; no shading; without radiant barrier in the roof.

A second analysis was, then, carried out only for zone 5, this time applying, first, shading in the large window and second, radiant barrier in the roof. Night ventilation is used same as before. The aim of this analysis was to investigate the contribution of these design measures on the improving of thermal performance even when daytime ventilation is allowed.

Although the performance improved when shading was implemented to the model, there was still a gradual increase in the number of hours that zone temperature exceeds 29°C, as the hours of daytime ventilation rises (see fig. 7.17). Nevertheless, the correlation decreased when compared to the previous result. The R^2 value now is 0.72. From zero to three hours of diurnal ventilation there was almost no difference in the numbers of overheating hours, while seven hours of diurnal ventilation can increase about 10% in the number of hours above 29°C compared to no daytime ventilation condition.

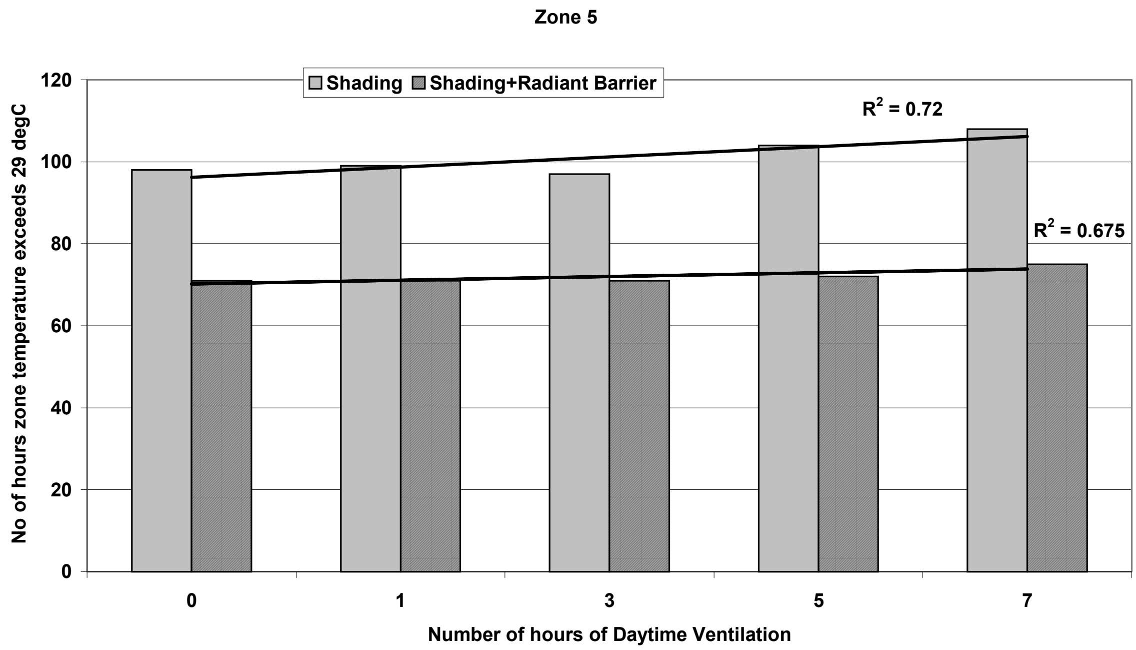


Figure 7.17: The influence of daytime ventilation on the thermal performance – shading and radiant barrier applied.

The addition of radiant barrier in the roof improved even more the thermal performance of this zone. It can be observed that, again, the correlation decreased. The correspondent R^2 value between the data was 0.67. As the design measures are implemented to the model, the negative effect of daytime ventilation tends to diminish.

From zero to five hours of diurnal ventilation there was a neglectable variation in the numbers of hours that zone temperature exceeds 29°C, whereas seven hours of daytime ventilation added 5.6% more hours above 29°C compared to no daytime ventilation.

The main conclusion from these analyses is that if all measures that help the performance of heavyweight building are been considered, the daytime ventilation has small effect on the internal conditions. Although, one has to keep in mind that, if many hours of daytime ventilation is allowed, the thermal performance may have a reduction (of about 5.6% in this case) in comparison to keeping the building closed during daytime. It is recommended that daytime ventilation should be kept to a minimum. Moreover, different open proportion of window may provide different results, although the trend of correlation lines would be the same.

7.6. Discussion and Conclusion:

The correlation analysis allowed verifying the relationship between some characteristics and their influence on internal conditions. The studied parameters were:

a) Mass area to opening area ratio and window to floor ratio in the **window size** analysis;

b) The **night ventilation** effect on indoor peak temperature reduction;

c) The **exposed surface** area of thermal mass;

d) The consequence of allowing **daytime ventilation** when thermal inertia and night ventilation are applied.

The main conclusion from this study was that the correlation between the data always decreases when a combination of design measures is applied to the model.

The main findings of each topic are summarised below:

Window Size:

- Mass to opening ratio analysis showed that increasing the area of mass while keeping a large window area has not significant effect on the internal conditions, once the right combination of design measures are taken to improve the thermal performance. The isolated parameter that contributes more to increase the thermal performance is night ventilation, as it is essential to dissipate the heat accumulated in the mass. Shading became also important from 24 m^2 thermal mass /m^2 window.
- The window to floor rate analysis has shown that if any design measure is taken, the increment of the glazing to floor ratio will increase the overheating hours in the room. From window to floor rate of 20%, shading is the more important isolated design requirement, but it is the combination of design measures that achieves the best result.

Night Ventilation:

- When night ventilation is applied, higher reductions on indoor peak temperature are achieved.
- The higher the outdoor temperature swing, the higher the peak reduction on the indoor temperature below the outdoor maximum.
- Higher the thermal inertia of the walls, higher the correlation between the reduction of the peak temperature inside and the outdoor temperature swing when night ventilation is applied.

- Design measures (shading and radiant barrier in the roof) integrated with night ventilation provide better response to the higher thermal inertia building as higher values of indoor peak reductions are achieved.

Exposed Surface of Thermal Mass:

- The best performance was achieved when all internal surfaces are exposed to heat exchange. The exception happens when the walls were covered because the lightweight finishing worked as insulation. However, this condition may change when internal gains are greater as the covered surfaces will not be able to absorb the excess of heat.
- When solar gain are greater due to large openings, the exposed surface of thermal mass has more influence on the internal conditions, as the greater the covered area, the higher the overheating hours of the room.
- According to this result, the exposed surface of mass has influence only when solar gain (or internal gain) is greater.

Daytime Ventilation:

- If design measures that help the performance of heavyweight building are been considered, the daytime ventilation has small effect on the internal conditions. But if many hours of daytime ventilation is allowed, the thermal performance may have a reduction. It is recommended that daytime ventilation should be kept to a minimum.

PART III

DESIGN GUIDELINES

WAYS TO IMPROVE THERMAL INERTIA

Part III covers the results of this research.

First, in chapter 8, the findings derived from the assessments of thermal inertia are used to define a series of design guidelines. The recommendations focus on the optimisation of thermal inertia in residential buildings in hot-humid climate

Conclusions are presented in chapter 9 with the aim of helping to determine the extent to which the evaluated parameters should be used to improve the indoor thermal conditions when the designer wish to take advantage of thermal inertia in that climate.

Chapter 8. Design Guidelines:

8.1. Introduction:

The present investigation has examined the role of thermal inertia as a cooling technique in the warm-humid climate of Southern Brazil. The aim of the research was to find out the limitations and applicability of this technique in that climate.

The adopted methodology encompasses a Field Experiment and Analytical work. The field experiment included measurements carried out in 4 residences with different thermal inertia characteristics. The main observations of the field studies led to the analytical work where Parametric Studies and Correlation Analysis were developed both based in simulations.

The findings derived from the results were used to define a series of design guidelines aimed at the improvement of the thermal performance of domestic buildings. The recommendations focus on the optimisation of thermal inertia in hot-humid climate.

8.2. Guidelines for Building Designers:

Walls:

- The use of higher thermal inertia walls require some design strategies to be applied, to help the building to achieve the best thermal performance. The design strategies are: night ventilation, shading and a higher thermal inertia roof system.
- When outdoor temperatures achieve extreme values (in this case, above 29° C), higher thermal inertia walls provide best internal conditions as reduction on overheating hours of about 50% are likely to be achieved, especially when solar gain is avoided and night ventilation applied.

Roof System:

- Rooms located in the upper floor have direct influence of the heat coming through the roof system and the roof design should be considered carefully. Building elements of higher thermal inertia are recommended.
- The use of a higher thermal inertia ceiling (concrete slab) and the application of radiant barrier in the roof system provided the best performance. When a concrete slab ceiling is used, a radiant barrier rather than insulation should be applied in the roof system.
- The use of a timber ceiling needs to be associated to the application of insulation or a radiant barrier.

Window Size and Shading:

- The use of a shading device provides a more significant decrease in the overheating hours than the reduction of the size of the window. Nevertheless, a large window to floor rate should be avoided (>20%), as the solar gain would be greater and more difficult to be obstructed.
- The use of an External Venetian Blind is more efficient than the use of a *Brise Soleil* as the first reduces the number of hours above 29°C in about 30% (resultant temperature), while the latter reduces it in about 13%. A Daylight level analysis should be performed to assure acceptable daylight level according to the room purpose.

Mass to Opening Ratio

- When design measures such as shading, night ventilation and radiant barrier in the roof are implemented, increasing the area of mass while keeping constant a large window to floor rate has not significant effect on the internal conditions. It means that a right combination of design measures has more impact in improving the thermal performance of a room than the augment of area of mass.
- Night ventilation is the more important design measure when the area of exposed thermal mass increases. Shading is the second important strategy and becomes the most significant on decreasing the overheating hours from about 25 m^2 thermal mass/m^2 window.

Window to Floor Ratio

- If any design measure is taken, the increment of the glazing to floor ratio will increase constantly the overheating hours due the solar gain through the window
- When a combination of design measures such as shading, night ventilation and radiant barrier in the roof are used, enlarging the glazing area does not reduce the thermal performance significantly, but still it has to be considered carefully.
- Shading has not the most significant effect on internal conditions in values of window to floor ratio up to 20%. From that proportion, this design strategy becomes the most important on improving the thermal performance of the room.
- If a large window is part of the design requirement and can not be avoided by the designer, the use of adequate summer shading is indispensable.

Night Ventilation:

- The higher the heat gain of a room, the higher the cooling effect of night ventilation, as the relative difference between indoor and outdoor temperature during the night would be greater. In this case, the higher the airflow rates, the higher the reduction of overheating hours.
- Night ventilation is very effective in reducing indoor peak temperature below the outdoor peak, as reductions of 5°C are likely to be achieved.
- If a room has a large window to floor rate (greater than 20%) allowing solar gain, only night ventilation strategy may not be enough to improve the zone's thermal performance and other measures needs to be taken.
- The higher the outdoor temperature swing, the higher the peak reduction on the indoor temperature below the outdoor maximum. Night ventilation has a major effect from 6°C of outdoor temperature swing. Then a careful analysis of the local climatic characteristics in terms of daily range of temperature is recommended when thermal inertia and night ventilation strategies are going to be applied in the building design.

Walls of different thermal inertia associated to the use of night ventilation:

- When night ventilation is applied, higher thermal inertia walls provides better thermal response in the building, as higher indoor peak reductions are achieved, especially when outdoor temperature swing is greater.
- The addition of the design measures, such as shading and radiant barrier in the roof integrated with night ventilation, provides higher values of indoor peak reductions to the model with higher thermal inertia walls when compared to lower thermal inertia walls.

Exposed Surface:

- The exposed surface of thermal mass seems to have more influence where solar gains are greater due to large openings. In this case, if any design measures are taken to help the thermal performance of a higher thermal inertia building, it is been shown that the greater the covered area by lightweight finishing, higher the overheating hours.
- When design measures such as shading, night ventilation and radiant barrier in the roof are provided the thermal performance improves and the influence of the area of exposed surface decreases.
- Adding carpet to the floor seems to have worsened the internal conditions and should be avoided.

- The best performance is achieved when all internal surfaces are exposed to heat exchange. The exception happens when the walls are covered because the lightweight finishing works as insulation. However, this condition may change when internal gains are greater as the covered surfaces will not be able to absorb the excess of heat.
- For summer condition, if lightweight finishing can not be avoided, shading is the critical strategy to be considered.
- It must be reminded that for winter, solar gain should be admitted into the room, thus the thermal storage process can happen in the exposed mass and be released to the room in the later cooler times.

Daytime Ventilation:

- When the zone is well protected from solar gains, the daytime ventilation seems not to interfere in the thermal performance.
- In the other hand, when solar gain is allowed into the room through a large window to floor rate (about 30%, in this case), daytime ventilation has influence on the thermal performance and should be avoided.
- As the design measures (shading and radiant barrier in the roof) are implemented to the building, the negative effect of daytime ventilation tends to diminish. However, if more than five hours of daytime ventilation is allowed, the thermal performance of the building may have a reduction. It is recommended that daytime ventilation should be kept to a minimum.

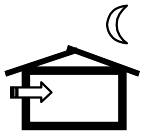
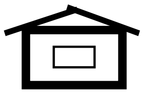
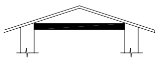
8.3. Summary:

A matrix for the parametric results was organised to indicate the effectiveness of each measure studied and can help to select the best alternative for a high mass building.

The parametric variation matrix shows the results for Zone 1 and Zone 5, considering the limit of 29°C only, as more significant reductions in the overheating hours were achieved at this temperature when design strategies are applied. The numbers of hours that zone temperature exceeds 29°C and the respective reduction (in percentage) compared to the base-case are shown in the matrix.

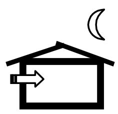
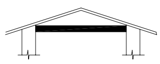
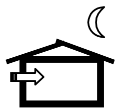
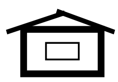
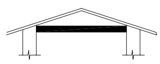
As a complementary information, the degree-hour was calculated for the base-temperature of 29°C. Degree-hour concept can be used for energy analysis to estimate the cooling requirements.

Table 8.1: Matrix for the parametric results.

Design Alternatives			**Zone 1**			**Zone 5**		
			Freq>29 / Reduction (%)		**Degree-hour (Tb=29)**	**Freq>29 / Reduction (%)**		**Degree-hour (Tb=29)**
Night Ventilation 		No nightvent	56	-	27.6	196	-	249.8
	Natural	25% open	49	12.5	21.7	164	16.3	214.5
		50% open	45	19.6	19.9	150	23.5	197.8
	Mechanical	10ach	44	21.4	18.9	147	25	194.7
		20ach	44	21.4	17.5	139	29	185.3
		30ach	44	21.4	16.7	132	32.6	179.9
Window 	Window to Floor Ratio	30%	-	-	-	196	-	249.8
		20%	-	-	-	186	5.1	237.1
		10%	-	-	-	182	7.1	230.3
	Solar Protection	No shading	-	-	-	203	-	314.4
		Brise Soleil	-	-	-	176	13.3	239.3
		Ext Blind	-	-	-	141	30.5	150.0
Roof System 	Concrete slab ceiling		40	-	19.7	152	-	177.8
	Timber ceiling		53	increase	33.5	170	increase	226.3
	Concrete slab + insulation		47	increase	23.4	136	10.5	138.6
	Timber + radiant barrier		44	increase	20.8	135	11.2	133.5
	Timber + insulation		41	increase	20.2	134	11.8	133.6
	Concrete slab +radiant barrier		34	15	15.1	123	19.1	112.6

The effectiveness of the design measures is summarized below in terms of reduction in the number of hours above 29°C when compared to the base-case and it can represent the priorities when selecting the alternatives for a higher thermal inertia building.

Table 8.2: Effectiveness scale of design alternatives for a higher thermal inertia building.

Zone 1	 21.4%	 15%	-
Zone 5	 32.6%	 30.5%	 19.1%

Night ventilation is the priority design measure to be applied for heavier buildings in this climate. Shading is also important when a zone has a large window facing a problematic orientation.

Overall, results of the present investigation has shown that the best thermal performance is achieved by a combination of the following design measures:

- Window to floor rate equal or smaller than 20%;
- A external blind shading device when the opening is located in a problematic orientation;
- At least 10 ach of night ventilation;
- Concrete slab ceiling in the upper floor;
- Radiant Barrier in the roof;
- Daytime ventilation avoided or kept to a minimum.

Chapter 9. Conclusions:

This research has investigated ways to improve thermal inertia in residential buildings located in the warm-humid climate of Southern Brazil. The performance of thermal inertia was evaluated first through a field experiment. The experimental data allowed discussing some aspects, which affect the performance of thermal inertia. Detail analysis was then undertaken through the use of numerical simulations. The findings provided useful information, which was translated to design guidelines for building designers.

Results of the present research have demonstrated that thermal inertia in buildings can not be considered as an isolated strategy.

The profiles of internal temperatures and statistical analysis obtained from the **Field Experiment** have permitted assessing the performance of houses with different levels of thermal inertia. The houses with higher thermal inertia in their envelope showed reduced indoor temperature fluctuation compared to the external climate. However, despite of higher thermal inertia, some rooms did not show best thermal performance. Some aspects, then, have emerged that need to be taken into consideration.

1. The influence of the roof system on upper floor rooms: all residences presented higher internal temperatures in the rooms located in the upper floor. It can be concluded that applying higher thermal inertia to the walls does not guarantee better performance in the house and higher level of thermal inertia in the ceiling should be added.
2. Size of the openings and adequate shading: the experiment has shown the dominant influence of a large window allowing solar gain. A special analysis was made through the study of solar access in the rooms that showed worst thermal performance in the higher thermal inertia houses. Shadow masks for the openings were drawn and allowed demonstrating the solar access in the ambient in the summer time. The high inertia of the surface of the construction components (walls, floors) which receives direct solar radiation will keep the heat for longer if it is not dissipated by ventilation.
3. The importance of applying night ventilation: night ventilation should be used to guarantee the dissipation of the heat that is stored in the structure. Also, the effect of daytime ventilation allowed by occupants.

Parametric Studies allowed finding the best combination of design strategies to be applied which improves the performance of a higher thermal inertia building. A number of variations including night ventilation rate, window size and shading devices, different levels of thermal inertia in the roof system and walls were evaluated through simulations. The number of hours that zone temperature exceeds 27°C and 29°C was the parameter used to access the comfort improvement. Results provided extensive knowledge about the optimisation of thermal inertial in residential buildings:

1. The effect of night ventilation was always positive, improving the thermal performance of the building compared to the model with no night ventilation. It was observed that the higher the heat gains of a room, the higher the cooling effect of night ventilation, as the relative difference between indoor and outdoor temperature during the night would be greater. However higher rates of night ventilation would be necessary to allow sufficient heat dissipation.

2. Window evaluation has shown that the influence of glazing surfaces allowing solar radiation coming into the room is more significant upon the mean radiant temperature. Also, it was demonstrated that providing appropriate shading leads to a better thermal performance in a room than reducing the size of the window only.

3. Roof System analysis has shown that the thermal characteristics of a timber ceiling are not enough to obstruct or absorb the amount of heat generated by the exposition of the roof to solar radiation and higher temperatures. It is shown that a timber ceiling needs to be associated to the use of insulation material or a radiant barrier to achieve a better thermal performance. Also, the roof system with a radiant barrier on a concrete slab ceiling achieved higher reduction in the overheating hours in all case-studies zones. The use of insulation material causes an increasing in the overheating hours for the zone located in the ground floor, although it has improved the performance of the zones located in the upper floor.

4. The analysis of frequency of temperatures considering different walls has demonstrated that lower thermal inertia wall has better performance for the limit of 27°C. As single brick wall has lower thermal capacity and smaller width, it is been confirmed that the heat accumulated in the structure is quickly dissipated during the night, when temperatures are lower, while higher thermal inertia wall keeps the surplus heat for longer. However, for the limit of 29°C, the higher thermal inertia wall provides best performance due to the higher thermal capacity, especially when solar gain is avoided and night ventilation applied.

The figure 9.1 illustrates the 24 hour variation of internal temperature for a high mass building and a low mass building. The relationship of temperature variation to upper and lower temperature criteria can be seen when the building has high or low solar gain.

The main advantage of a higher mass building is that the variation of internal temperature is small and it is close to the average of external temperature. It happens in a more effective way when the building has low solar gain. The variation of internal temperature of a low mass building is larger and presents higher peaks. In this case, when the building has high solar gain, the indoor peak temperature is close (or coincident) with the outdoor peak.

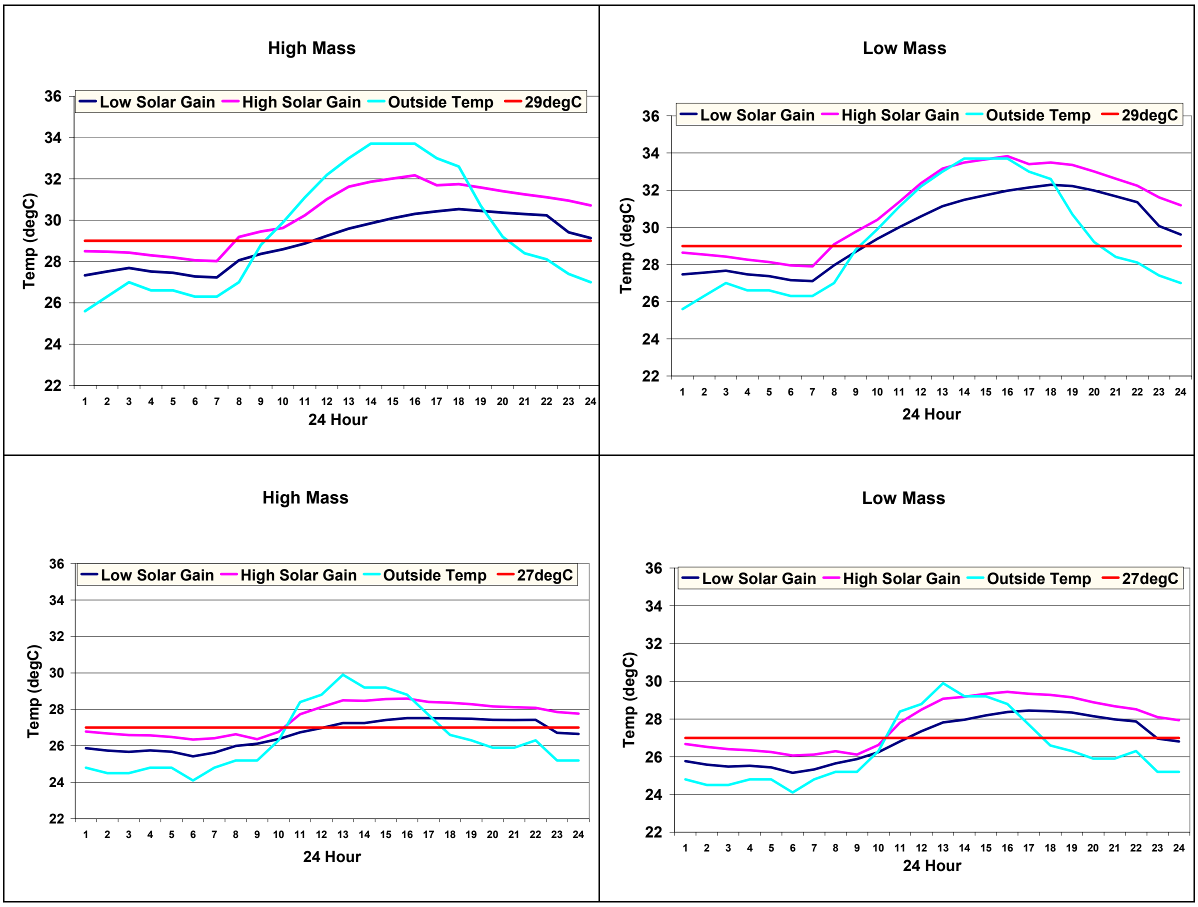


Figure 9.1: Variation of internal temperature and relationship to upper and lower temperature criteria for a high mass building and a low mass building.

Through the **Correlation Analysis** some relations were studied and the influence of some parameters on the internal conditions revealed. To accomplish this analysis, first the model was considered without any design measure to improve the thermal performance, e.g. no shading in the window (clear glass), roof without radiant barrier and only daytime ventilation by natural means. Thus, a second evaluation was performed, where the best combination of the design measures defined by the results of parametric studies was applied to the model. The assessment has included the following parameters: *window size* through mass area to opening area ratio and window to floor ratio analyses, the *night ventilation* effect on indoor peak temperature reduction, the *exposed surface area of thermal mass* and the effect of *daytime ventilation*.

The main conclusion from this study was that the correlation between the data always decreases when a combination of design measures is applied to the model. It means that, when a right combination of design characteristics is adopted in the higher thermal inertia building, the influence of each studied parameter (highlighted above) on internal conditions is minimum. Results of the relations have pointed out:

1. Mass to opening ratio analysis showed that increasing the area of mass while keeping a large window area has not significant effect on the internal conditions, once design measures such as shading, night ventilation and radiant barrier in the roof are taken to improve the thermal performance. The parameters that contributed more for the thermal performance were night ventilation and shading.

2. The window to floor ratio analysis has shown that if any design measure is taken, the increment of the glazing to floor ratio will increase the overheating hours in the room. Shading is the more important design requirement from 20% of window to floor rate.

3. Night ventilation effect on indoor peak reduction analysis showed that when night ventilation was applied, higher reductions on indoor peak temperature were achieved compared to the building with no night ventilation (reductions of 5°C can be achieved). Also, there was a higher correlation between the reduction of the peak temperature inside and the outdoor temperature swing when walls of higher thermal inertia are used. Moreover, design measures (shading and radiant barrier in the roof) integrated with night ventilation provided better response to the higher thermal inertia building as higher values of indoor peak reductions are achieved. It was also demonstrated that night ventilation has a major effect from 6°C of outdoor temperature swing.

4. Analysis of the exposed surface of thermal mass has demonstrated that the best performance was achieved when all internal surfaces are exposed to heat exchange. The exception happens when the walls were covered because the lightweight finishing worked as insulation. However, this condition may change when internal gains are greater as the covered surfaces will not be able to absorb the excess of heat. In addition, when solar gain is allowed into the room, lightweight finishing has more influence on internal conditions, as the greater the covered area, the higher the overheating hours of the room.

5. Daytime ventilation had a small effect on internal condition when the design measures were applied. Even so, it was concluded that it should be kept to a minimum.

6. Finally, the equations representing the correlation with R^2 values close to 1 can be used to obtain information in each specific topic (window size, exposed surface of thermal mass, night ventilation and daytime ventilation), once the characteristics of the room to be evaluated are similar to those of the case-studies.

Recommendation for Future Work:

It was observed that the performance of a higher thermal inertia building depends on certain aspects, as the analysis of different rooms has shown different response in terms of thermal performance. The location of the room (upper floor or ground floor), its volume and if it is well protected from solar gains, all theses characteristics have influence on thermal inertia performance. The impact of the design measures (shading, window size, night ventilation and radiant barrier in the roof) was more significant in the room with the following characteristics: located in the upper floor under the influence of the roof system, small volume, large window to floor rate allowing solar gain.

It is suggested that different room's configuration should be investigated as this may lead to different thermal performances. Results in this research only can be extended to rooms with similar characteristics of the case studies. Hence, it is recognised that further investigation should be undertaken in order to establish a relation between thermal inertia performance and different room's volumes to be able to expand the results to many situation.

This research focused only on residential buildings. Therefore, it is suggested that commercial buildings should be studied to evaluate the influence of internal gains and the different occupancy pattern on the performance when higher thermal inertia is applied.

If a mechanical system is used to implement night ventilation, further consideration will be useful in terms of the impact in the energy consumption together with a cost-benefit analysis.

Additional experimental work should be undertaken to validate the results considering a longer period. Also, to confirm some aspects studied through simulation, such as the influence of the exposed surface of thermal mass and the relationship with direct solar gain and/or internal heat gain.

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APPENDICES

Appendix A1 – Results of monitoring.

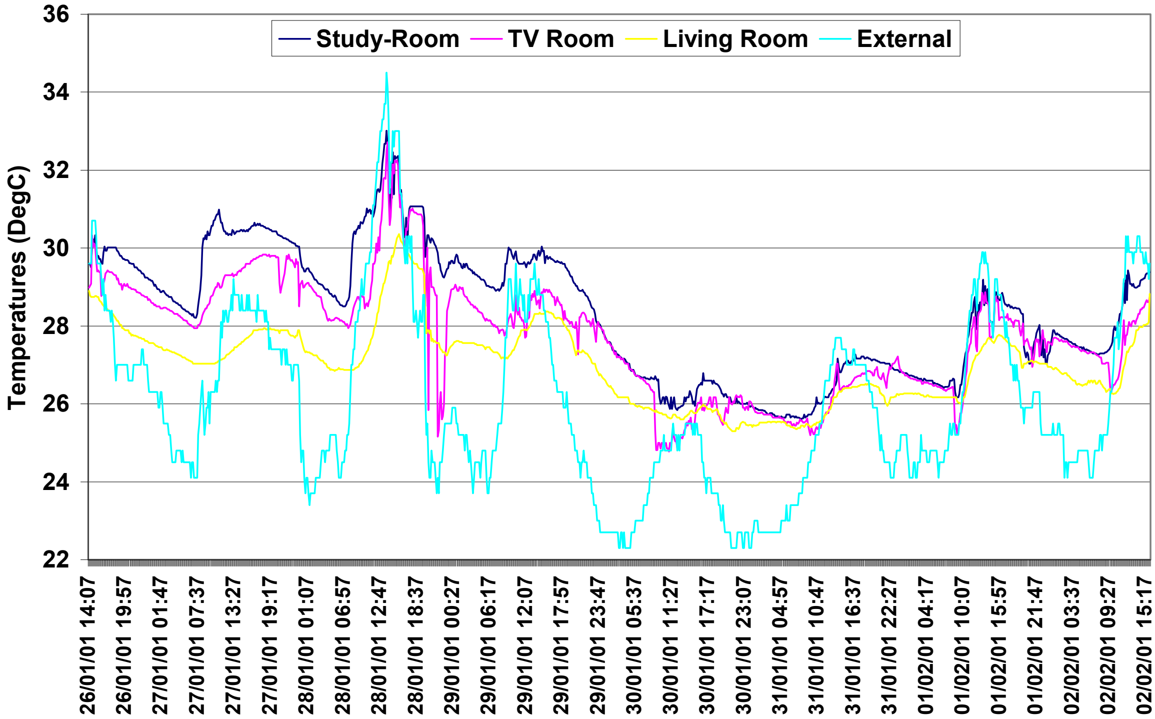

Figure A1.1 – House 1 – Temperatures (ºC) - from January 26th to February 2nd.

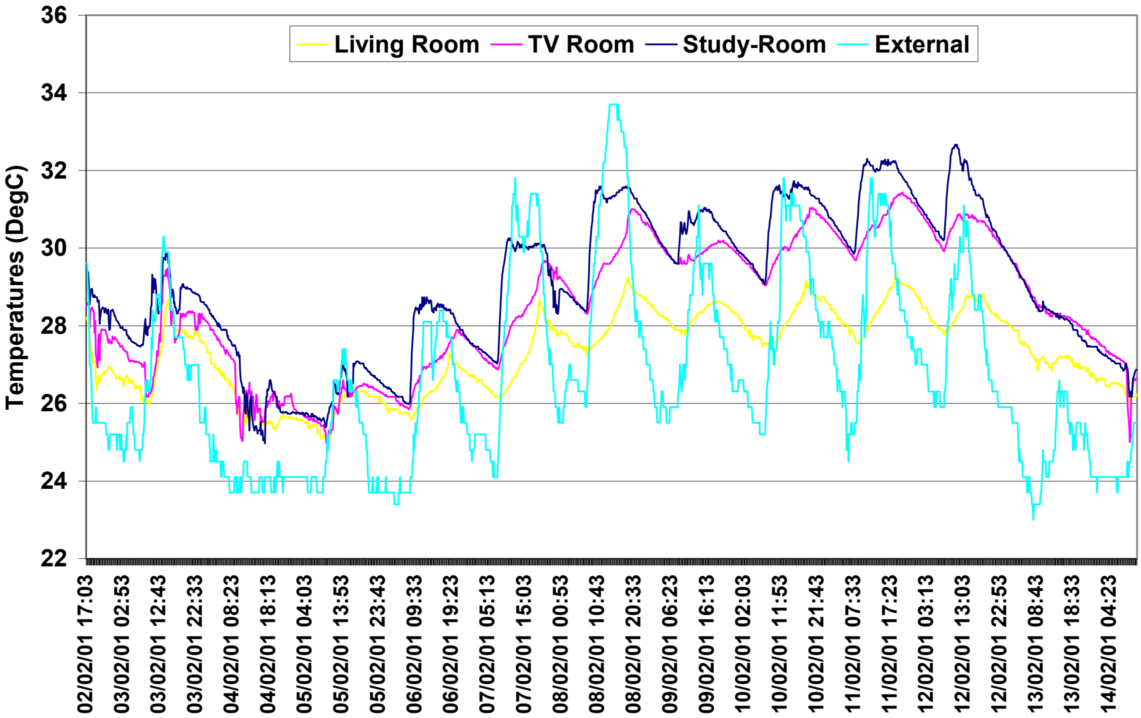

Figure A1.2 – House 1 – Temperatures (ºC) – from February 2nd to February 14th.

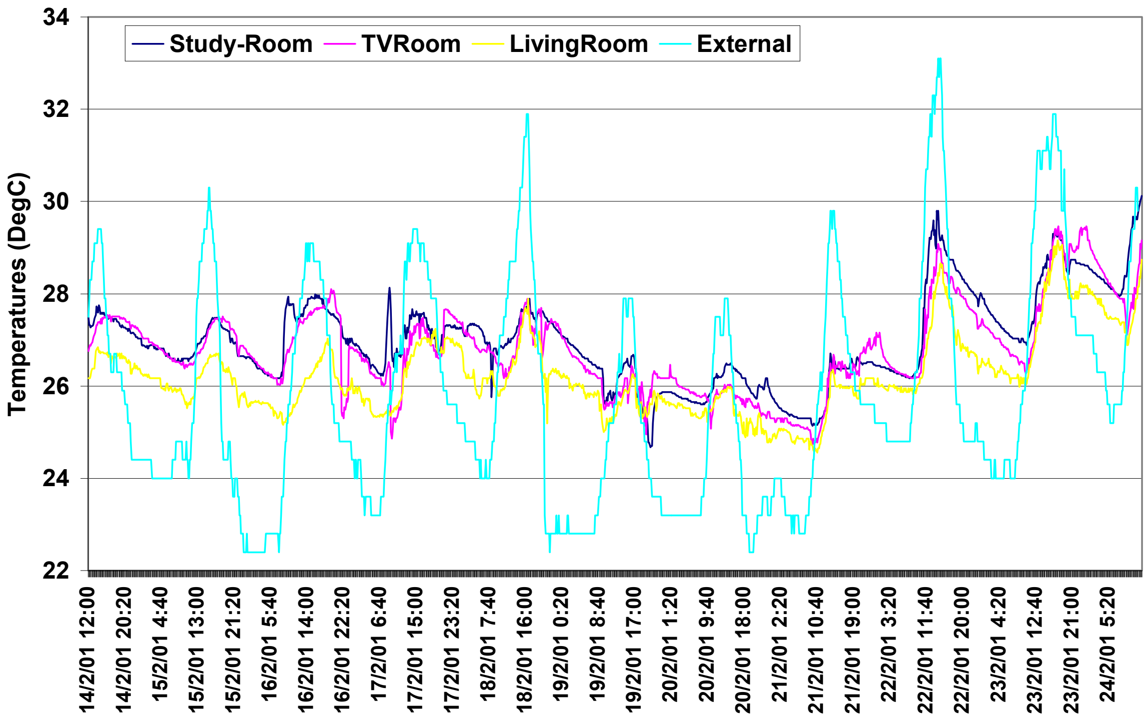

Figure A1.3 – House 1 – Temperatures (ºC) – from February 14th to February 24th.

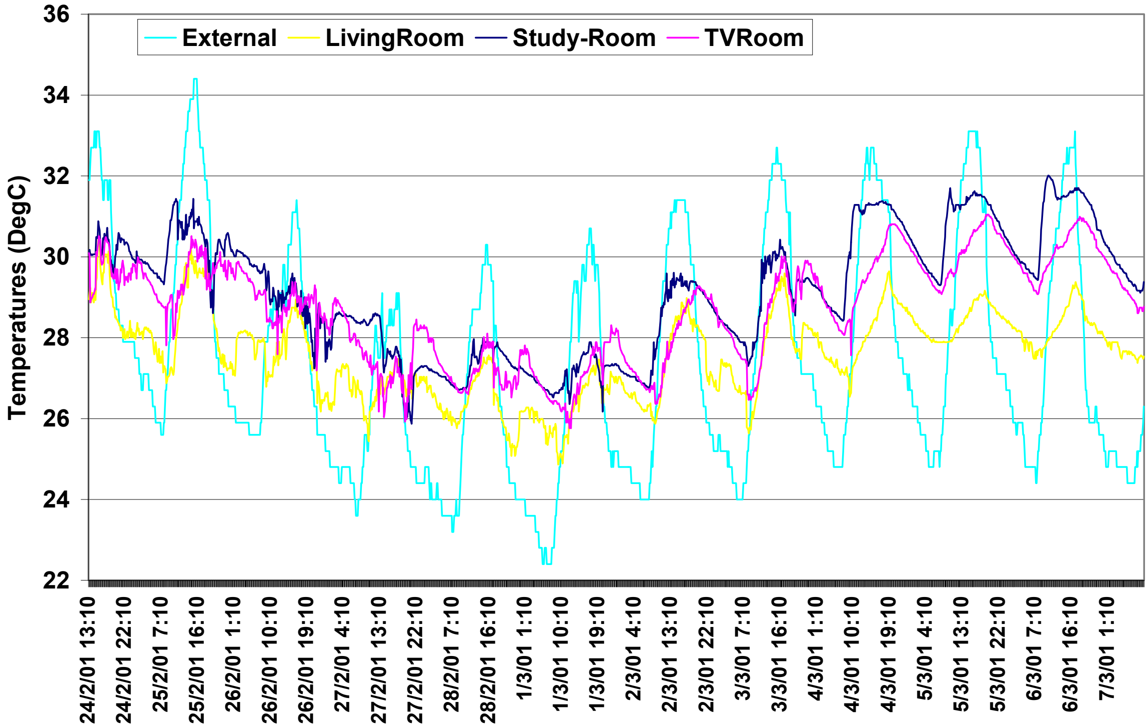

Figure A1.4 – House 1 – Temperatures (ºC) – from February 24th to March 7th.

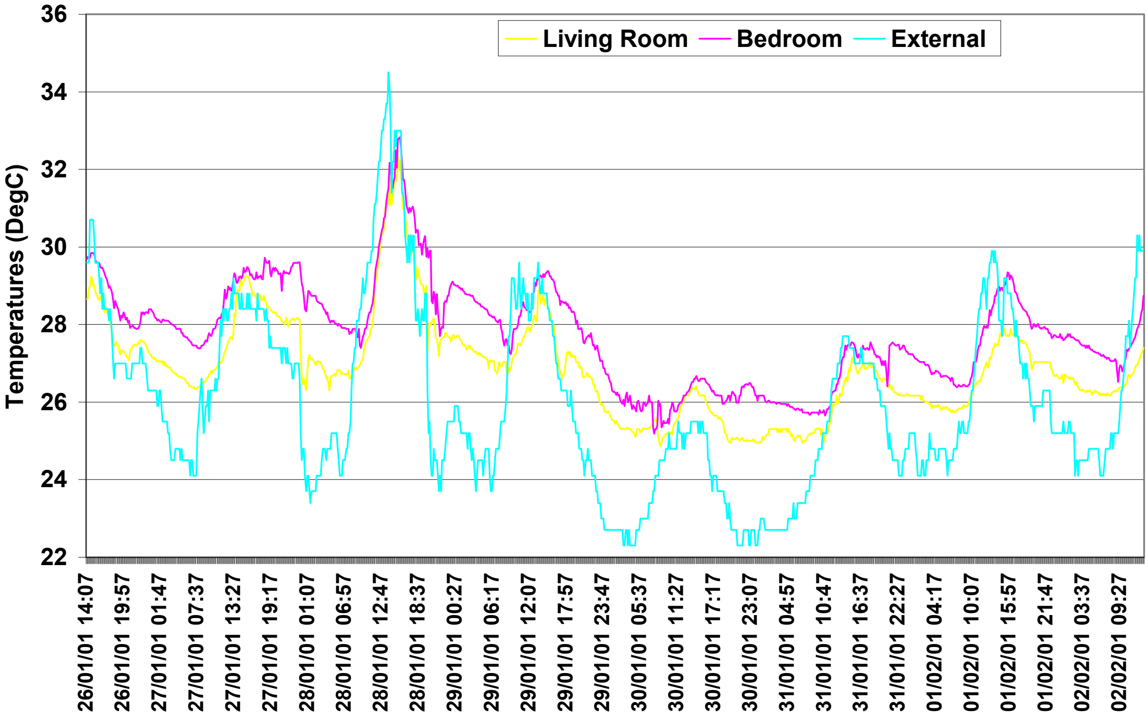

Figure A1.5 – House 2 – Temperatures[1] (ºC) - from January 26^{th} to February 2^{nd}.

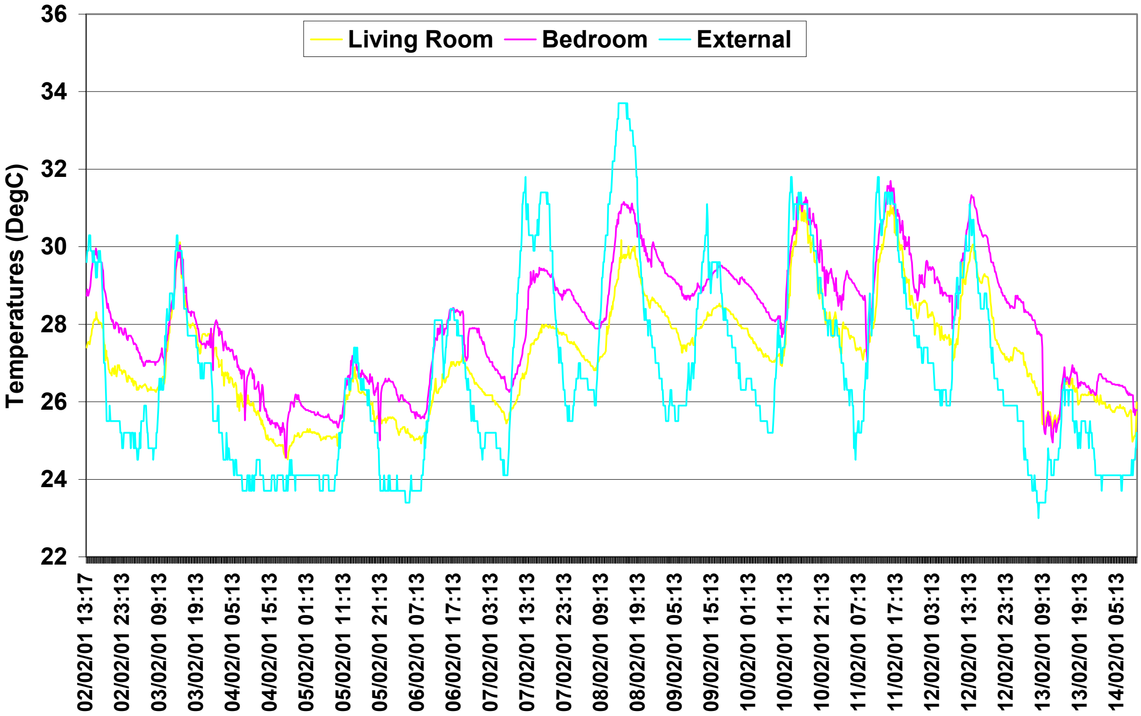

Figure A1.6 – House 2 – Temperatures (ºC) – from February 2^{nd} to February 14^{th}.

[1] External data of temperature are from sensor installed outside house 1.

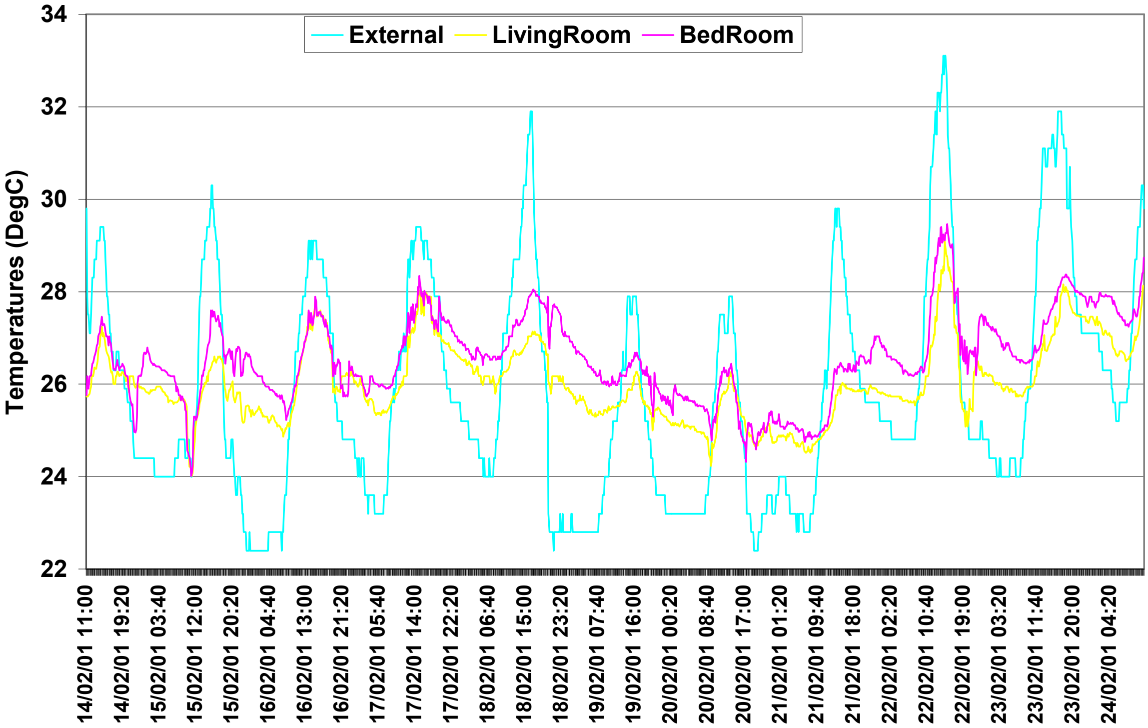

Figure A1.7 – House 2 – Temperatures (ºC) – from February 14th to February 24th.

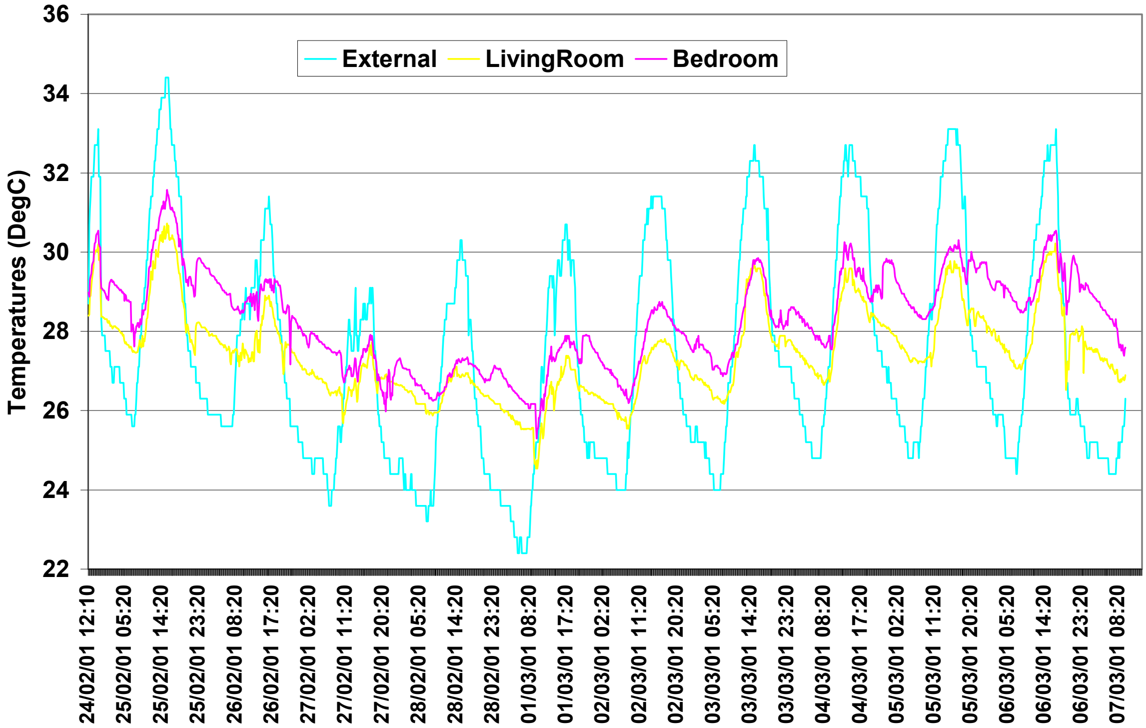

Figure A1.8 – House 2 – Temperatures (ºC) – from February 24th to March 7th.

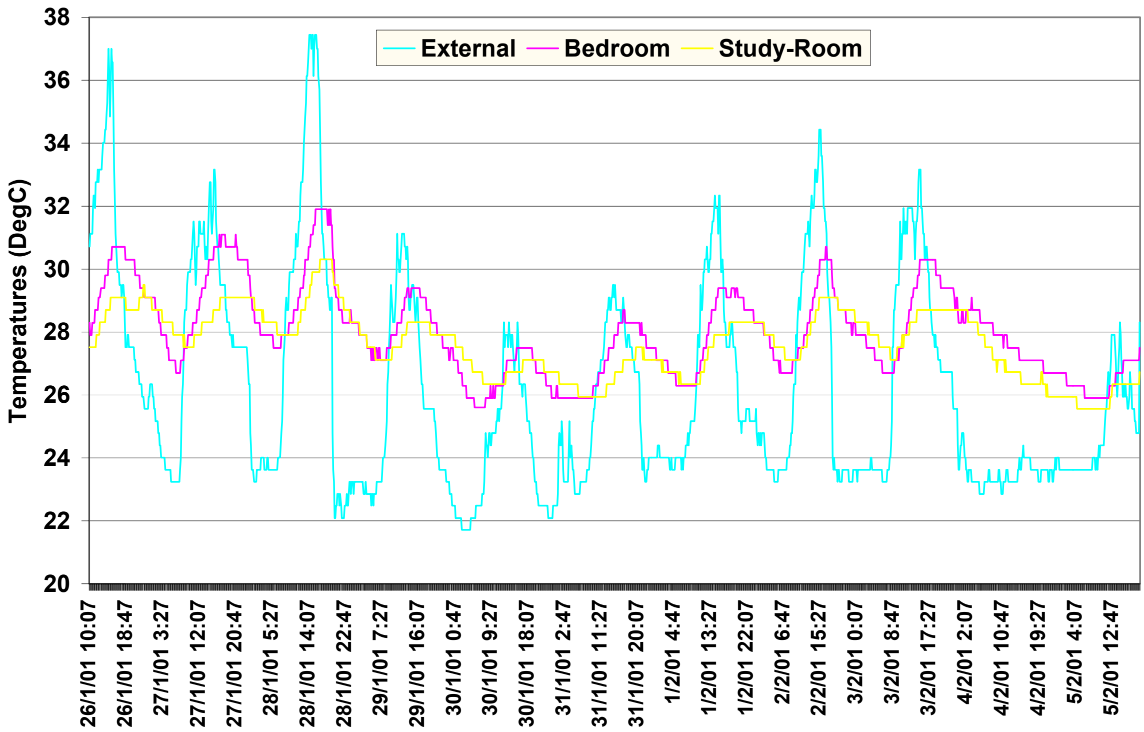

Figure A1.9 – House 3 – Temperatures (ºC) – From January 26th to February 5th.

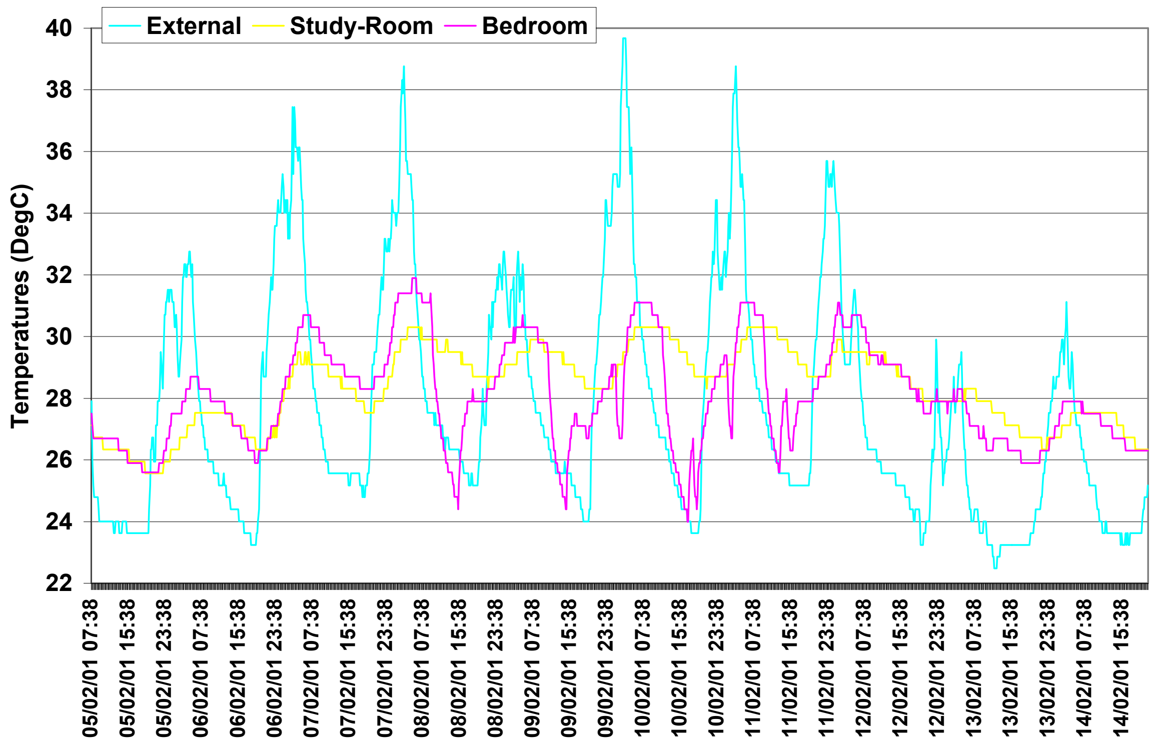

Figure A1.10 – House 3 – Temperatures[2] (ºC) – from February 5th to February 14th.

[2] The low values of temperature registered in the bedroom in the period from 08/02 to 11/02 were due to the use of air conditioning during the night. This fact can be seen also in the graph of humidity (fig.24), which shows low values during night-time in the same period.

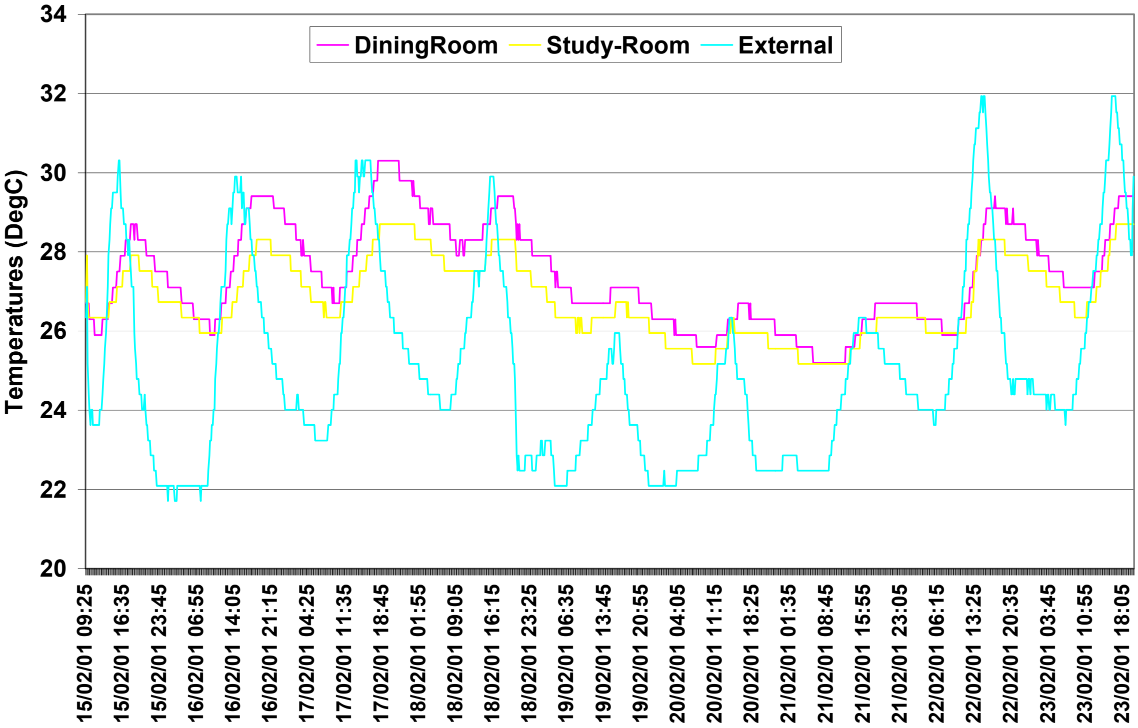

Figure A1.11 – House 3 – Temperatures[3] (ºC) – from February 15th to 23rd.

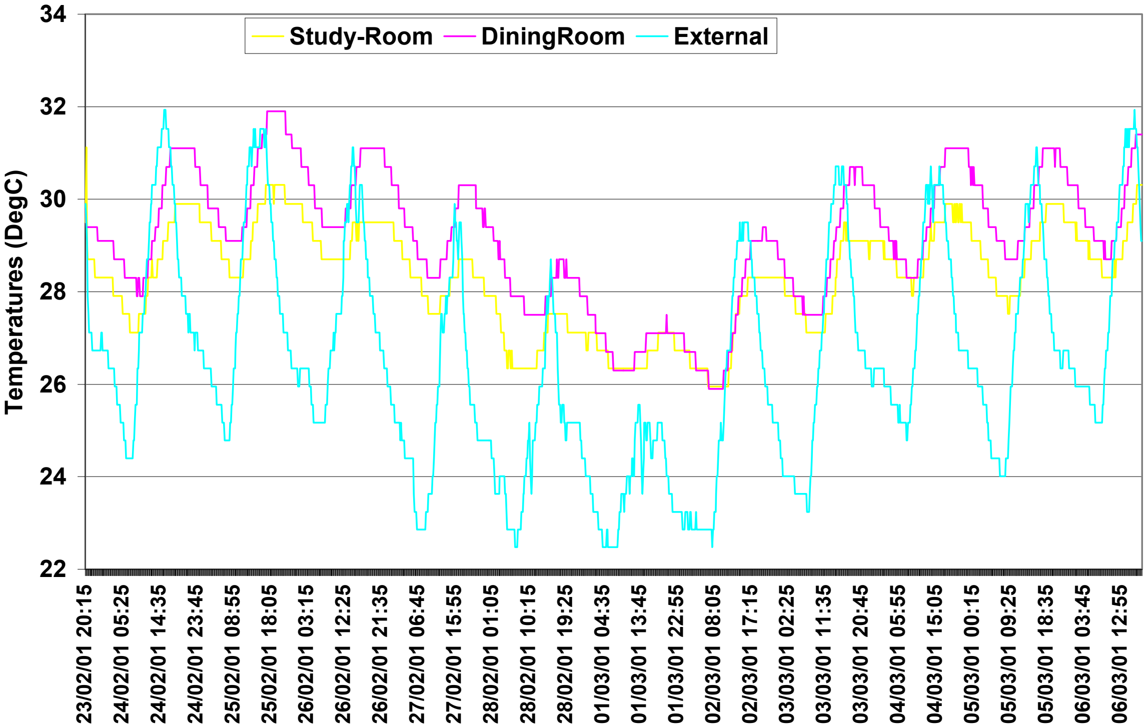

Figure A1.12 – House 3 – Temperatures (ºC) – from February 23rd to March 6th.

[3] From February 15th the instruments were changed from the bedroom to the dining room, which is also located in the upper floor and it has one of the external walls facing Southwest.

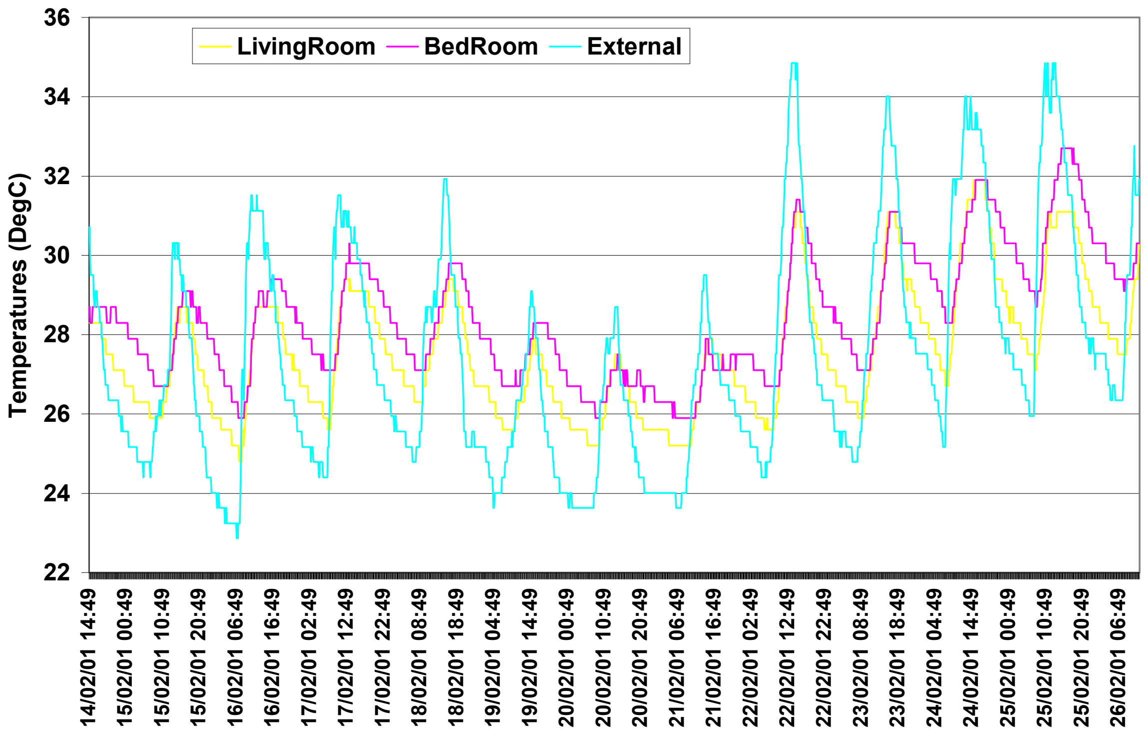

Figure A1.13 – House 4 – Temperatures (ºC) – from February 14th to February 26th.

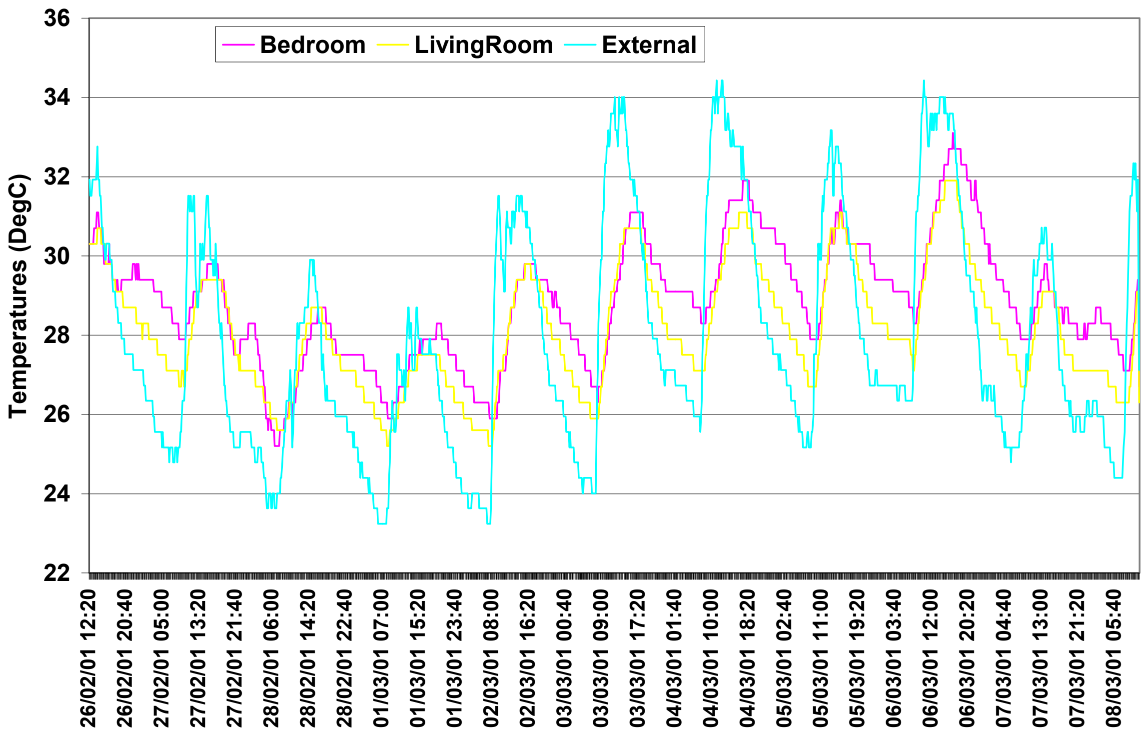

Figure A1.14 – House 4 – Temperatures (ºC) – from February 26th to March 8th.

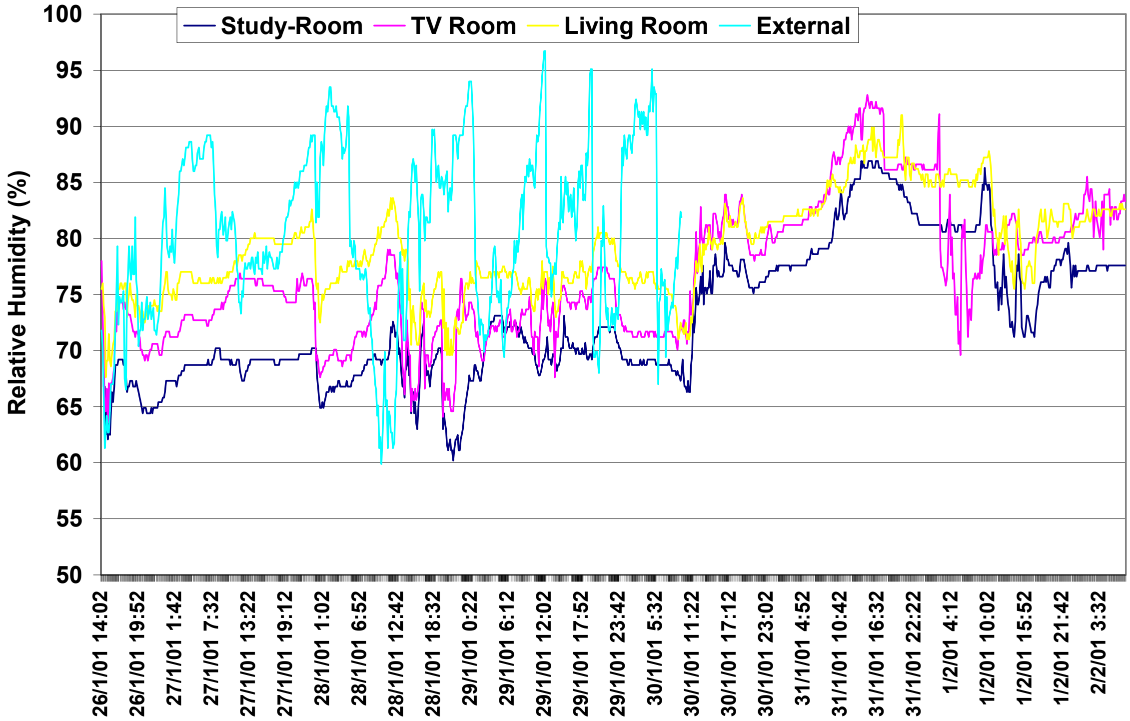

Figure A1.15 – House 1 – Relative Humidity[4] (%) – from January 26th to February 2nd.

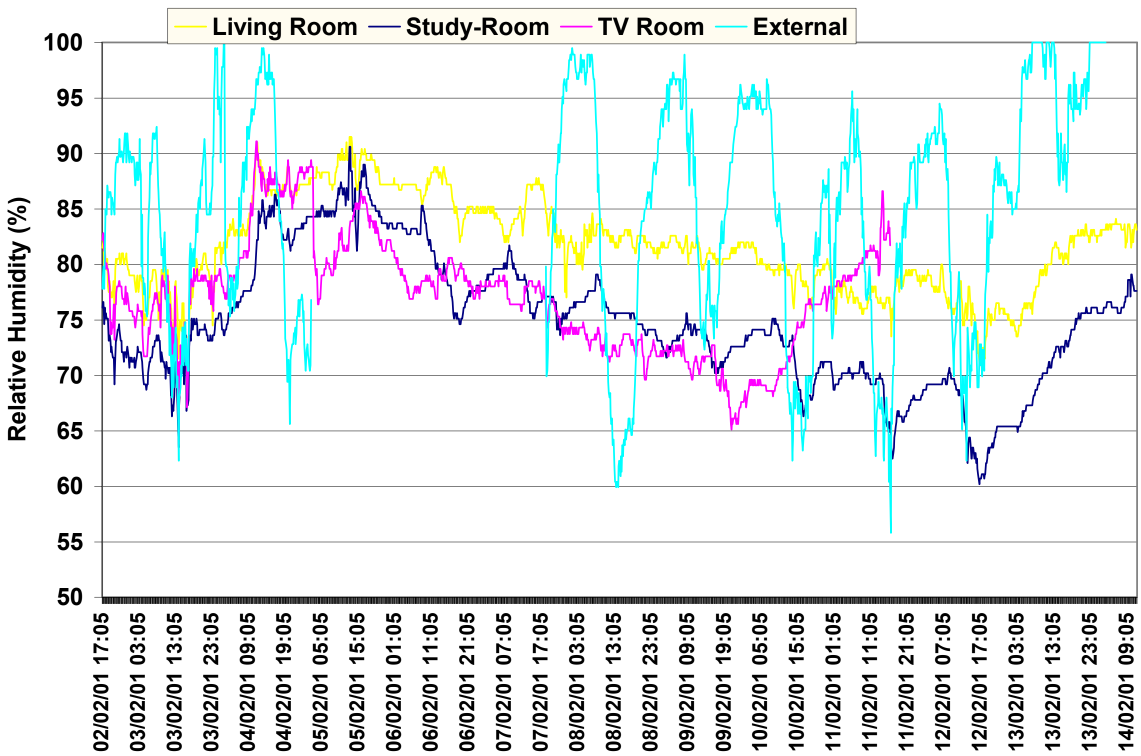

Figure A1.16 – House 1 – Relative Humidity (%) – from February 2nd to 14th.

[4] The Relative Humidity external sensor stopped registering from 30/01 to 02/02 and from 05/02 to 07/02.

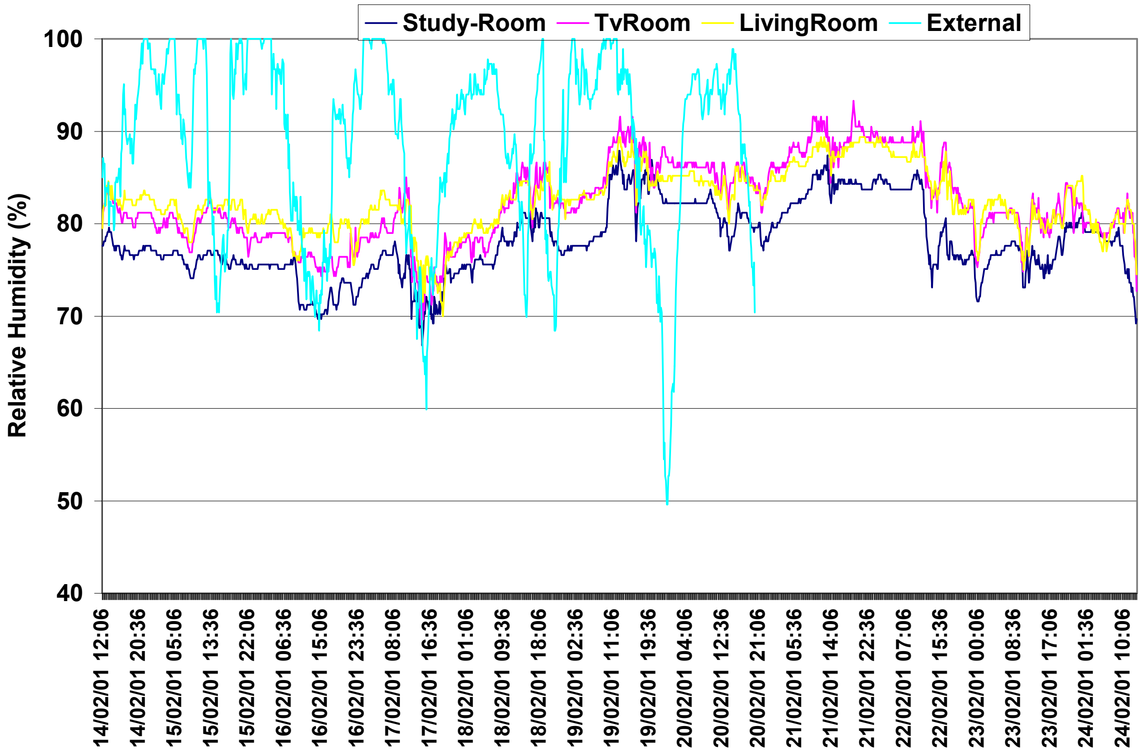

Figure A1.17 – House 1 – Relative Humidity[5] (%) – from February 14th to 24th.

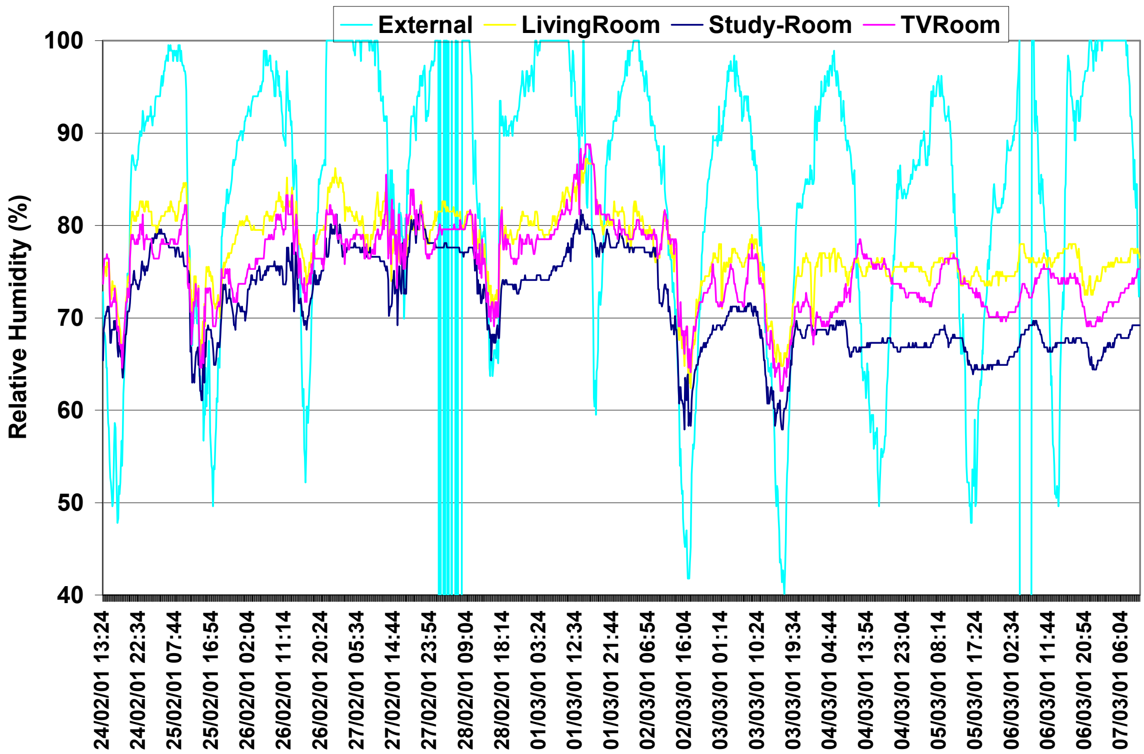

Figure A1.18 – House 1 – Relative Humidity (%) – from February 24th to March 7th.

[5] The sensor of Relative Humidity showed some problem and it stopped to register on February 20th. It continues to present some problems in the next graph.

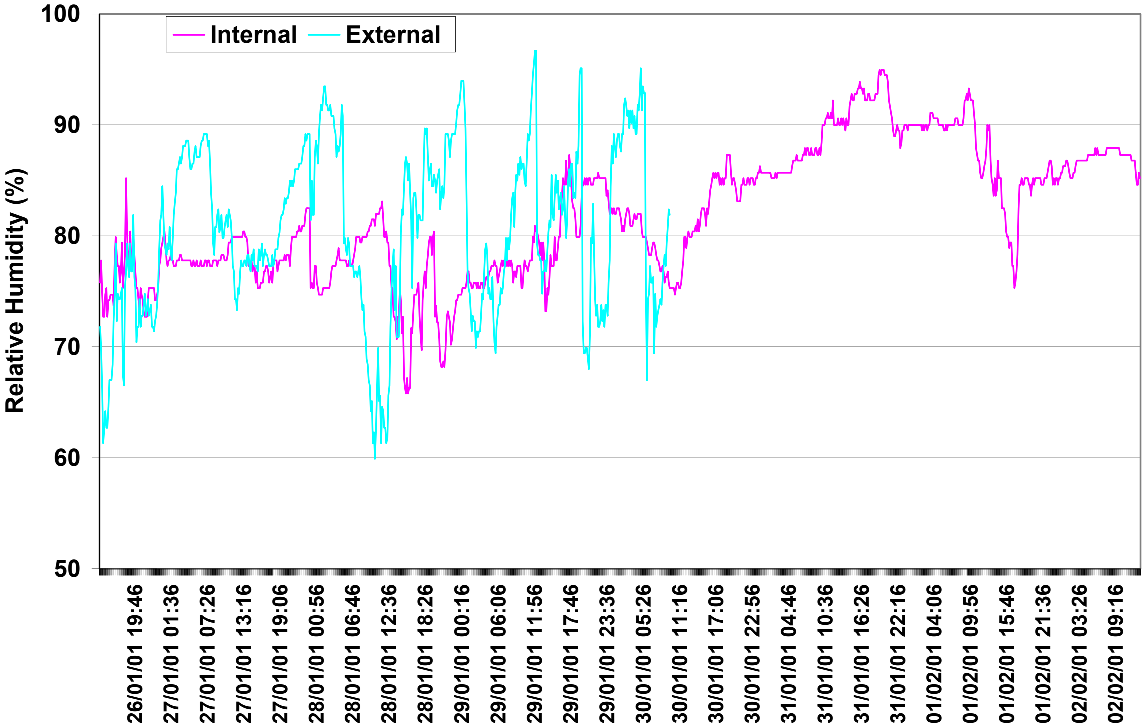

Figure A1.19 – House 2 – Relative Humidity[6] (%) – from January 26th to February 2nd.

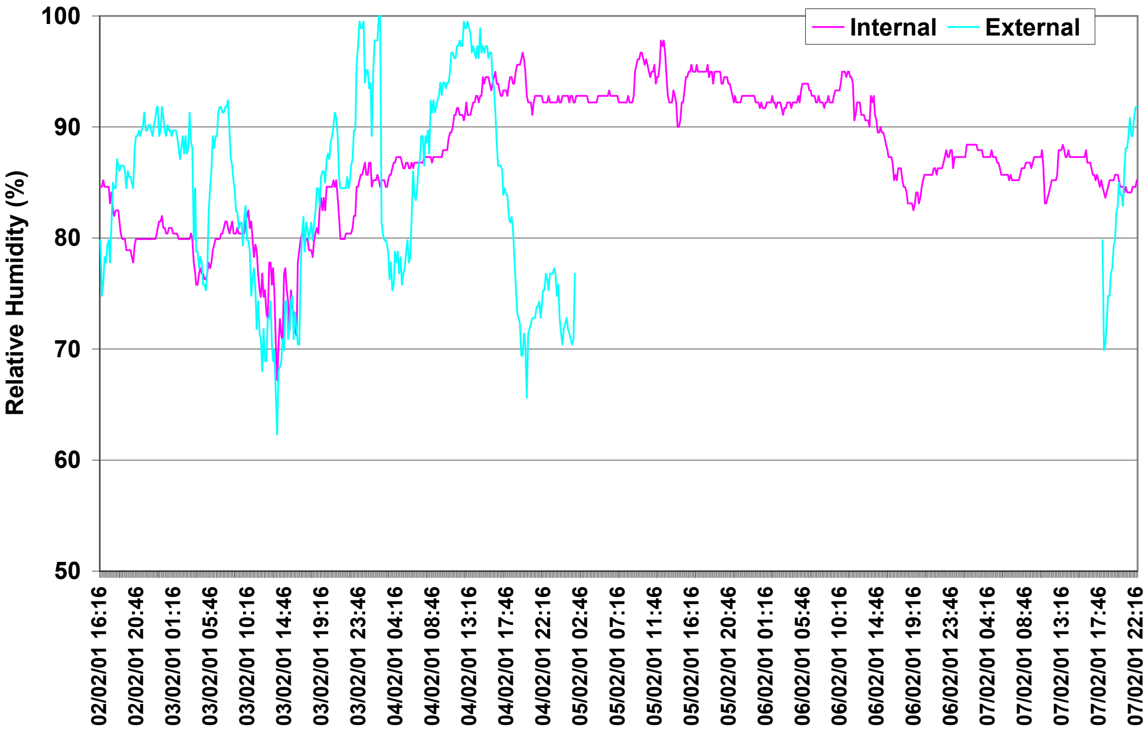

Figure A1.20 – House 2 – Relative Humidity (%) – from February 2nd to 7th.

[6] External data of relative humidity are from sensor installed outside house 1, which showed problems as mentioned before.

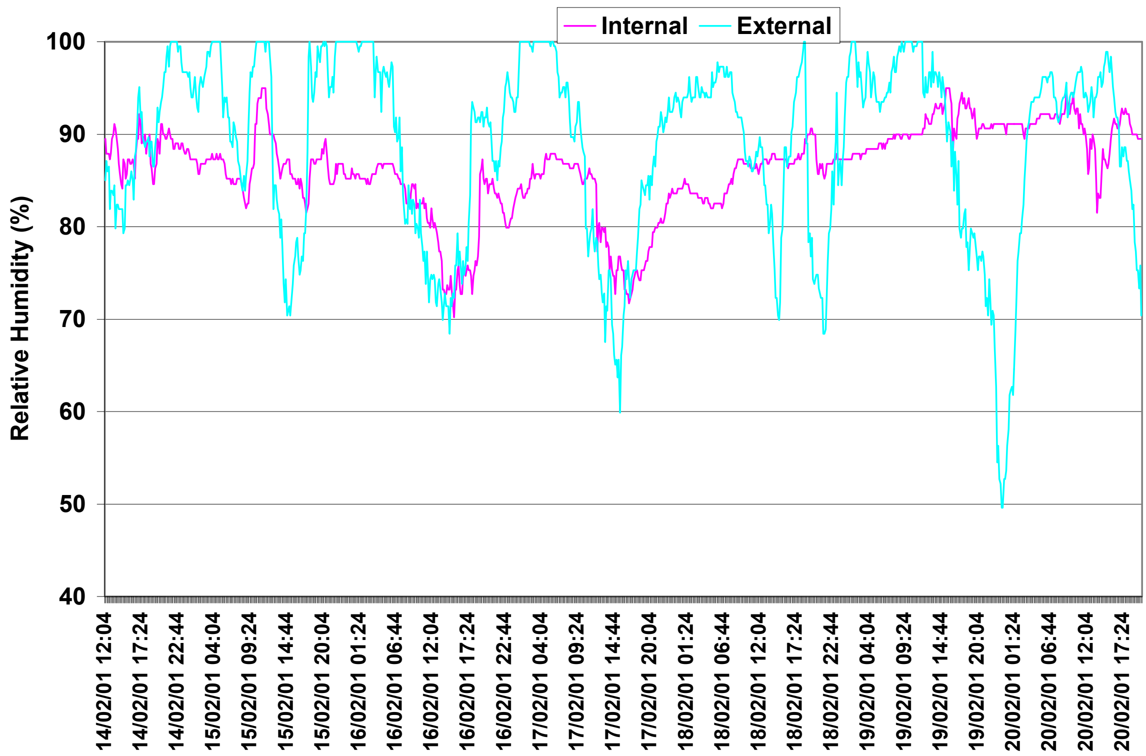

Figure A1.21 – House 2 – Relative Humidity[7] (%) – from February 14th to 20th.

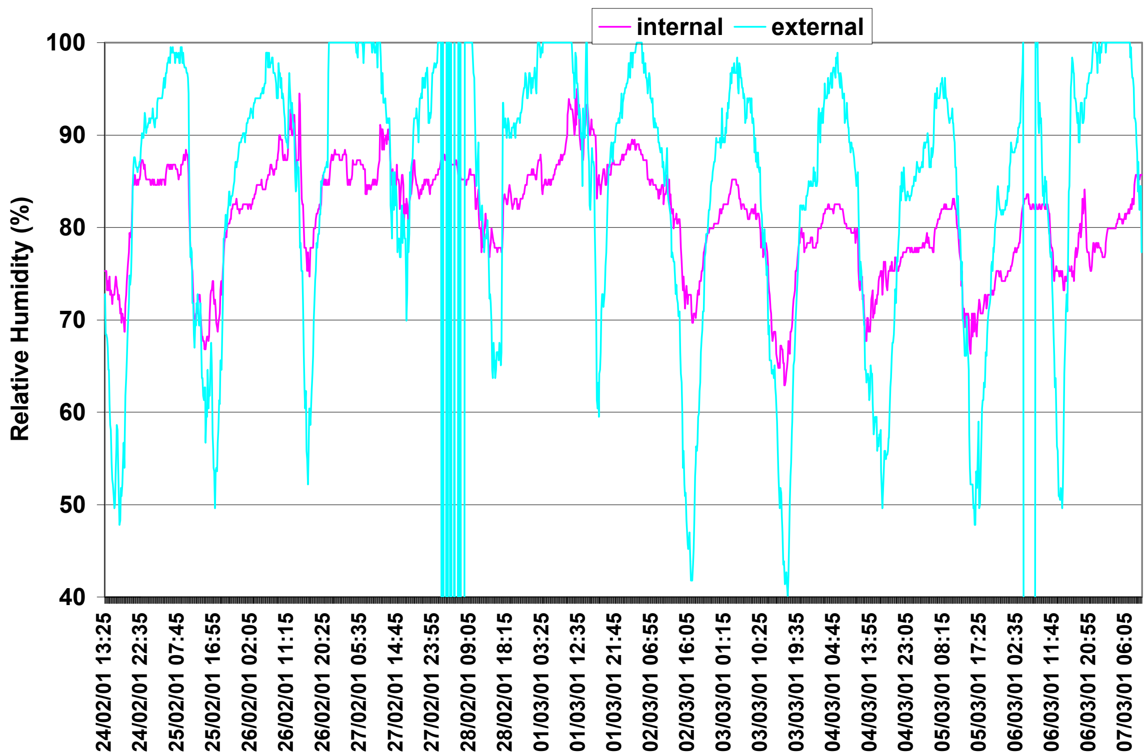

Figure A1.22 – House 2 – Relative Humidity (%) – from February 24th to March 7th.

[7] The internal relative humidity was not registered by the instrument from February 7th to 14th.

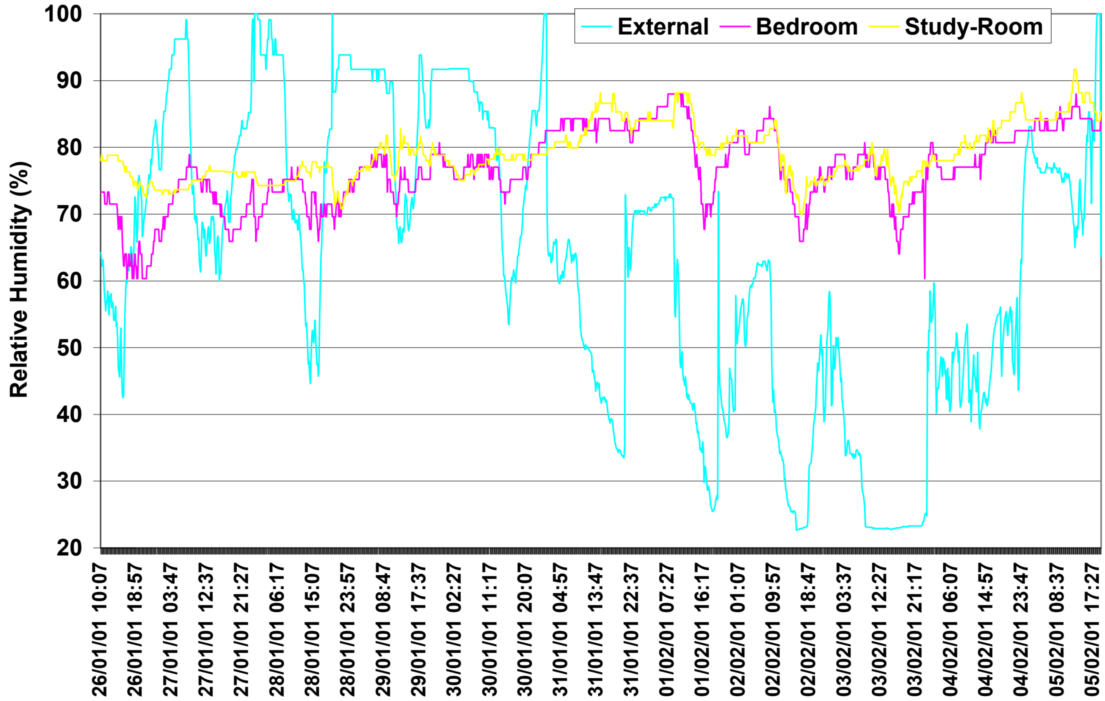

Figure A1.23 – House 3 – Relative Humidity[8] (%) – from January 26th to February 5th.

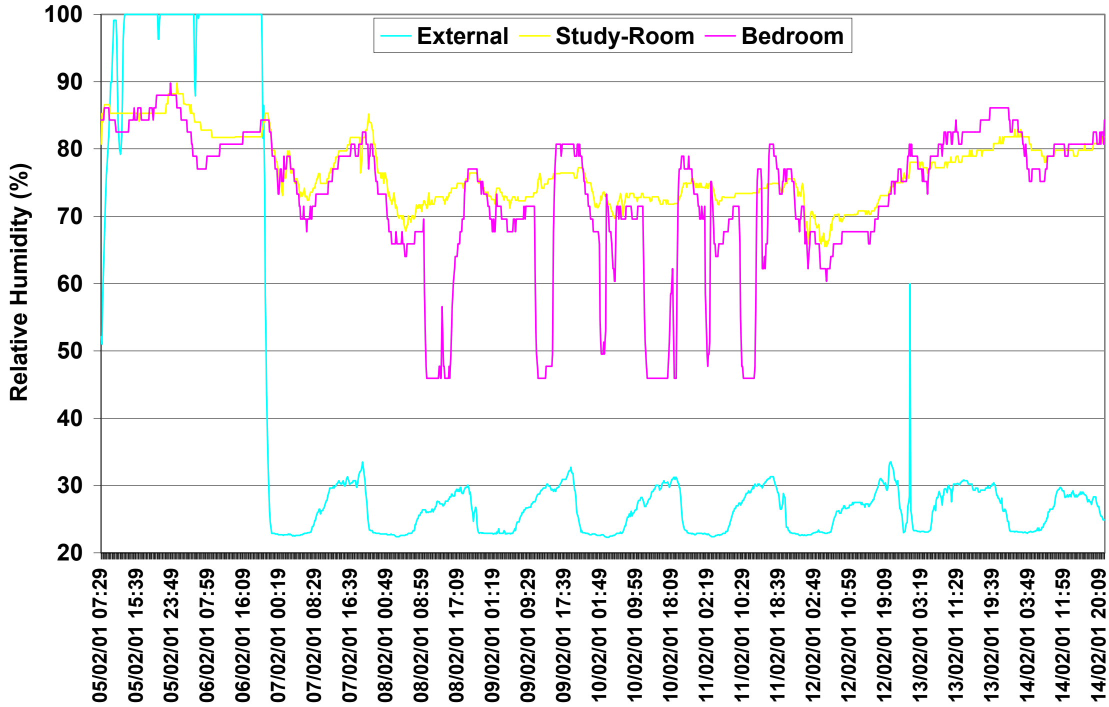

Figure A1.24 – House 3 – Relative Humidity (%) – from February 5th to 14th.

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8 The external sensor of relative humidity started to show problems, registering low values for humidity, which are not according to the reality. Probably, there was some condensation in the instrument, due to strong rain that occurred in the period. From February 15th, this instrument was changed by the one that was measuring inside.

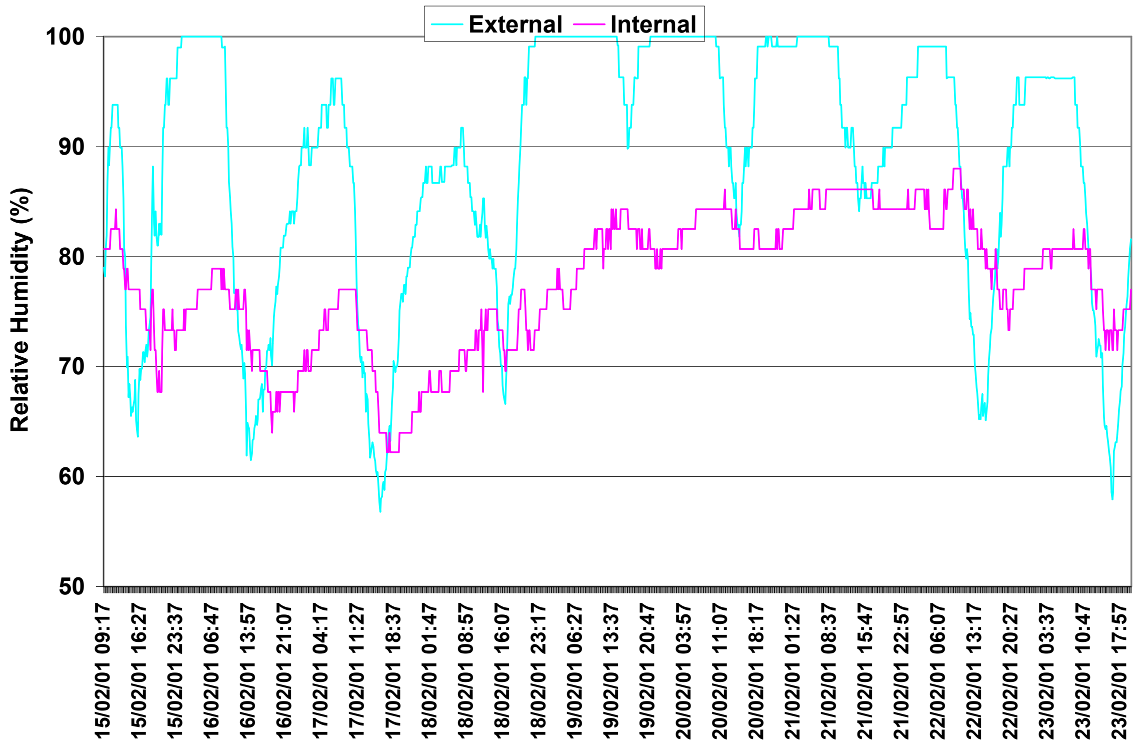


Figure A1.25 – House 3 – Relative Humidity[9] (%) – from February 15th to 23rd.

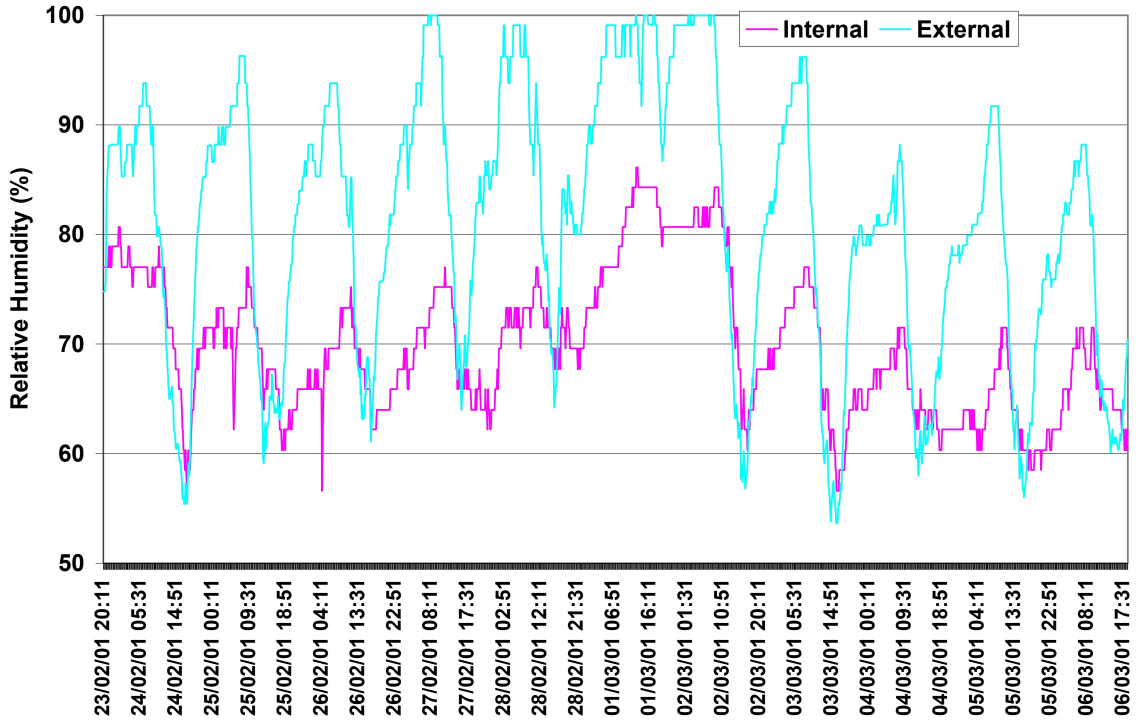


Figure A1.26 – House 3 – Relative Humidity (%) – from February 23rd to March 6th.

9 The latter relative humidity sensor placed outside has not presented problem. From that date, the internal relative humidity is been monitored in only one room.

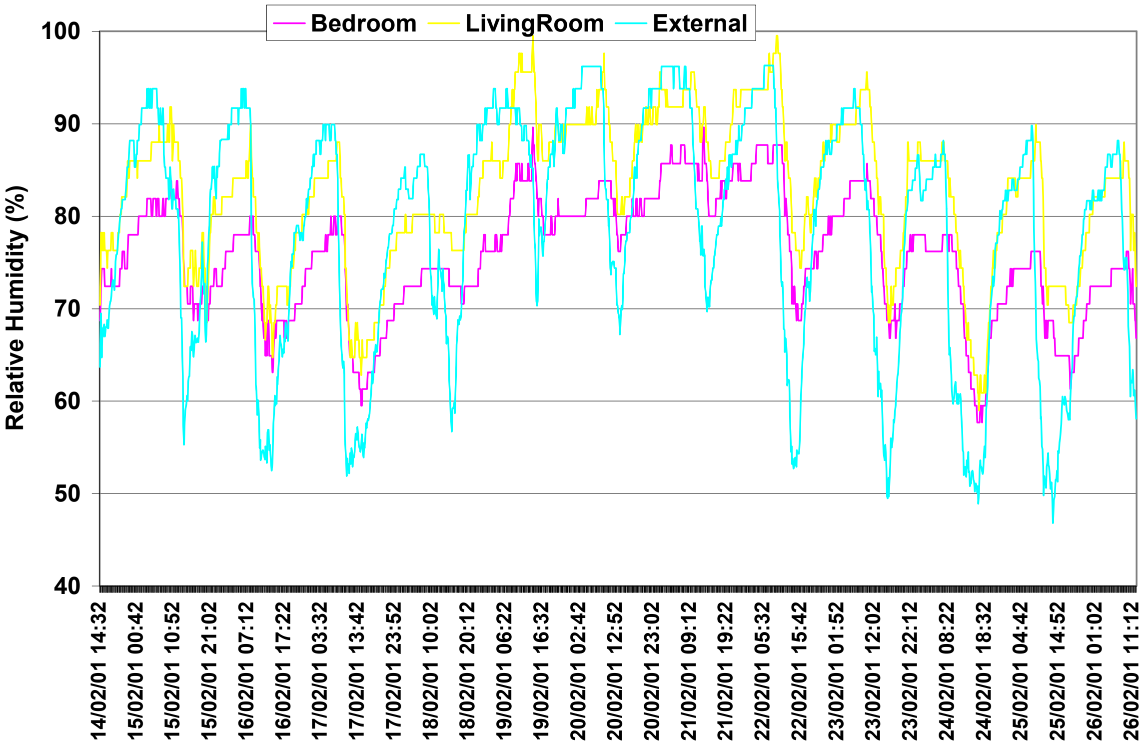


Figure A1.27 – House 4 – Relative Humidity (%) – from February 14th to 26th.

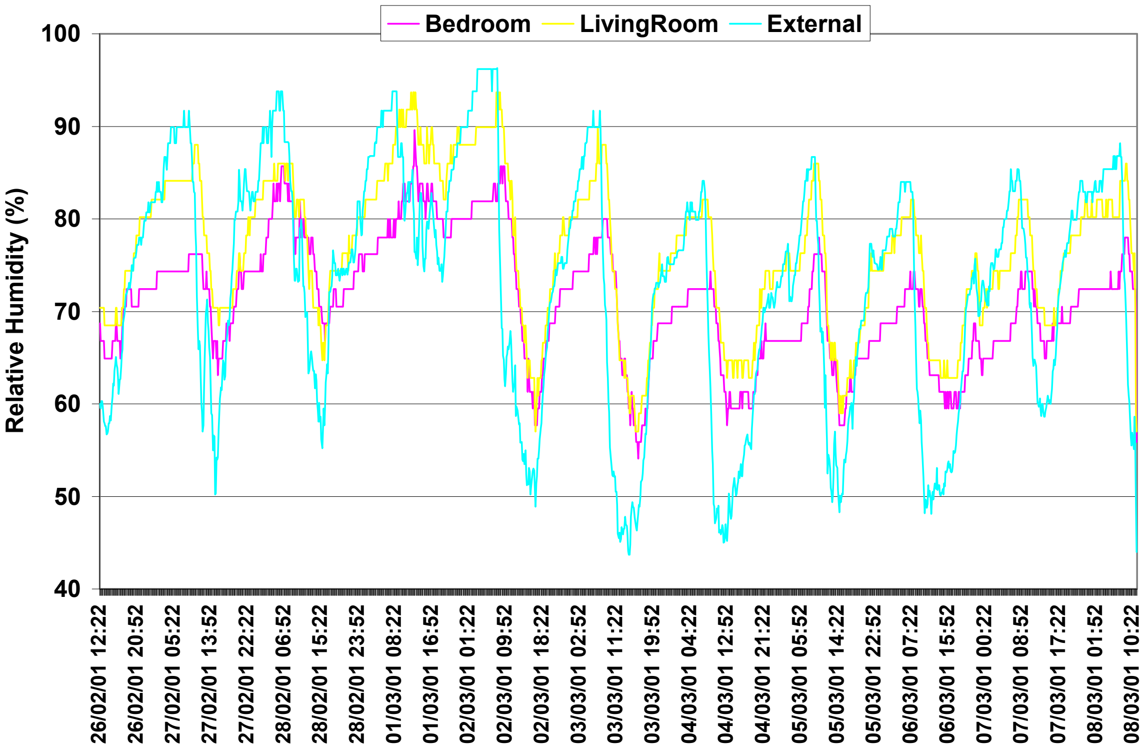


Figure A1.28 – House 4 – Relative Humidity (%) – from February 26th to March 8th.

Appendix A2 - TAS Main Input Data for the Base-case

A2.1 Building Elements:

Building Element	C-Code	Construction Name	Substitute building element	Substitution schedule	Shading feature number
1 Groundfloor	piso/1	slate	0	0	0
2 Internal wall	parede/1	granite wall	0	0	0
3 External wall	parede/1	granite wall	0	0	0
4 Ceiling / Upperfloor	ceiling/5	concrete slab	0	0	0
5 P	door/1	wooden door	0	0	5
6 P2	door/1	wooden door	0	0	0
7 P3	glass/8	3mm clear glass	0	0	0
8 J1	glass/8	3mm clear glass	0	0	4
9 P4	glass/10	3mm clear glass/venetian	0	0	3
10 P5	glass/10	3mm clear glass/venetian	0	0	2
11 J2	glass/9	3mm clear glass/extshade	0	0	1
12 J3	glass/8	3mm clear glass	0	0	0
13 roof2	telhado/1	tile roofing without insul	0	0	0
14 no floor	divide/1	super transparent divide	0	0	0
15 no wall	divide/1		0	0	0

A2.2 Internal Conditions:

A2.2.1. Zone: Living room

Occupation Period	Occupation Duration (h)	Infiltration Air (ach)	Ventilation Air (ach)	Lighting Gains (W/m^2)	Occupancy Sensible Gains (W/m^2)	Occupancy Latent Gains (W/m^2)	Equip. Sensible Gains (W/m^2)	Equip. Latent Gains (W/m^2)
1	11	1.0	0.0	0.0	0.0	0.0	0.0	0.0
2	2	1.0	0.0	0.0	3.0	0.0	7.0	0.0
3	5	1.0	0.0	0.0	3.0	0.0	0.0	0.0
4	6	1.0	0.0	2.0	0.0	0.0	0.0	0.0
5								
6								
7								
8								

A2.2.2. Zone: TV room

Occupation Period	Occupation Duration (h)	Infiltration Air (ach)	Ventilation Air (ach)	Lighting Gains (W/m^2)	Occupancy Sensible Gains (W/m^2)	Occupancy Latent Gains (W/m^2)	Equip. Sensible Gains (W/m^2)	Equip. Latent Gains (W/m^2)
1	8	1.0	0.0	0.0	0.0	0.0	0.0	0.0
2	10	1.0	0.0	0.0	0.0	0.0	0.0	0.0
3	3	1.0	0.0	6.0	1.5	0.0	0.0	0.0
4	3	1.0	0.0	0.0	0.0	0.0	0.0	0.0
5								
6								
7								
8								

A2.2.3. Zone: Study-room

Occupation Period	Occupation Duration (h)	Infiltration Air (ach)	Ventilation Air (ach)	Lighting Gains (W/m^2)	Occupancy Sensible Gains (W/m^2)	Occupancy Latent Gains (W/m^2)	Equip. Sensible Gains (W/m^2)	Equip. Latent Gains (W/m^2)
1	8	1.0	0.0	0.0	0.0	0.0	0.0	0.0
2	5	1.0	0.0	0.0	1.5	0.0	0.0	0.0
3	5	1.0	0.0	0.0	0.0	0.0	0.0	0.0
4	6	1.0	0.0	0.0	0.0	0.0	0.0	0.0
5								
6								
7								
8								

A2.3 Aperture Types:

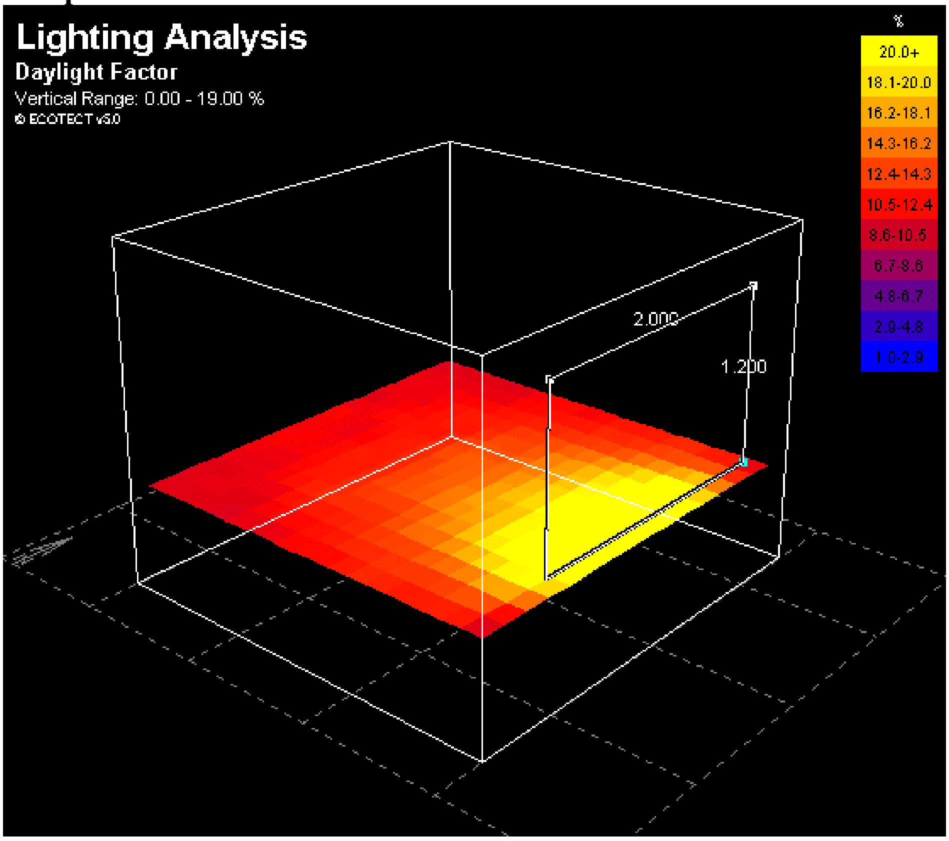
Building element	Window Height (m)	Window Width (m)	Window Area (m^2)	Sheltered?	Aperture Schedule	Openable Proportion
5. P	2.1	1.15	2.41	yes	a	0.50
6. P2	2.1	0.70	1.47	no	1	1.0
7. P3	2.1	2.60	5.46	no	1	0.50
8. J1	1.2	1.15	1.38	yes	a	0.25
9. P4	2.1	1.20	2.52	yes	b	0.25
10. P5	2.1	1.00	2.10	yes	b	0.25
11. J2	1.2	2.00	2.40	yes	b	0.25
12. J3	1.2	1.20	1.44	yes	b	0.25
14. no floor	0.0	0.00	0.00	no	1	1.0
15. no wall	0.0	0.00	0.00	no	1	1.0
17. Pl	2.10	0.70	1.47	yes	a	0.50
19. J4	0.60	0.50	0.30	yes	b	0.25
22. ceiling/ no floor	0.0	0.00	0.00	no	1	1.0

Appendix A3 - Daylight Analysis for Window of the Zone 5

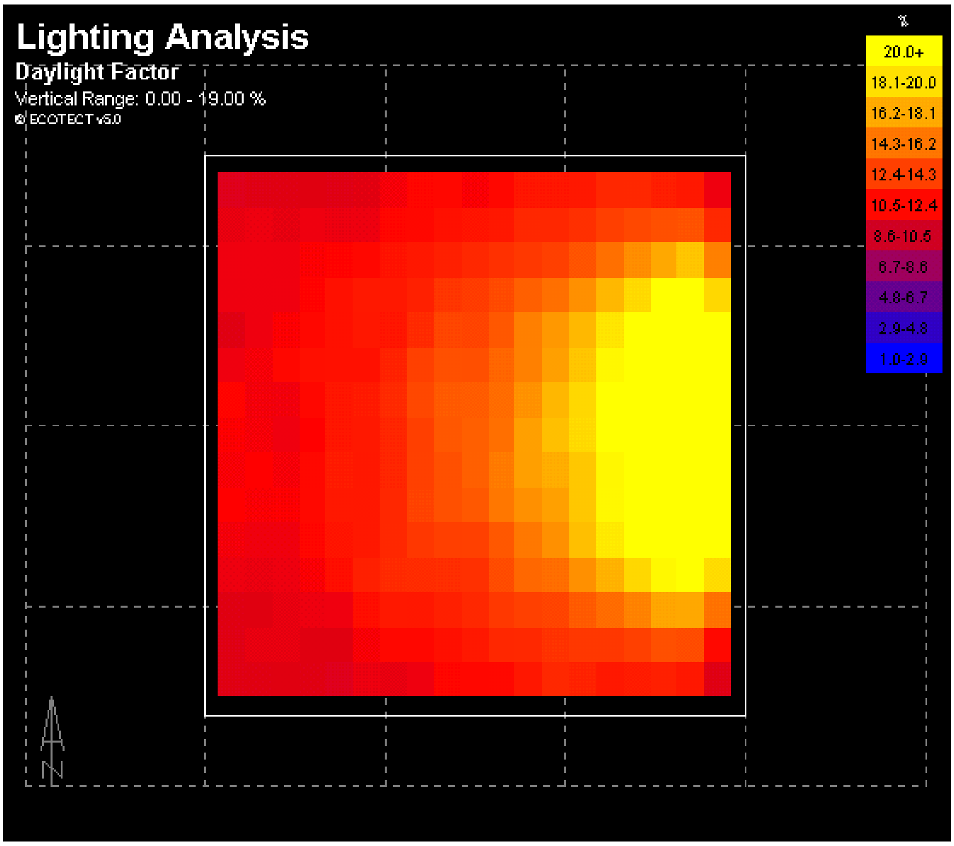
A3.1. Different Sizes of Window: clear glass

A3.1.1. Window to Floor ratio = 32%

Perspective View:

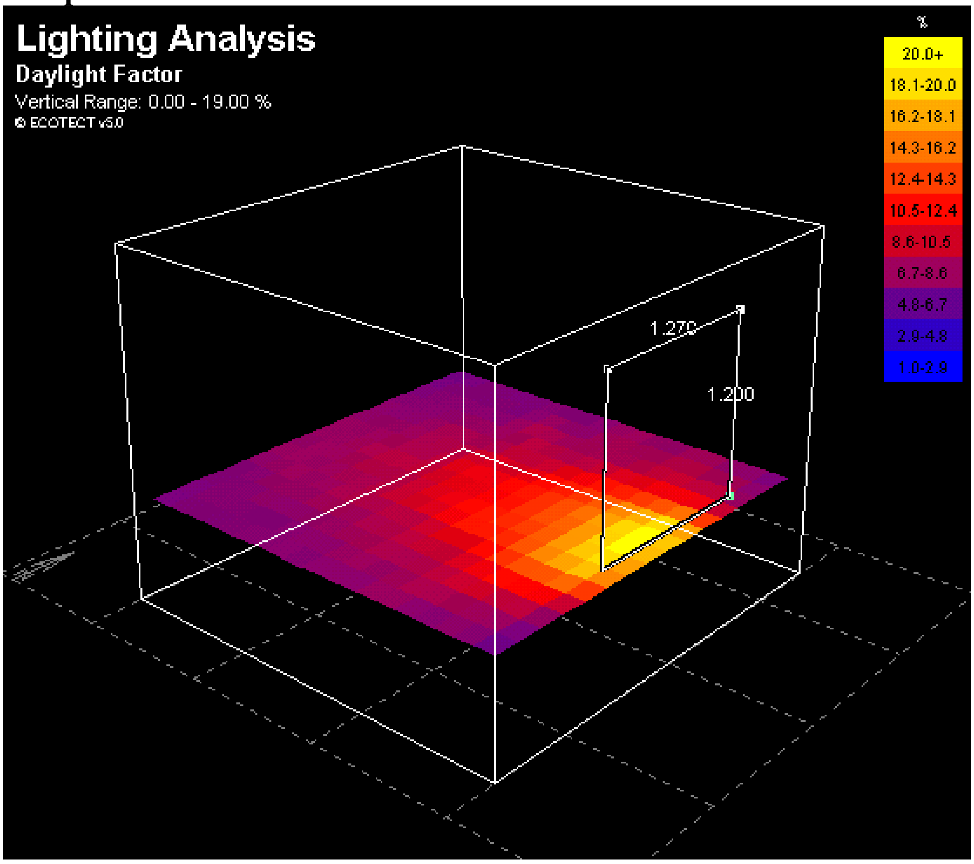


Plan:

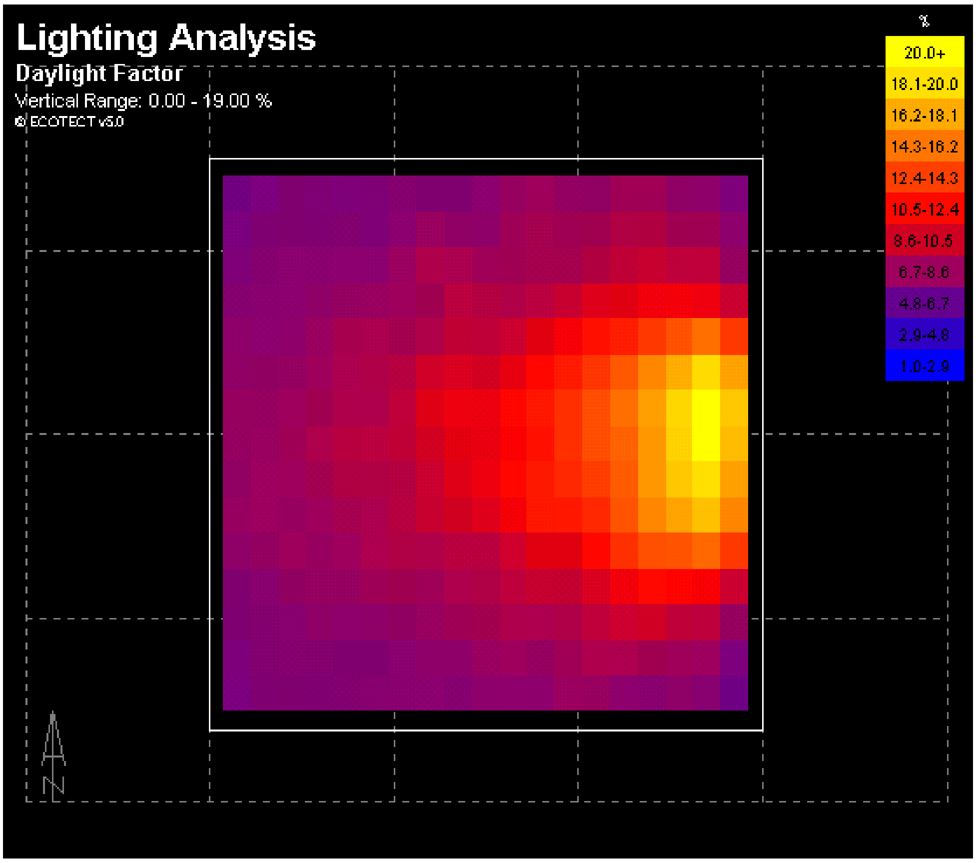


A3.1.2. Window to Floor ratio = 20%

Perspective View:

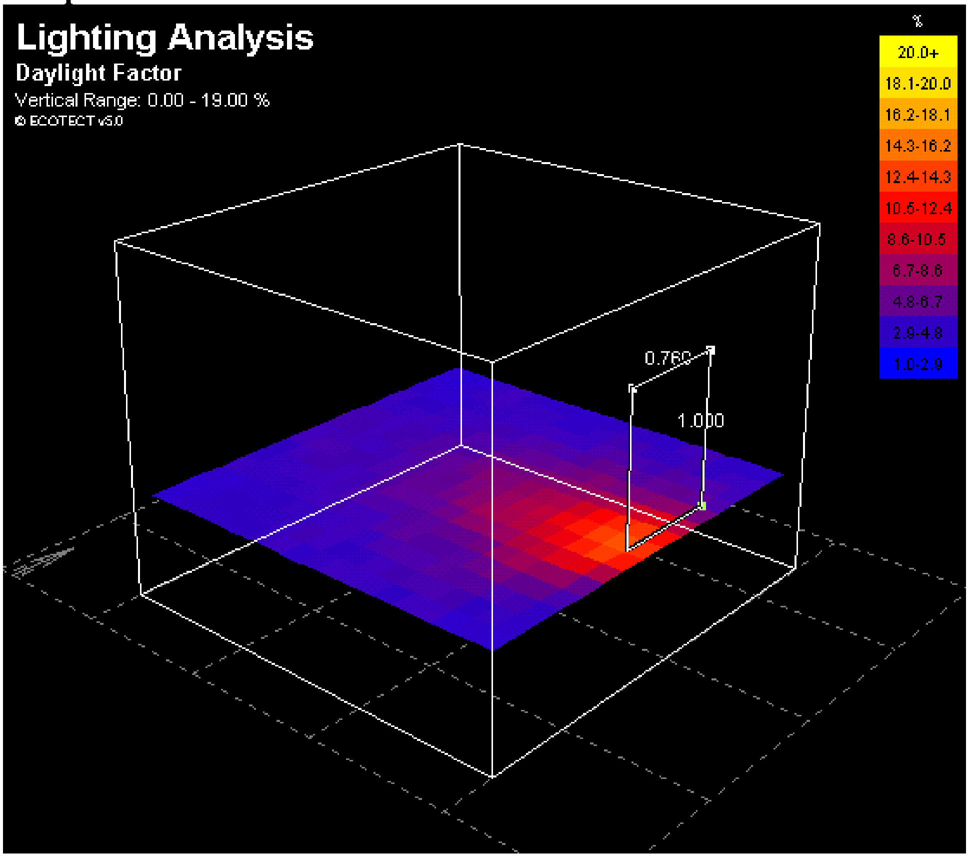


Plan:

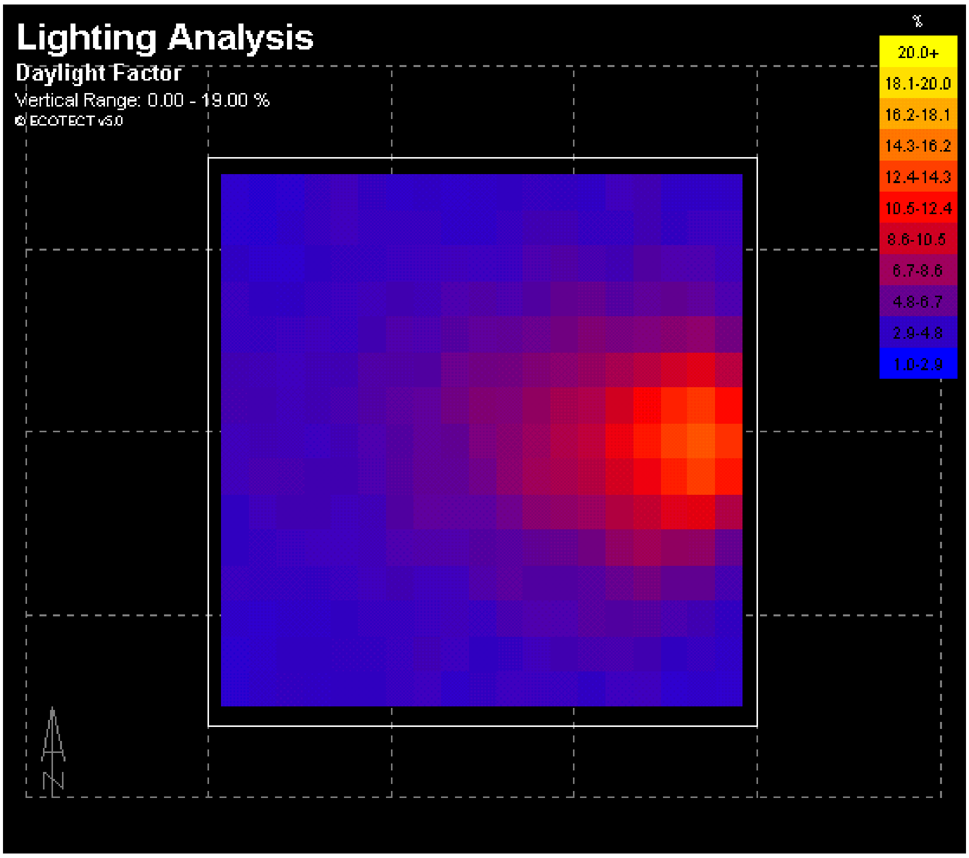


A3.1.3. Window to Floor ratio = 10%

Perspective View:



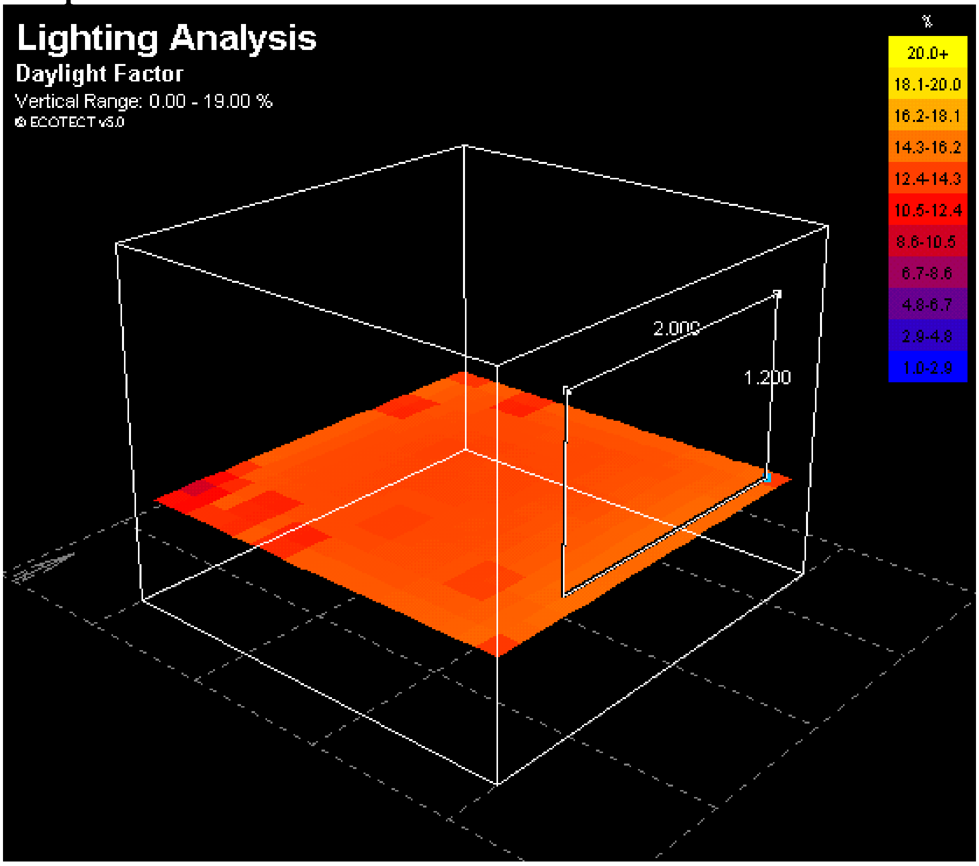
Plan:



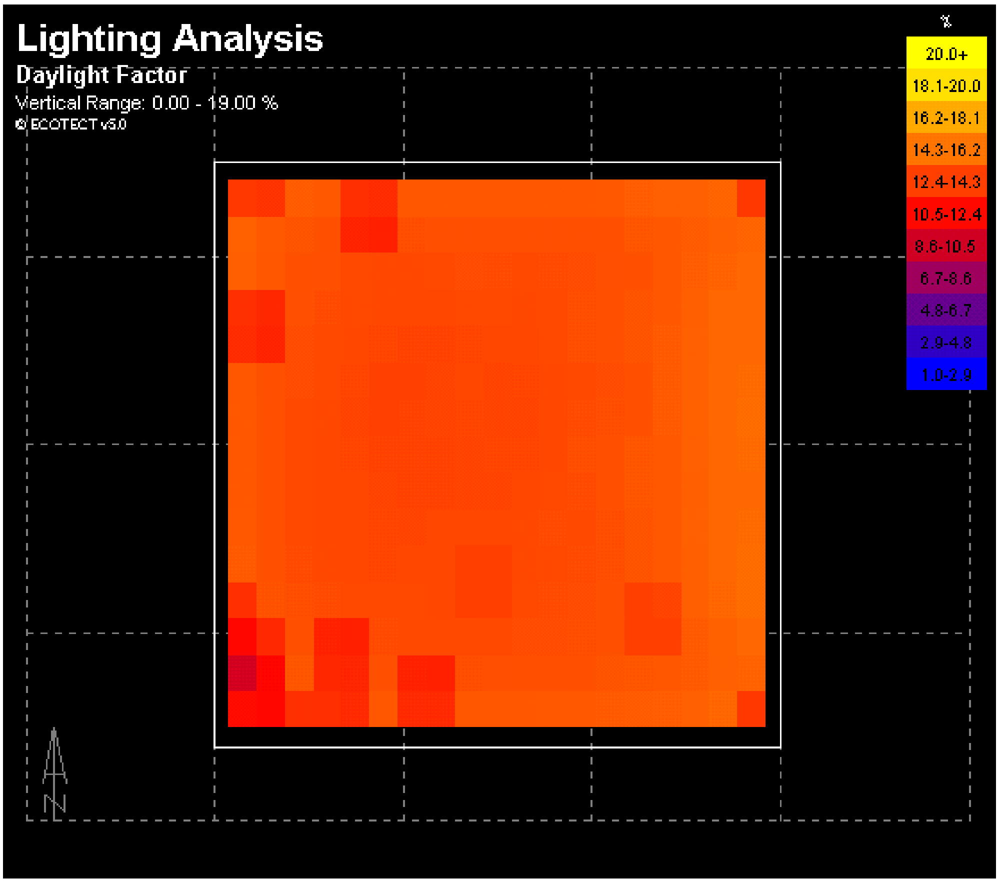
A3.2. Different Sizes of Window: clear glass + external blind (transmittance = 0.07)

A3.2.1. Window to Floor ratio = 32%

Perspective View:

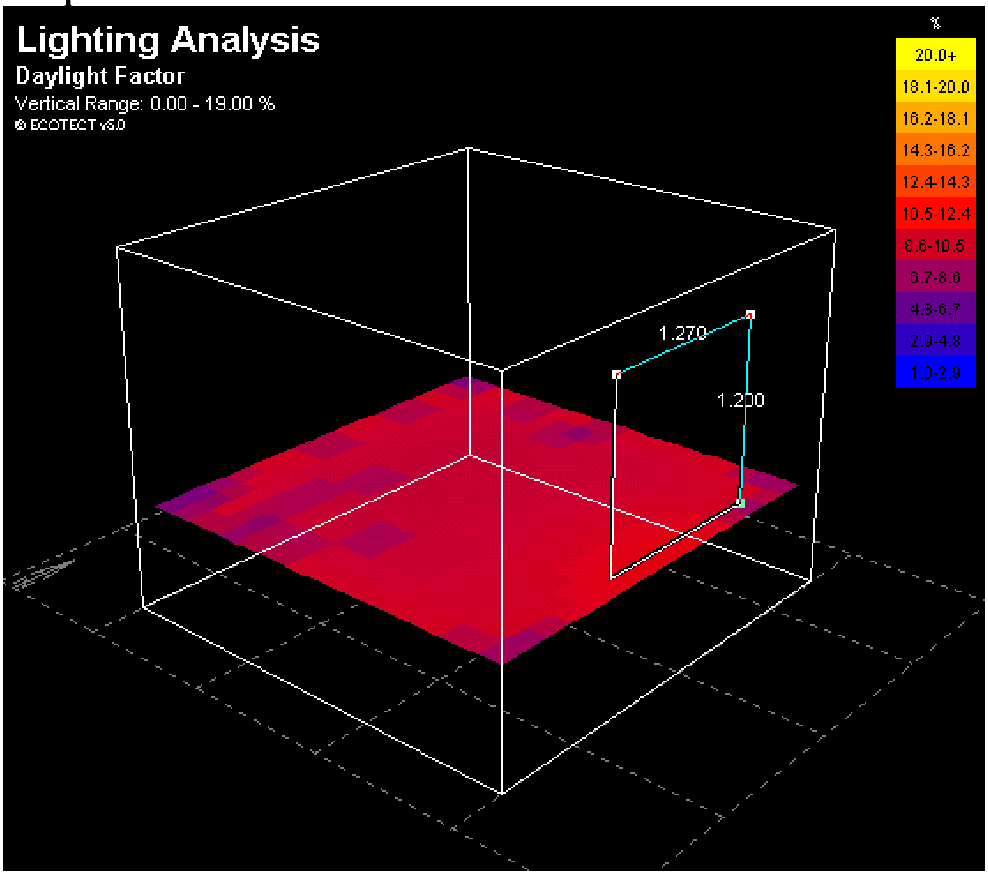


Plan:

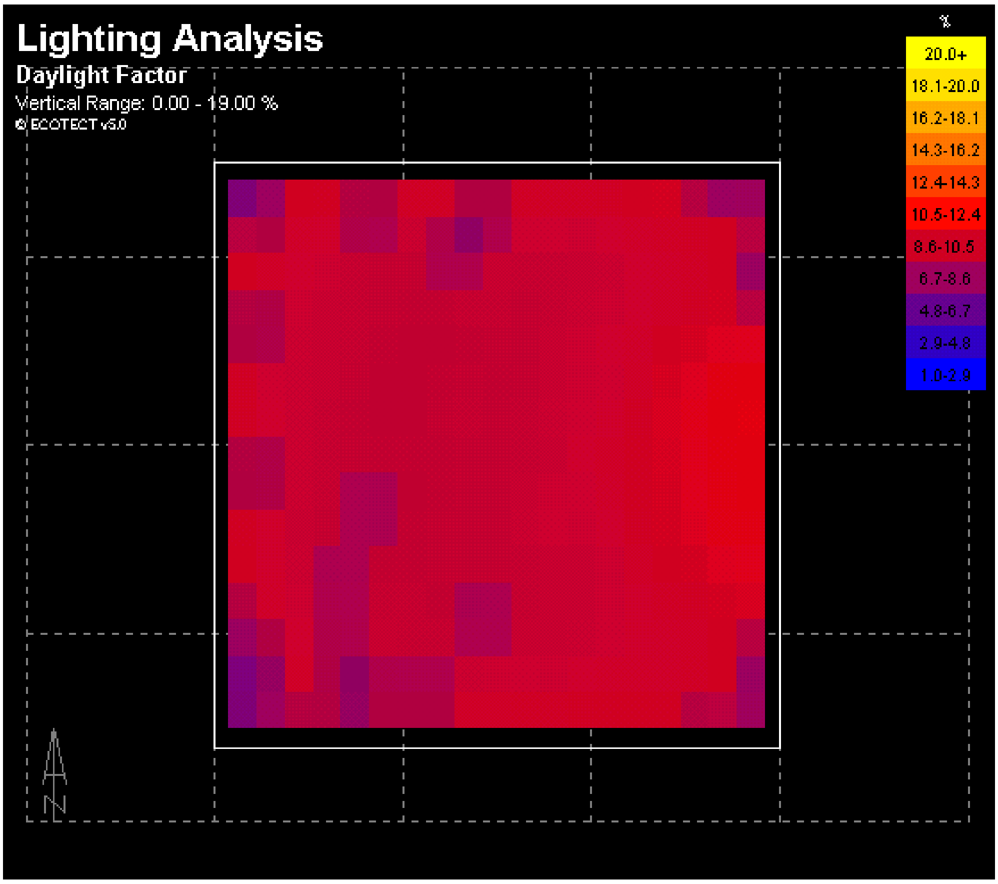


A3.2.2. Window to Floor ratio = 20%

Perspective View:

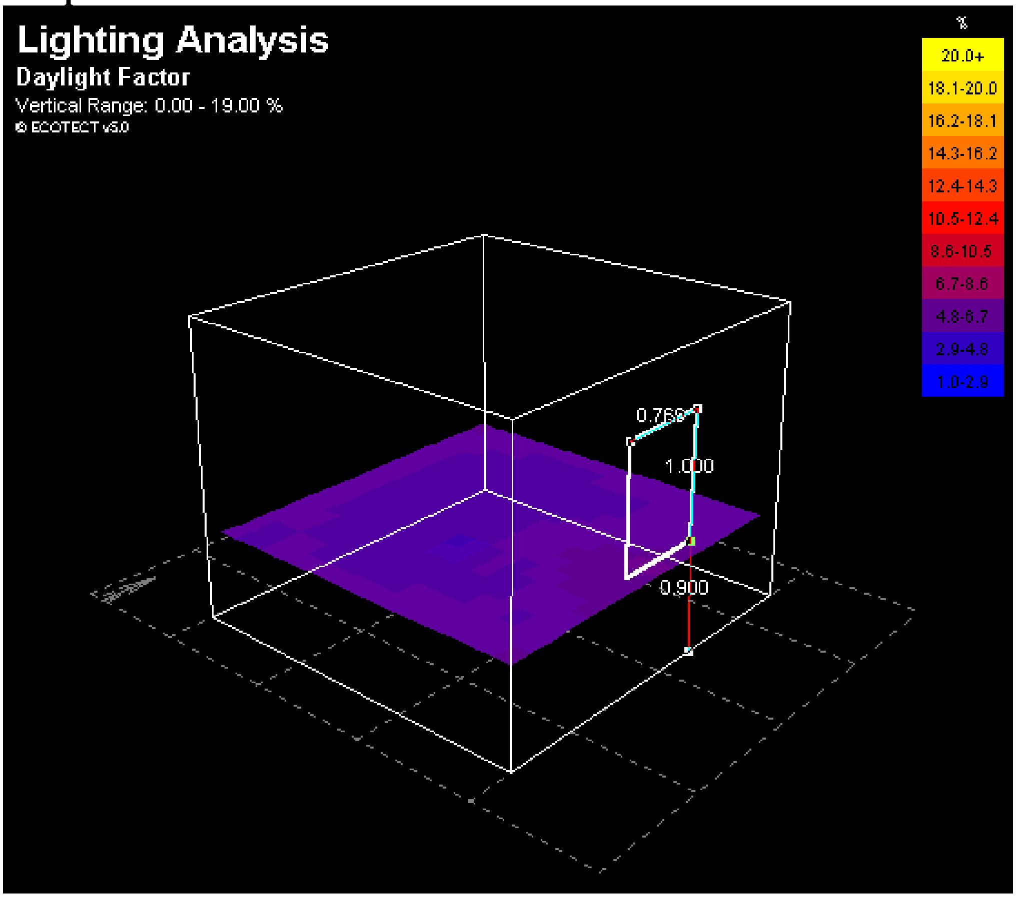


Plan:

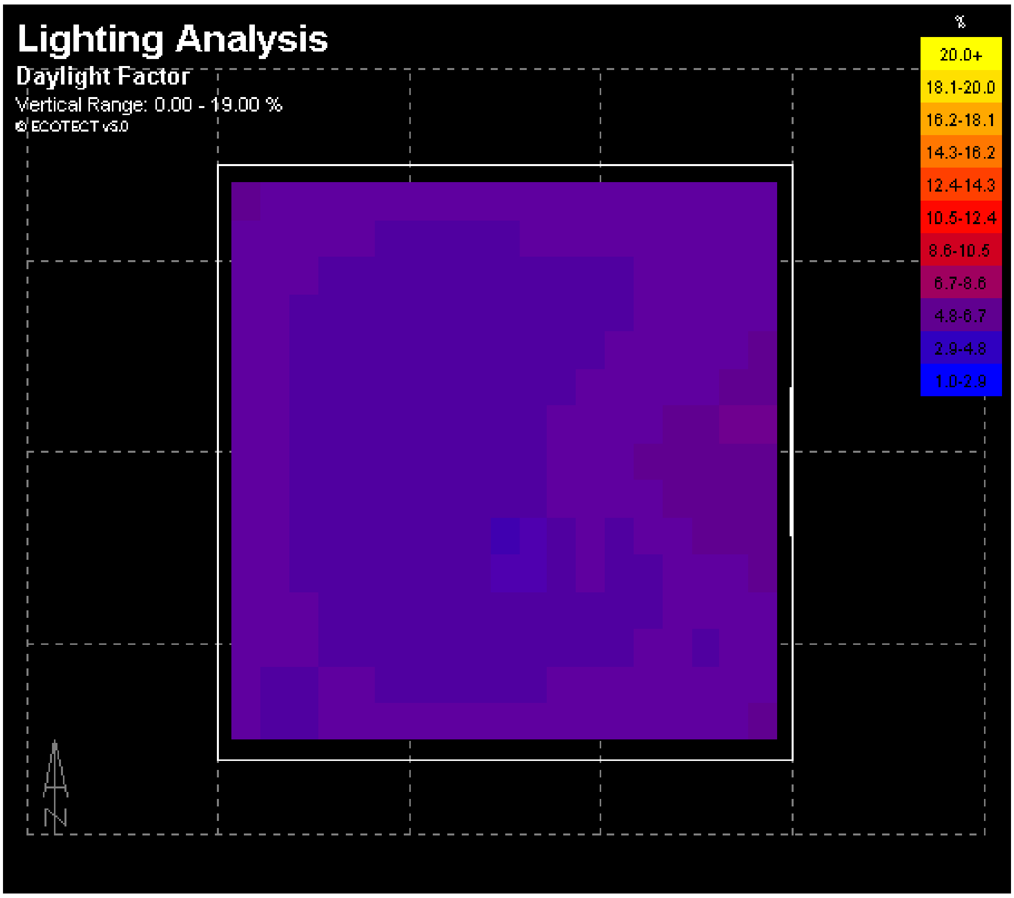


A3.2.3. Window to Floor ratio = 10%

Perspective View:



Plan:



Appendix A4 - Equations representing the correlation studies.

A4.1 Mass area to opening area ratio:

From figure 7.1:

$y = 0.6071x^2 - 7.0357x + 203.14$ ($R^2 = 0.9704$) – Base-case

From figure 7.2:

$y = -0.1786x^2 + 0.6786x + 75.571$ ($R^2 = 0.7866$) – Model Improved

A4.2 Window to floor ratio:

From figure 7.4:

$y = 14.429x + 128$ ($R^2 = 0.9827$) – Base-case

From figure 7.5:

$y = 0.5429x + 71.6$ ($R^2 = 0.5429$) – Model Improved

A4.3 Indoor peak reductions:

From figure 7.7 (Zone 1):

$y = 0.6757x - 2.8576$ ($R^2 = 0.8027$) – No Night Ventilation

$y = 0.8131x - 3.3367$ ($R^2 = 0.8087$) – Natural Ventilation

$y = 0.8079x - 3.2357$ ($R^2 = 0.8089$) – Mechanical Ventilation

From figure 7.8 (Zone 5):

$y = 0.7212x - 4.501$ ($R^2 = 0.7281$) – No Night Ventilation

$y = 0.7858x - 4.5408$ ($R^2 = 0.6941$) – Natural Ventilation

$y = 0.7705x - 4.3484$ ($R^2 = 0.6879$) – Mechanical Ventilation

From figure 7.9 (Zone 1):

$y = 0.8243x - 3.0797$ ($R^2 = 0.8221$) Granite

$y = 0.7219x - 2.7742$ ($R^2 = 0.7797$) Double brick

$y = 0.6236x - 2.3973$ ($R^2 = 0.727$) Single brick

From figure 7.10 (Zone 5):

y = 0.8065x - 3.2019 (R^2 = 0.7611) Granite

y = 0.7213x - 3.2224 (R^2 = 0.6709) Double brick

y = 0.6049x - 2.6206 (R^2 = 0.6604) Single brick

A4.4 Exposed Area of thermal mass:

From figure 7.11 (Zone 1):

y = 2.2952x + 38.994 (R2 = 0.3374) – Base-case

From figure 7.12 (Zone 5):

y = 2.5462x + 174.83 (R2 = 0.8124) – Base-case

From figure 7.13 (Zone 1):

y = 1.3133x + 34.892 (R2 = 0.1409) – Model Improved

From figure 7.14 (Zone 5):

y = 0.2269x + 74.252 (R2 = 0.0183) – Model Improved

A4.5 Daytime Ventilation:

From figure 7.15 (Zone 1):

y = 0.7x + 38.5 (R^2 = 0.3224)

From figure 7.16 (Zone 5):

y = 3.2x + 102.8 (R^2 = 0.9734)

From figure 7.17 (Zone 5):

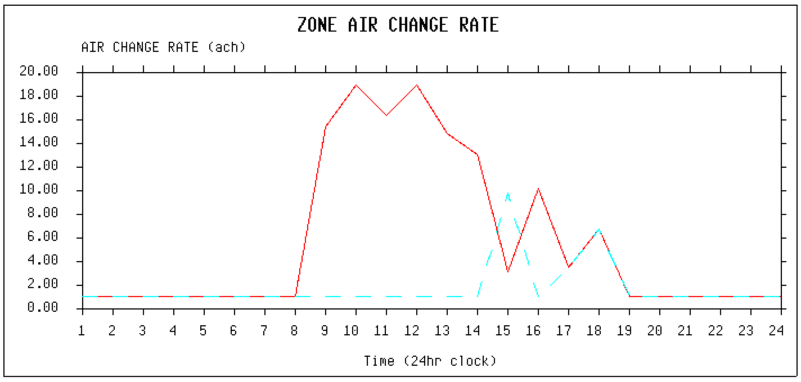
y = 2.5x + 93.7 (R^2 = 0.72) - Shading

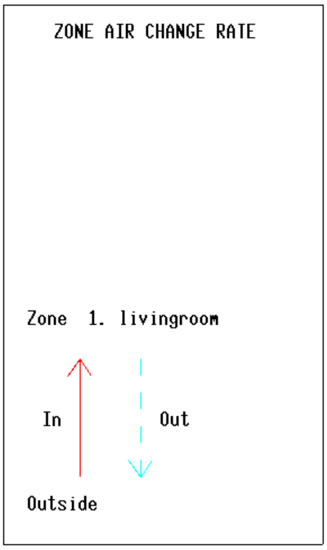
y = 0.9x + 69.3 (R^2 = 0.675) – Shading + Radiant Barrier

Appendix 5 - Daytime Ventilation by Natural Means – Hourly values of airflow.

A5.1. 25% open proportion of window - Zone 1:

Page	Building Name	Building Data File	Version	Time	Date	Consultant	Program
19	house1	house1.bdf.03	67	16:33:04	29:Aug:03		A-Tas 8.40





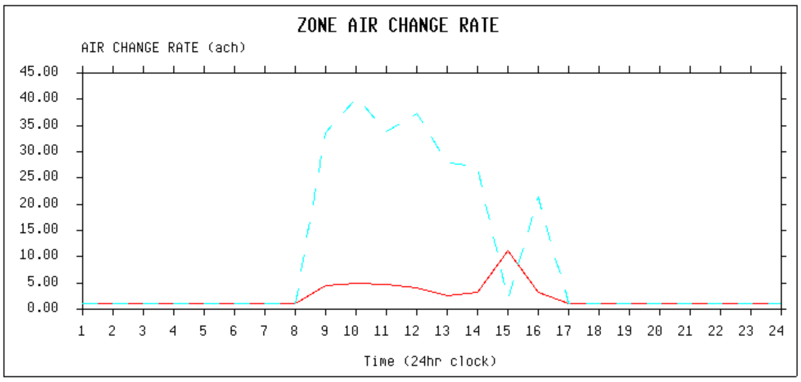
Time (24 hr clock)	Air Flow In (ach)	Air Flow Out (ach)	Time (24 hr clock)	Air Flow In (ach)	Air Flow Out (ach)
1	1.000	1.000	13	14.810	1.000
2	1.000	1.000	14	13.075	1.000
3	1.000	1.000	15	3.135	9.764
4	1.000	1.000	16	10.186	1.000
5	1.000	1.000	17	3.493	3.492
6	1.000	1.000	18	6.742	6.742
7	1.000	1.000	19	1.000	1.000
8	1.000	1.000	20	1.000	1.000
9	15.470	1.000	21	1.000	1.000
10	18.961	1.000	22	1.000	1.000
11	16.379	1.000	23	1.000	1.000
12	18.993	1.000	24	1.000	1.000

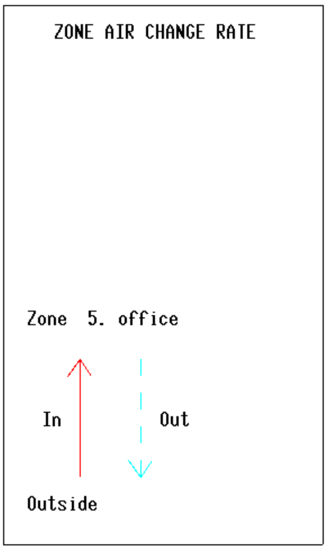
Day 46: Thursday, Feb 15 (WEEKDAY)
Weather: BR_Florianop_fev.wfl

Print
Exit

A5.2. 25% open proportion of window - Zone 5:

Page	Building Name	Building Data File	Version	Time	Date	Consultant	Program
20	house1	house1.bdf.03	67	16:41:17	29:Aug:03		A-Tas 8.40





Time (24 hr clock)	Air Flow In (ach)	Air Flow Out (ach)	Time (24 hr clock)	Air Flow In (ach)	Air Flow Out (ach)
1	1.000	1.000	13	2.638	28.112
2	1.000	1.000	14	3.127	26.879
3	1.000	1.000	15	11.061	1.933
4	1.000	1.000	16	3.313	21.423
5	1.000	1.000	17	1.000	1.000
6	1.000	1.000	18	1.000	1.000
7	1.000	1.000	19	1.000	1.000
8	1.000	1.000	20	1.000	1.000
9	4.541	33.636	21	1.000	1.000
10	4.919	40.247	22	1.000	1.000
11	4.631	33.870	23	1.000	1.000
12	4.052	37.185	24	1.000	1.000

Day 46: Thursday, Feb 15 (WEEKDAY)
Weather: BR_Florianop_fev.wfl

Print
Exit

Appendix 6 – Glossary and List of Symbols

Absorptance – the ratio of absorbed to incident solar radiation on a surface.

Air Change per Hour (ach) – a unit that denotes the number of times a house exchanges its entire volume of air with outside air in an hour.

Air Temperature – the temperature of the air. In TAS, air temperature is calculated by balancing heat gains and losses at the air point.

Aperture Factor – area of the aperture as a fraction of the area of the surface it is associated with.

Conduction – the heat moving from a warmer to a colder region in the same substance without mass transfer; this type of heat transfer depends on the thermal conductivity of the material.

Convection – heat transfer between a surface and adjacent fluid (usually air or water) and by the flow of fluid from one place to another.

Convection, Forced – convection resulting from forced circulation of a fluid, as by fan, jet or pump.

Convection, Natural – circulation of gas or liquid (usually air or water) due to differences in density resulting from temperatures changes.

Daylight – visible part of global solar radiation.

Daylight factor – ratio of the illuminance at a given point on a given plane due to the light received directly or indirectly from a sky of assumed or known illuminance distribution, to the illuminance on a horizontal plane due to an unobstructed hemisphere of this sky.

Degree-hour for cooling – the cumulative temperature difference above a base temperature (T_b).

Dehumidification – removal of water vapour from air by chemical or physical methods.

Density (ρ) – the mass of a unit of volume of material.

Direct Gain – the transmission of sunlight directly into the space to be heated where it is converted to heat by absorption on the interior surfaces.

Emissivity – the ratio of the radiant energy emitted from a surface at a given temperature to the energy emitted by a black body at the same temperature.

Glare – condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or to extreme contrast.

Global Radiation – the total solar radiation falling on a surface, e.g. the sum of the direct and diffuse radiation.

Heat Capacity (HC)– the amount of heat necessary to raise the temperature of a unit volume of the material or unit area of the surface by one degree. Volumetric Heat Capacity is used to characterise a material, while Heat Capacity is used in the description of building components.

Humidity – water vapour within a given space.

Illuminance – quotient of the luminous flux incident on an element of the surface containing the point, by the area of that element. Lux – SI unit of illuminance: illuminance produced on a surface of area of 1 square meter by a luminous flux of 1 lumen uniformly distributed over that surface.

Infiltration – the uncontrolled movement of outdoor air into the interior of a building through cracks around windows and doors or in walls, roofs and floors.

Internal Gains – the energy dissipated inside the space by people (body heat) and appliances (lighting, cooker, etc.) A proportion of this energy contributes to the space heating requirements.

Mass-area-to-Opening-area Ratio – the ratio of the total surface area of massive elements in a direct-gain building to the direct gain glazing area. Massive elements include floors, walls or ceilings.

Mean Radiant Temperature (MRT) – the weighted average of the zone's surface temperatures, modified by the effects of radiant gains (plant, incidental gains and the diffuse component of solar gain). The mean radiant temperature calculated by TAS takes account of the diffuse solar radiation flux, which an occupant of the zone would experience and which would contribute to the occupant's perception of radiant temperature.

Mean Bias Error (MBE) – indicates the mean difference between different data. In this thesis, between the predicted values from the measured values.

Moisture Content – (or Humidity ratio): the ratio of the mass of water vapour to the mass of dry air.

Obstruction – anything outside a building, which prevents the direct view of part of the sky.

Overcast Sky – cloudy sky.

Relative Humidity (RH) – the ratio of the amount of water vapour in the atmosphere to the maximum amount of water vapour that could be held at a given temperature.

Resultant Temperature – the average of air temperature and mean radiant temperature.

Saturation Point – maximum amount of water vapour that is held by a given temperature (which corresponds to a Relative Humidity of 100%).

Solar absorptance – the fraction of incident solar radiation that is absorbed upon striking a surface.

Solar Gain – solar radiation passing through glass areas, which contributes to space heating.

Specific Heat (c) - the amount of heat required to raise the temperature of a unit mass of a material by one degree (and thus the heat stored inside a material).

Sensible Heat – the heat content causing an increase in the temperature.

Solar Radiation – radiation emitted by the sun, including infrared radiation, ultraviolet radiation and visible light.

Stratification - phenomenon, which is result of the hot air being collected near the ceiling due to the difference in air densities.

Surface coefficient (h) – the reciprocal of the thermal resistance of the air film adjacent to the surfaces. Surface coefficient comprises two factors: radiative (h_r) and convective (h_c) exchanges. (h_i for internal and h_e for external surfaces).

Temperature Swing – the range of temperature between day and night.

Thermal Conductivity (λ) - the rate of heat flow across a unit area of a homogeneous material of unit thickness.

Thermal Resistivity ($1/\lambda$) – reciprocal of thermal conductivity. This parameter describes the resistance of materials and air spaces to heat transfer.

Thermal Conductance (c) – the thermal transmittance through 1 square meter of material of a given thickness for each K temperature difference between its surfaces. The reciprocal of thermal conductance is the thermal resistance (r) of an element.

Thermal Resistance (R) –. The total thermal resistance of a building component to the heat flow between indoor and outdoor air.

Thermal Transmittance (U-value)– the thermal transmission through 1 square meter area of a given structure (a building element): it is the reciprocal of the total thermal resistance R.

Thermal Diffusivity ($\propto$) – the ratio between the thermal conductivity and the volumetric heat capacity.

Thermal Effusivity (b) – the capacity of a material to absorb and release heat. It is the square root of the product of thermal conductivity, density and specific heat.

Thermal insulation – a material having a relatively high resistance to heat flow and used principally to retard heat flow.

Window to Floor Ratio – the ratio of the area of window to the floor area.