University
of Aveiro
2014

Department of Civil Engineering

Luis Carlos Ferreira Caleiro

Dynamic Simulation of Strategies for Thermal Comfort using Phase Change Materials

Simulação Dinâmica de Estratégias para Conforto Térmico usando Materiais de Mudança de Fase

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Dissertation to be presented to University of Aveiro to meet the partial requirements necessary to obtain a Master's degree in Civil Engineering, written under the scientific orientation of Dr. Romeu da Silva Vicente, Assistant Professor at the Department of Civil Engineering of University of Aveiro and under the scientific co-orientation of Dr. Maria Fernanda da Silva Rodrigues, Assistant Professor at the Department of Civil Engineering of University of Aveiro.

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acknowledgements

With this, the final and most important step into my academic graduation is complete. This work has showed me how dedicated one must be in order to finish a project that upholds a high standard of quality and scientific value.
It has been a constant test on my values as a human being and a big contributor to my betterment as a person.

With that in mind, I'd like to thank my scientific orientator and professor, Dr. Romeu da Silva Vicente for his time and knowledge and my co-orientator and Professor, Dr. Fernanda Rodrigues for her help and words of encouragement.

A special thanks is in order to the PhD student, António Figueiredo, for his help was precious through the early stages of this work, and was always ready and available to help.

An equal important person to thank is my friend José Figueira, who never doubted me and helped me whenever possible.

At last, would like to thank my parents and brother, without whom, I'd of never been able to complete this work.

Keywords PCM, Phase Change Material, DuPont™ Energain®, Thermal Comfort, Dynamic Building Simulation

abstract Nowadays, as global warming becomes one of the most urgent problems in the world, there is a need to find better ways to utilize energy: not only in the field of energy production, transmission, distribution, and consumption, but also in the area of energy storage. With energy storage technologies, it is possible to overcome the contradiction between the energy production and consumption, alleviate the tense production load of power plants at peak hours, and reduce consumers' electricity costs by avoiding higher peak hour tariffs.

Thermal energy storage, or heat and cold storage, allows the storage of heat or cold to be used later. This method needs to be reversible so it allows for multiple cycles. The technology that was studied for this effect was Phase Change Materials or PCMs.

With that in mind, and with the help of dynamic building simulation software, EnergyPlus, several scenarios of an existing build that has PCM incorporated were studied in order to ascertain the real effect the technology is having on the case study, including thermal comfort.

Palavras-chave

PCM, Materiais de Mudança de Fase, DuPont™ Energain®, Conforto Térmico, Simulação Dinâmica de Edificios

resumo

Hoje em dia, com o aquecimento global a tornar-se um dos problemas mais urgentes da Terra, há necessidade de encontrar melhores maneiras de utilizar energia: não apenas no campo da produção de energia, transmissão, distribuição e consumo, mas também na área de armazenamento de energia. Com tecnologias de armazenamento de energia, é possível de ultrapassar a contradição entre a produção e consumo, aliviar a tensão que existe na produção nas estações de energia nas horas de pico e reduzir o custo de electricidade aos utentes ao evitar as tarifas nas horas de pico.

A armazenagem de energia calorífica, do calor e frio, permite o armazenamento de calor ou frio para ser usado mais tarde. Este método precisa de ser reversível para permitir vários ciclos deste processo. A tecnologia estudada para este efeito foi os materiais que mudam de fase, ou PCMs (Phase Change Materials).

Com isto em mente, e com a ajuda de software de simulação dinâmica, EnergyPlus, vários cenários de um edifício existente que tem PCM incorporado foram estudados em ordem de poder concluir o verdadeiro efeito que a tecnologia está a ter no caso estudo, incluindo o conforto térmico.

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Chapter 1

Introduction

Chapter 1- Introduction

1.1.Overview

Energy consumption levels throughout the world are very high, but 40% of the total used energy is attributed to buildings alone. This includes energy used for controlling the climate in buildings, energy used for appliances, lightning and other installed equipment (Laustsen, 2008).

In Portugal, with around 3,9 million houses, the building's sector contribute to a 17.7% of the final energy consumption and 30% of the electricity consumption (ADENE, 2012).

As evidenced by Figure 1, most of the energy consumed comes from heating rooms and living space.

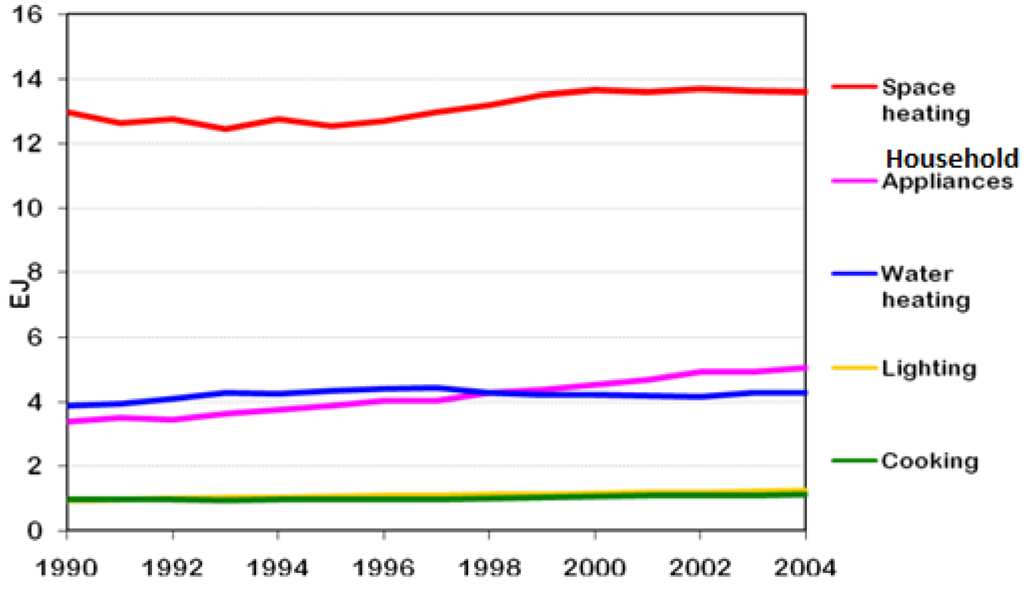

Figure 1-Energy Consumption by type; source: 30 years of energy use in IEA countries. Y axis- EJ=Exajoule=10^{18} J; adapted from (Laustsen, 2008)

Nowadays, as global warming becomes one of the most urgent problems in the world, there is a need to find better ways to utilize energy: not only in the field of energy production, transmission, distribution, and consumption, but also in the area of energy storage. With energy storage technologies, it is possible to overcome the contradiction between the energy production and consumption, alleviate the tense production load of power plants at peak hours, and reduce consumers' electricity costs by avoiding higher peak hour tariffs.

Moreover, energy storage technologies are badly needed to aid in the utilization of renewable energy sources. Currently, most of the renewable energy sources, especially wind energy and solar energy, are time-constrained energy sources, whose available energy densities are variable and unevenly distributed during different daily hours. Therefore, energy storage systems can be used to store the excess renewable energy in high production hours, make up for the low production valleys, and better integrate renewable energy generation into the local electricity grids (Sunliang *et al*, 2010).

Phase change materials (PCMs) represent a technology that may reduce peak loads and HVAC energy consumption in buildings. It has indoor temperature stabilization potential, and peak load reduction potential. PCM-oriented research on buildings has investigated two primary applications: passive and active building systems. Previous PCM studies have shown that they can have important benefits in relation to thermal comfort, energy savings, and perhaps HVAC downsizing when thermalstorage is added to buildings (Tabares *et al*, 2012).

In conclusion, such high energy consumptions have detrimental effects on the environment, but also contribute to the rapid disappearance of fossil fuels. It must be avoided by carefully studying and planning energy efficient solutions that help reduce heating and cooling loads and by consequence, increase thermal comfort for the users.

1.2.Objectives of the dissertation

One of the main objectives of this dissertation is to determine whether the usage of PCMs in the studied building is working as intended. As such, dynamic building simulation software (in this case, EnergyPlus) will be used to model and analyse the effect it is having by comparing two rooms, one without PCMs and one with. Several other studies will be carried out, such as including PCM on walls that currently do not have it, different types of PCMs, dividing the room in half and a solution for comfort depending on the results.

Another objective is to determine how comfortable users are in all of the scenarios by using standard EN15251 which provides the framework for this analysis.

This document was also written in a way that is easy to read, simple and objective.

1.3.General Structure of the Dissertation

This document will be divided into the following sections:

- Chapter 1, Introduction in which is described and commented the high energy use of current buildings, the focus of the study in question and the objectives planned for this dissertation
- Chapter 2, Introduction to Phase Change Materials (PCMs) and main applications
- Chapter 3, Introduction to Dynamic Building Simulation
- Chapter 4, Description of the case study
- Chapter 5, Dynamic Simulation applied to the case study
- Chapter 6, Data analysis of the different models developed in Chapter 5
- Chapter 7, Conclusions and future developments
- Bibliographic references

Chapter 2

Phase Change Materials (PCMs)

Chapter 2- Phase Change Materials (PCMs)

2.1 Introduction

In thermodynamics, a phase is defined as a state of matter which is homogeneous throughout, not only in chemical composition, but also in physical state. The concept of solids and liquids is related primarily to the kinetics (or energy) of the molecules. Solids consist of molecular structures where the mobility is effectively zero and the molecules only vibrate, while liquids possess larger amplitude motion and a higher degree of disorder compared to solids. Changing between a low energy phase and a higher energy phase therefore requires the addition or removal of energy. The addition of energy to a material leading to melting is known as an endothermic process, while the removal of energy leading to freezing is known as an exothermic process.

Melting/ crystallisation/ vaporisation/ condensation are 1st order transitions. These transitions are explained simply as involving a latent heat and a change in heat capacity of the material. 2nd order transitions, such as glass transitions involve only changes in heat capacity. Latent heat storage (the focus of this paper) is limited to the 1st order. These phase changes involve a re-arrangement of particles at a molecular level within a material, with heat storage/release taking place at a specific range of temperatures (the phase change temperature range).

For the purpose of buildings improvement, emphasis has been placed on the solid-liquid phase change and more recently on solid-solid phase change, as they both offer the smallest volume changes; in the order of 10% and is chemically and physically more stable (Gowreesunker, 2013).

2.2. Different kinds of thermal energy storage

Thermal energy storage, or heat and cold storage, allows the storage of heat or cold to be used later. This method needs to be reversible so it allows for multiple cycles. Figure 2 shows the most common methods.

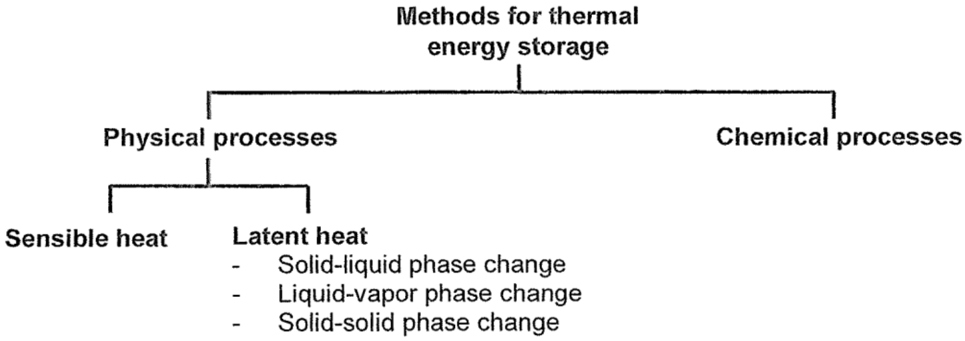

Figure 2- Different methods of thermal energy storage (Mehling, 2008)

2.2.1. Sensible heat

One of the most common ways of thermal energy storage is as sensible heat. As figure 3 shows, heat transferred to the storage material leads to a temperature increase. A sensor can detect this increase in temperature and is thus called sensible heat (Mehling, 2008).

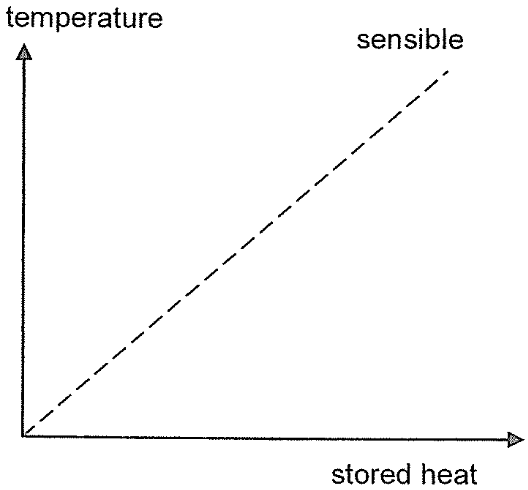

Figure 3- Temperature increase in sensible heat storage. Temperature vs Stored heat (Mehling, 2008)

The ratio of stored heat to temperature increase is dependent on the heat capacity of the storage material and the amount of material, volume or mass. Sensible heat storage is often used with solids like stone or brick, or liquids like water, as storage material. Gases have very low volumetric heat capacity and are therefore not used for sensible heat or cold storage. Sensible heat storage is already used in households for domestic heating and domestic water heating (Mehling, 2008).

2.2.2. Latent heat

If heat is stored as latent heat, a phase change of the storage material is used. There are several options with distinct advantages and disadvantages. The phase change solid-liquid by melting and solidification can store large amounts of heat or cold, if a suitable material is selected. Melting is characterized by a small volume change, usually less than 10%. If a container can fit the phase with the larger volume, usually the liquid, the pressure is not changed significantly and consequently melting and solidification of the storage material proceed at a constant temperature. Upon melting, while heat is transferred to the storage material, it still keeps its temperature constant at the melting temperature, also called as phage change temperature, as shown schematically on figure 4 (Mehling, 2008).

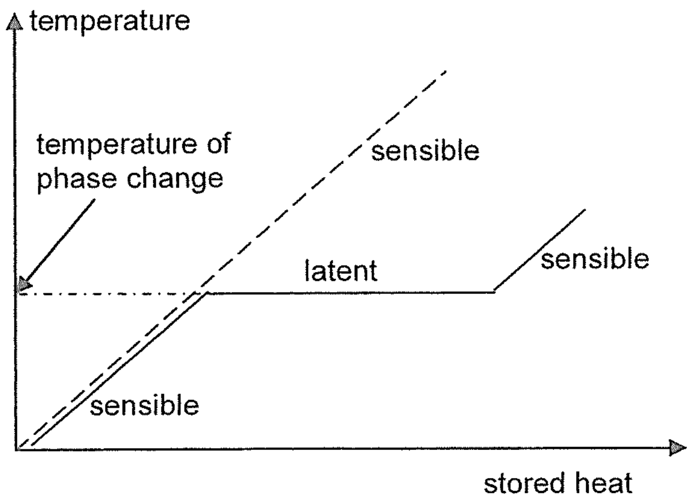

Figure 4- Latent heat storage. Temperature vs Stored heat. (Mehling, 2008)

If the melting is completed, further transfer of heat results again in sensible heat storage. The storage of the heat of melting cannot be detected from the temperature, because the melting proceeds at a constant temperature. The heat supplied upon melting is therefore called latent heat, and the process latent heat storage. Because of the small volume change, the stored heat is equal to the enthalpy difference (as shown in Equation 2.1)

$$\Delta Q = \Delta H = m\, q_{s \to l} \qquad (2.1)$$

The latent heat, that is the heat stored during the phase change process, is then calculated from the enthalpy difference ΔH between the solid and the liquid phase. In the case of solid-liquid phase change, it is called solid-liquid phase change enthalpy, melting enthalpy, or heat of fusion. Materials with a solid-liquid phase change, which are suitable for heat or cold storage, are commonly referred to as latent heat storage material or simply PCM.

In general, the term "latent heat" describes the heat of solid-solid, solid-liquid, and liquid-vapour phase changes. However, the terms "latent heat storage" and "phase change material" are commonly only used for the first two kinds of phase changes, and not for liquid-vapour phase changes. In a liquid-vapour phase change, the phase change temperature strongly depends on the boundary conditions, and therefore the phase change is not just used for storage of heat alone. Usually it is connected with a pressure and a temperature difference between charging and discharging (Mehling, 2008).

2.2.2.1. Requirements

To assure a properly functioning PCM, these requirements must be met (Mehling, 2008):

- Physical requirements, regarding storage and release of heat
  - ✓ Suitable phase change temperature to assure storage and release of heat in an application with given temperatures for heat source and heat sink
  - ✓ Large phase change enthalpy to achieve high storage density compared to sensible heat storage
  - ✓ Reproducible phase change, also called cycling stability to use the storage material as many times for storage and release of heat as required by an application (may go from 1 in case of a fire, or several thousands of cycles when used for heating and cooling of buildings
  - ✓ Little subcooling to assure that melting and solidification can proceed in a narrow temperature range
  - ✓ Good thermal conductivity to be able to store or release the latent heat in a given volume of the storage material in a short time, that is with sufficient heating or cooling power
- Technical requirements, regarding the construction of a storage
  - ✓ Low vapour pressure to reduce requirements of mechanical stability and tightness on a vessel containing the PCM
  - ✓ Small volume change to reduce requirements of mechanical stability on a vessel containing the PCM
  - ✓ Chemical stability of the PCM to assure long lifetime of the PCM if it is exposed to higher temperatures, radiation, gases and more

- ✓ Compatibility of the PCM with other materials to assure long lifetime of the vessel that contains the PCM, and of the surrounding materials in the case of leakage of the PCM
- ✓ Safety constraints (depending on active laws)

2.2.2.2. Materials

Table 1 shows different storage densities for different storage methods. (Mehling, 2008)
As it shows, PCM can store about 3 to 4 times more heat per volume than what is stored as sensible heat which can be a significant advantage in many applications like in domestic space heating.

Table 1- Different storage densities for different storage methods. (Mehling, 2008)

	MJ/m3	kJ/kg	Comment
Sensible heat			
granite	50	17	ΔT= 20 °C
water	84	84	ΔT= 20 °C
Latent heat of melting			
water	306	330	melting temperature 0 °C
paraffins	180	200	melting temperatures 5 °C - 130 °C
salt hydrates	300	200	melting temperatures 5 °C - 130 °C
salts	600-1500	300-700	melting temperatures 300 °C - 800 °C
Latent heat of evaporation			
water	2452	2450	ambient conditions
Heat of chemical reaction			
H2 gas (oxidation)	11	12000	300 k, 1 bar
H2 gas (oxidation)	2160	12000	300 k, 200 bar
H2 liquid (oxidation)	8400	12000	20 k, 1 bar
fossil gas	32	-	300 k, 1 bar
gasoline	33000	43200	
Electrical energy			
zinc/manganese oxide battery	-	180	
lead battery	-	70-180	

Since the PCM used in the case study (later discussed in detail in chapter 5) is paraffin based, that material will be briefly mentioned.

Paraffin consists of hydrocarbon chains of alkanes with the general monomer formula C_nH_{2n+2}. They exist mainly as liquids and waxy solids and are one of the most commonly used commercial organic PCMs. Commercial grade paraffin's are obtained from petroleum distillation and are not pure substances, but a mixture of different hydrocarbons.

The advantages of paraffin's are that they are more chemically stable than inorganic substances due to the strong chemical alkane bonds; they melt congruently and super heating does not pose a problem, hence nucleating agents are not usually employed. They show high heats of fusion and they are safe and non-reactive. Conversely, paraffin's have low thermal conductivity; they have a relatively higher solid – liquid volume change compared to other PCM; they are flammable and because commercial grade paraffin contains various hydrocarbons, the melting temperature ranges are not clearly defined. (Gowreesunker, 2013)

2.3. Possible applications of latent heat storage with solid-liquid phase change

Potential fields of application of PCM can be found directly from the basic differences between sensible and latent heat storage.

In regards to temperature control, as shown on the left of figure 5, heat can be supplied to or extracted from a phase change material without a significant change of its temperature. Therefore, PCM can be used to stabilize the temperature in an application. Examples include the use of ice on a drink, stabilization of indoor temperature or the temperature in transport boxes.

In regards to storage, as shown on the right of figure 5, PCMs are also able to store large amounts of heat or cold at comparatively small temperature change.

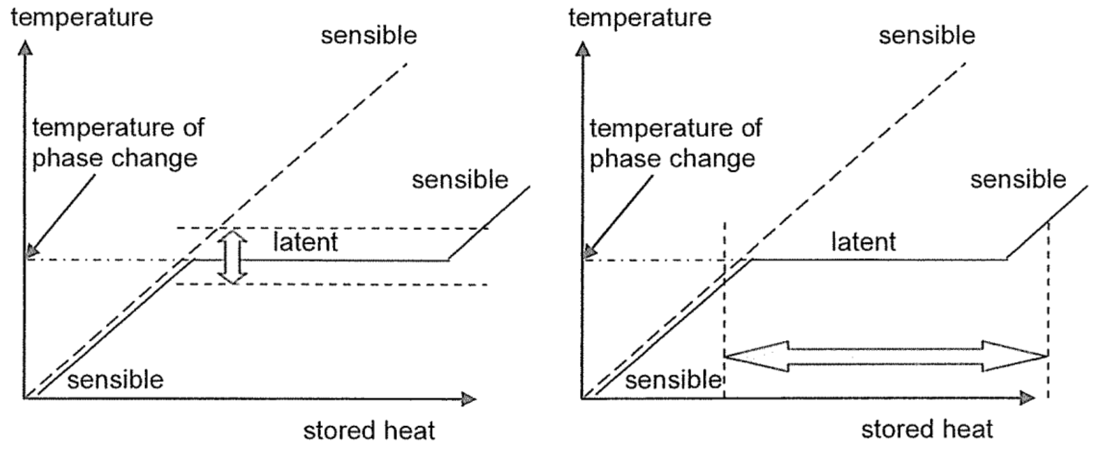

Figure 5- Potential fields of application of PCM: temperature control on the left and storage and supply of heat or cold with small temperature change on the right (Mehling, 2008).

2.4. Summary

In sum, Phase Change Materials allow for energy storage and there are two kinds of methods for heat storage, sensible and latent heat. The method must be reversible in order to allow for multiple cycles. The type used in this study, latent heat, allows for heat to be stored during the phase change whilst keeping the temperature constant (figure 4). Different materials can be used as the storage material, and each has its own advantages and disadvantages that must be taken into consideration when picking the best. PCMs can then be potentially used for temperature control by allowing the storage of heat without temperature variation and to store large amounts of heat or cold.

Although not mentioned, hysteresis can be an important factor, but for this study it was disregarded and only the enthalpy curve for the heating process was used.

Chapter 3

Dynamic Building Simulation

Chapter 3- Dynamic Building Simulation

3.1. Introduction

To evaluate the effect of PCMs a static analysis is not acceptable due to its limitations, leaving out dynamic simulation software as the only option. It contains iterative solution algorithms that help find the optimal building and energy system design. They also allow for optimal equipment scheduling while taking into account the dynamics of the building's energy system and the anticipated future building energy load. This leads to minimization of a user-specific cost function such as energy use, subject to state constraints like thermal comfort and indoor air quality (Hensen, 2012).

Dynamic Building Simulation also allows for visualization of temperatures or certain conditions at any point in time/space.

There are several programs that fit this description, but only a few will be discussed.

See figures 6, 7 and 8 for the graphical interface on each software.

3.2. Related Softwares

3.2.1. DesignBuilder w/ EnergyPlus Integration

"DesignBuilder combines advanced energy simulation with the fastest modelling technology on the market so that architects, engineers and energy assessors can reduce a building's impact on the environment" (DB, 2013).

DesignBuilder allows you to:

- Easily compare design alternatives
- Optimise your design at any stage with client's variable objectives
- Model even complex buildings quickly
- Effortlessly import existing BIM and CAD design data
- Generate impressive rendered images and movies
- Simplify EnergyPlus thermal simulation

In addition, EnergyPlus integration allows for:

- Advanced dynamic thermal simulation at sub-hourly timesteps

- Provide environmental performance data such as energy consumption, carbon emissions, room comfort at annual, monthly, daily, hourly, and sub-hourly intervals
- Report solar gains on surfaces, surface temperatures and radiant exchanges
- Access an extensive range of results for buildings and systems
- Assess passive performance, thermal mass, and temperature distribution
- Export surface temperatures and airflow rates as boundary conditions for detailed CFD analysis
- Size heating and cooling systems

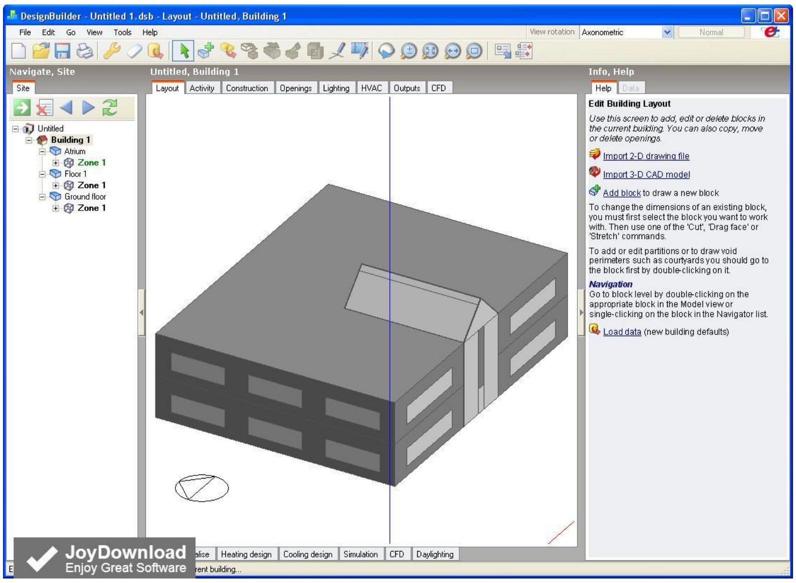

Figure 6- DesignBuilder interface (joydownload, 2014)

3.2.2. IDA Indoor Climate and energy

"IDA (...) is an innovative and trusted whole-year detailed and dynamic multi-zone simulation application for study of thermal indoor climate as well as the energy consumption of the entire building. The physical models of IDA ICE reflect the latest research and best models available, and the computed results compare well with measured data. While serving a global market, IDA ICE is adapted to local languages and requirements (climate data, standards, special systems, special reports, product and material data).

(...) An advantage of using a modern general-purpose variable time step solver, rather than the hand-coded component subroutines of all other available whole-building simulators, is that it automatically adapts to the nature of the problem. By choice of tolerance parameters, you can effectively eliminate numerical errors and see how the equations truly behave – even with a time resolution of seconds if needed" (equa solutions, 2014).

Figure 7- IDA simulation software (equa solutions, 2014)

3.2.3. SketchUp Make with EnergyPlus

"EnergyPlus is an energy analysis and thermal load simulation program. Based on a user's description of a building from the perspective of the building's physical make-up and associated mechanical and other systems, EnergyPlus calculates heating and cooling loads necessary to maintain thermal control setpoints, conditions throughout a secondary HVAC system and coil loads, and the energy consumption of primary plant equipment. Simultaneous integration of these—and many other—details verify that the EnergyPlus simulation performs as would the real building." (energy.gov, 2014)

EnergyPlus has the following capabilities:

- Integrated, simultaneous solution where the building response and the primary and secondary systems are tightly coupled (iteration performed when necessary)
- Sub-hourly, user-definable time steps for the interaction between the thermal zones and the environment; variable time steps for interactions between the thermal zones and the HVAC systems (automatically varied to ensure solution stability)
- ASCII text based weather, input, and output files that include hourly or sub-hourly environmental conditions, and standard and user definable reports, respectively
- Heat balance based solution technique for building thermal loads that allows for simultaneous calculation of radiant and convective effects at both in the interior and exterior surface during each time step
- Transient heat conduction through building elements such as walls, roofs, floors, etc. using conduction transfer functions

- Improved ground heat transfer **modeling** through links to three-dimensional finite difference ground models and simplified analytical techniques
- Combined heat and mass **transfer** model that accounts for moisture adsorption/desorption either as a layer-by-layer integration into the conduction transfer functions or as an effective moisture penetration depth model (EMPD)
- Thermal comfort models based on activity, inside dry bulb, humidity, etc.
- Anisotropic sky model for improved calculation of diffuse solar on tilted surfaces
- Advanced fenestration **calculations** including controllable window blinds, electrochromic glazings, layer-by-layer heat balances that allow proper assignment of solar energy absorbed by window panes, and a performance library for numerous commercially available windows
- Daylighting controls including interior illuminance calculations, glare simulation and control, luminaire controls, and the effect of reduced artificial lighting on heating and cooling
- Atmospheric pollution calculations that predict CO2, SOx, NOx, CO, particulate matter, and hydrocarbon production for both on site and remote energy conversion

In addition, EnergyPlus does not include a user friendly graphical interface, and for this reason, SketchUp Make with the legacy OpenStudio plugin will be used to model the building.

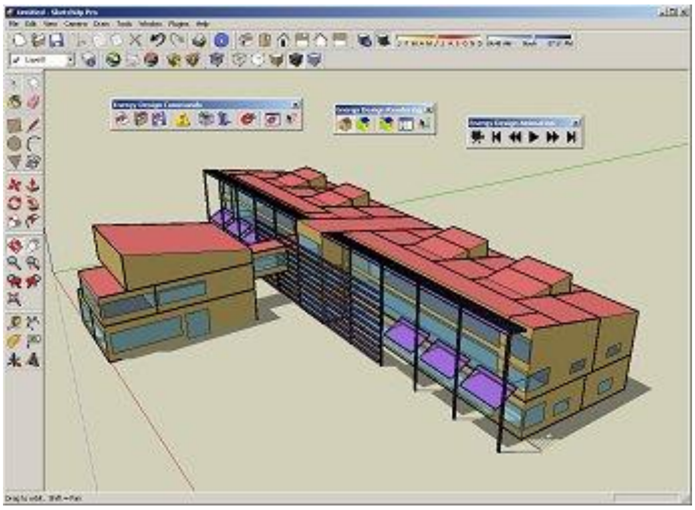

Figure 8- SketchUp with OpenStudio interface (bldgsim, 2014)

The reasons why these softwares were the ones used include:

- Free
- OpenSource, very flexible and can be manipulated
- Scientific Community uses EnergyPlus, and there are many forums dedicated to it

Chapter 4

Description of the Case Study

Chapter 4- Description of the case study

- 4.1. Location
- 4.2. Available Data
  - 4.2.1. Climatic Data
  - 4.2.2. Sensors and study performed
- 4.3. Local climate characterisation
- 4.4. Architecture
- 4.5. Materials and Construction Characterisation
  - 4.5.1. Materials
  - 4.5.2. Construction Characterization

Chapter 4- Description of the case study

4.1. Location

The building is located in the University of Aveiro, Portugal at the following coordinates:

- Latitude 40°37'50.52" N
- Longitude 8°39'24.44" W

It is 8 Km away from the nearby ocean, thereby subjected to constant winds. It is however protected somewhat by nearby buildings. Figure 9 and 10 show the location in Portugal and the construction area respectively. Construction for the building began in mid-2011 and finished in late 2013. It has a total area of implantation of 1584 m^2. The building in question is called CICFANO and stands for Multi-Disciplinary Complex of Physical Sciences Applied to Nanotechnology and Oceanography.

Figure 9- Location of the building on the map of Portugal (Google Earth, 2014)

Figure 10- Location within the University of Aveiro (Google Earth, 2014)

4.2. Available Data

4.2.1. Climatic Data

There were two sources of data available. One was averages taken from 29 years and the other was data recorded for the analysis period by the Department of Physics of University of Aveiro which is located next to the case study building. As such, to have the most accurate EnergyPlus model, the data recorded locally was used. The data includes the parameters described in table 2.

Table 2- Available Data Parameters

Available Parameters	Units
Temperature	°C
Relative Humidity	%
Solar Radiation	W/m^2
Wind speed	m/s
Wind Direction	º

The EnergyPlus weather files are processed hourly, but the climatic data is recorded every 10 minutes. As such, an hour by hour average was calculated and was the input to replace on the weather file.

4.2.2. Sensors and study performed

For this study, two sensors were placed in accordance to the standard ISO 7726-1998 which states that the probe must be placed outside of the effect of radiation from neighbouring heat sources amongst other conditions. Their location can be seen on figure 11 and 12, room with PCM (sensor 1) and room without PCM (sensor 2) respectively. The data collected will be analysed on chapter 6. The product datasheet for the sensors' are available on annex A. During the recorded time frame (May 2014) the room without PCM was occupied by people, and a registry of the occupation, blackout and lighting schedule was made in order to have a more precise model.

During this time, the windows were closed in the morning, and opened when nearing the night time, to ensure the cycles of the PCM were always completed.

Each analysed room has 129.6 m^2 of area, 27 m^2 of glazing area and are orientated to south west

Figure 11- Sensor's 1 location on the room with PCM

Figure 12- Sensor’s 2 location on the room without PCM

4.3. Local climate characterisation

According to the Koppen climate classification, Aveiro, Portugal is located in a Dry-summer subtropical or Mediterranean Climate (Csb). Under the Köppen-Geiger system, "C" zones have an average temperature above 10 °C in their warmest months, and an average in the coldest between 18 to −3 °C. The second letter indicates the precipitation pattern: "s" represents dry summers. A dry month is a month with less than one-third that of the wettest winter month, and with less than 30 mm of precipitation in a summer month. The third letter indicates the degree of summer heat: "b" indicates an average temperature in the warmest month below 22 °C, and with at least two months averaging above 10 °C.

Figure 13 shows the average wind speed for the validation period (May 2014) and figure 14 the frequency of wind direction, both for the region of Aveiro.

Figure 15 shows the average temperature for the month of May, and figure 16 the horizontal solar radiation for different dates of 2014, both for the region of Aveiro.

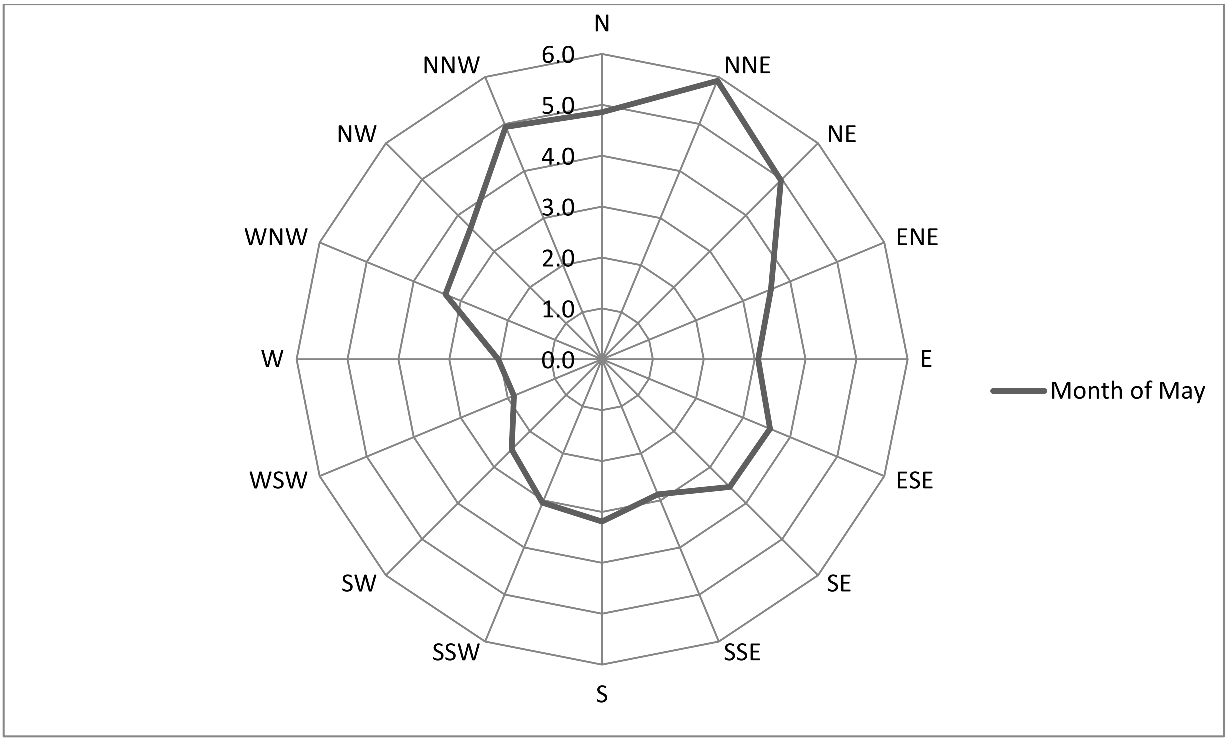

Figure 13- Average wind speed for each direction in [m/s]

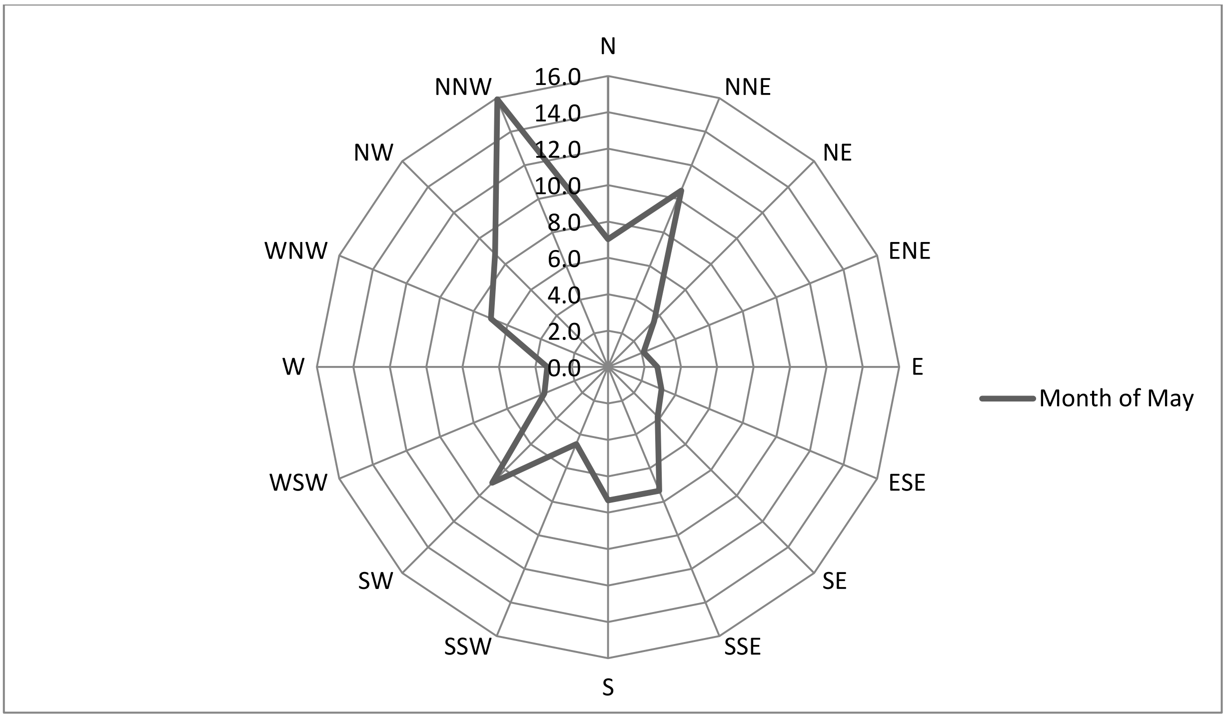

Figure 14- Frequency of wind direction in [%]

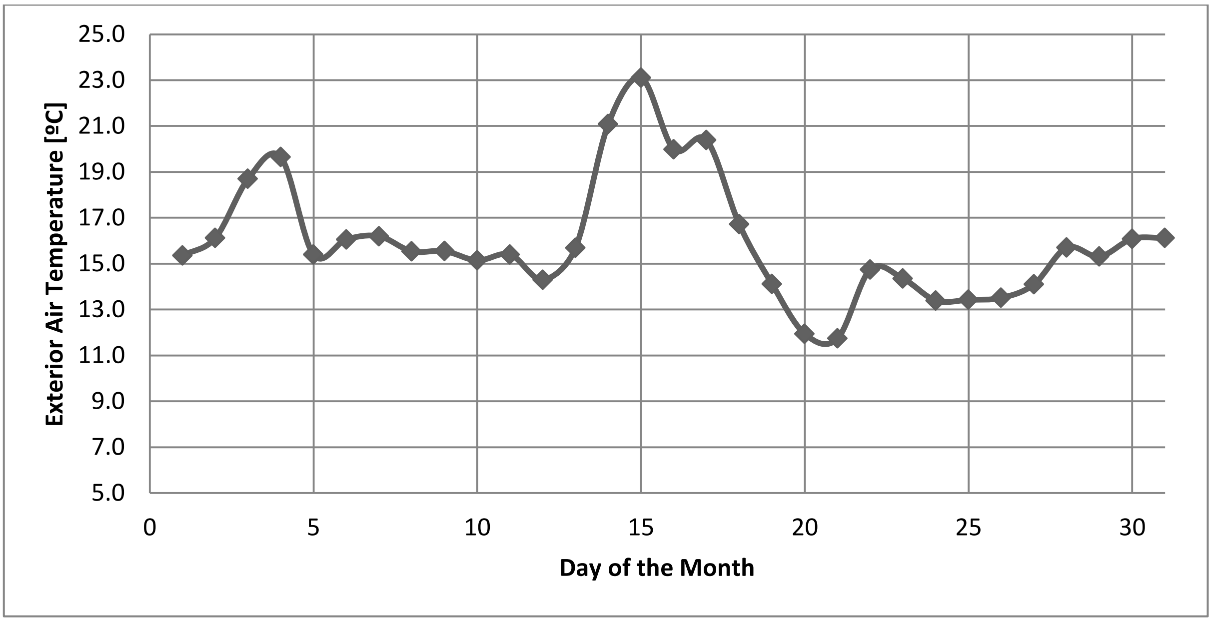

Figure 15- Average daily air temperature for May 2014

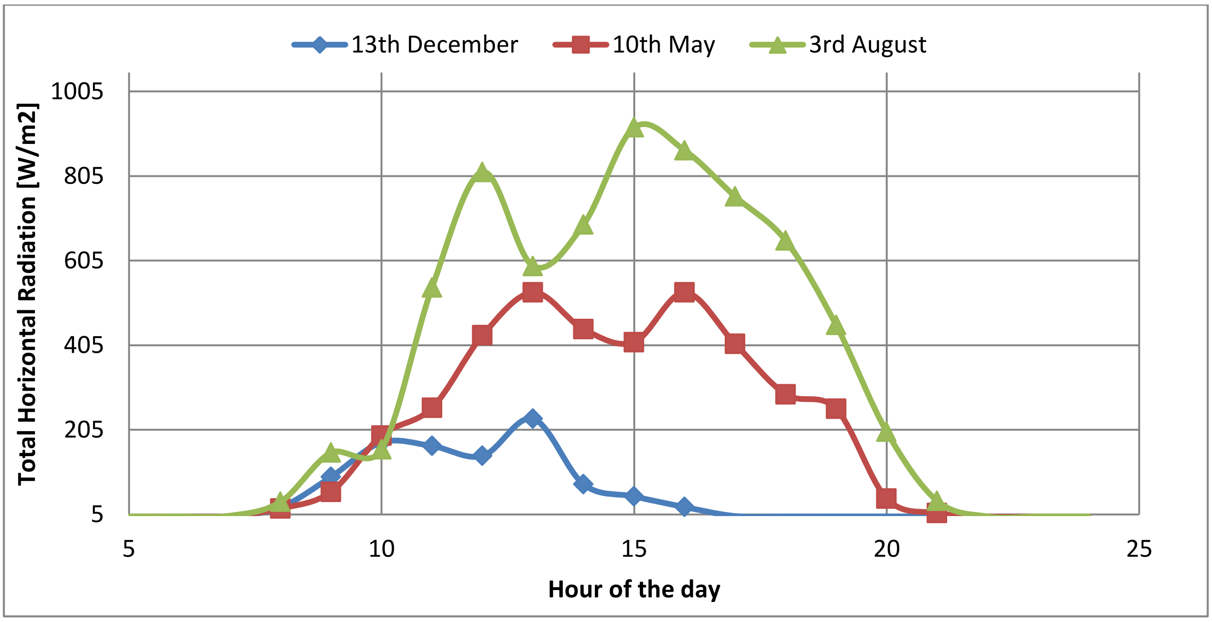

Figure 16- Horizontal Total Solar Radiation of different dates in 2014

4.4. Architecture

The building in question is intended to be an investigation focused building, with a few rooms to serve as offices and more than half of its area devoted to laboratories. It has 4 floors and the top floor serves as a maintenance area. Each floor has roughly 587 m^2 of area. Figure 17 serves as orientation and shows where the North is facing. Figures 18 through 20 represent the floor plans of floor 0 through 3 (floor 1 and 2 have identical architectures). Figure 21 a longitudinal cut, figure 22 a rear and frontal view and figure 23 a side view.

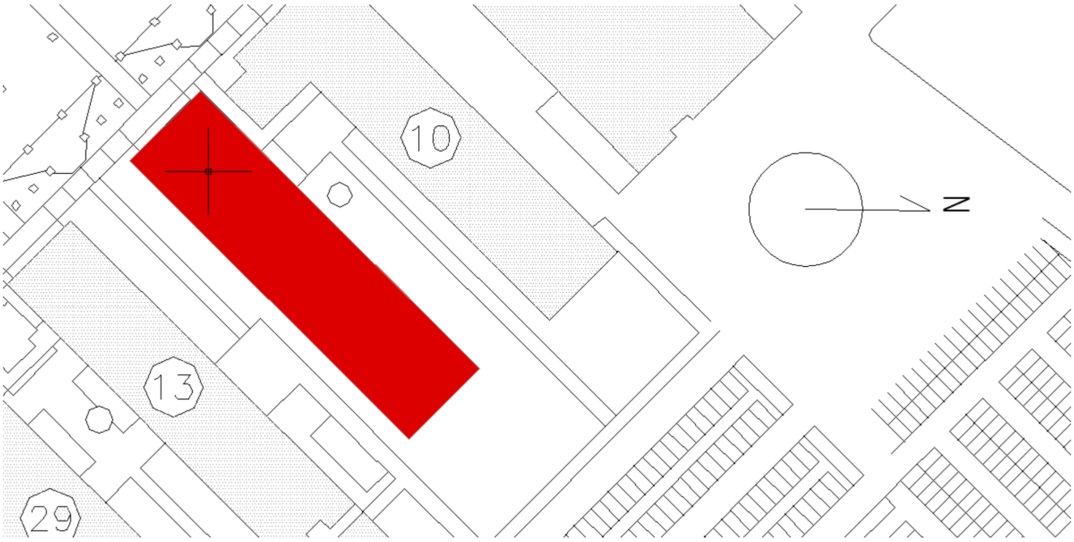

Figure 17- Direction of North in relation to the building

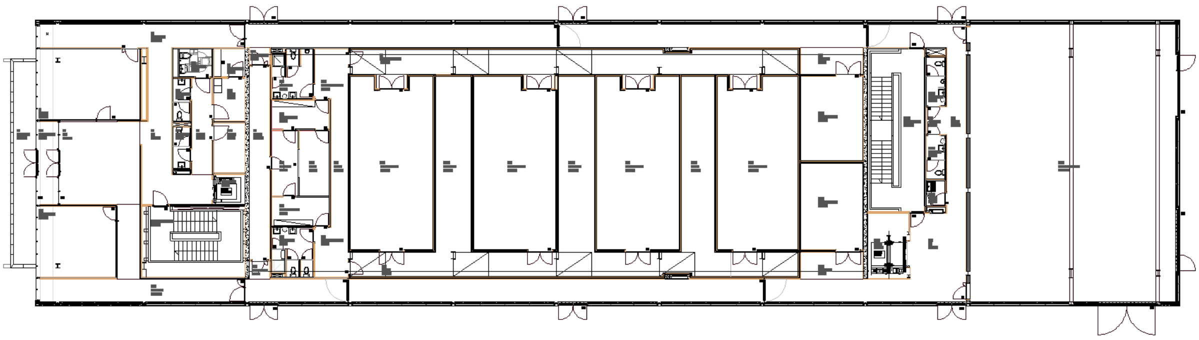

Figure 18- Bottom Floor

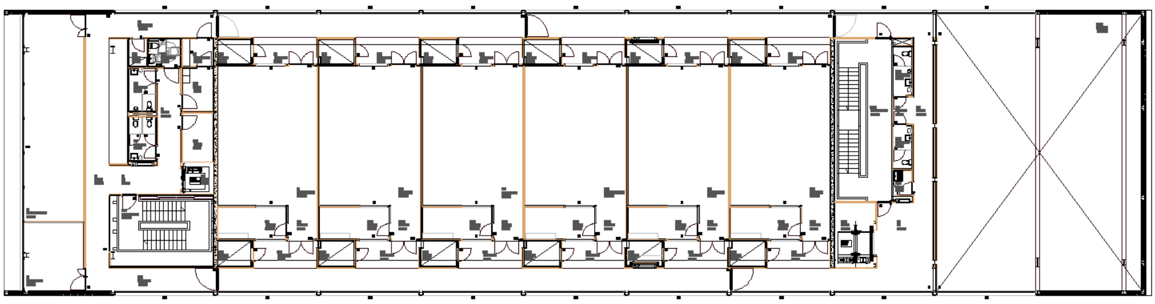

Figure 19- 1st and 2nd Floor

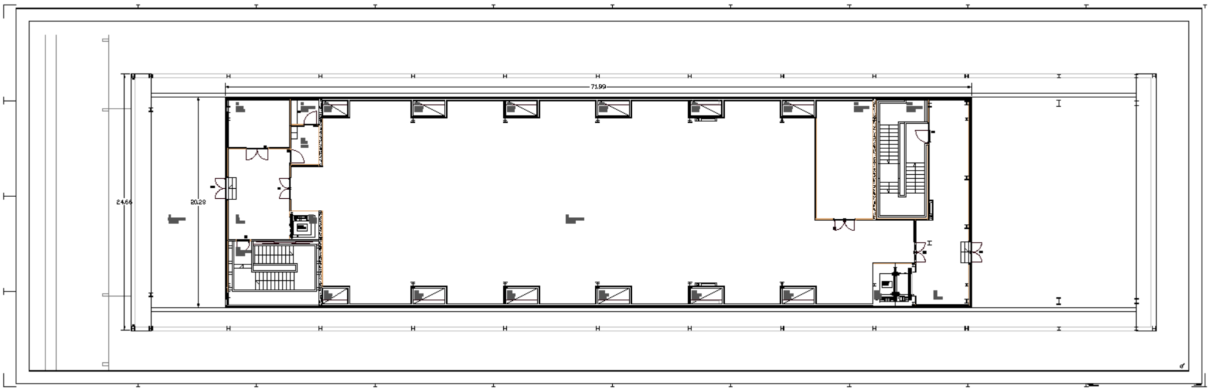

Figure 20- 3rd Floor

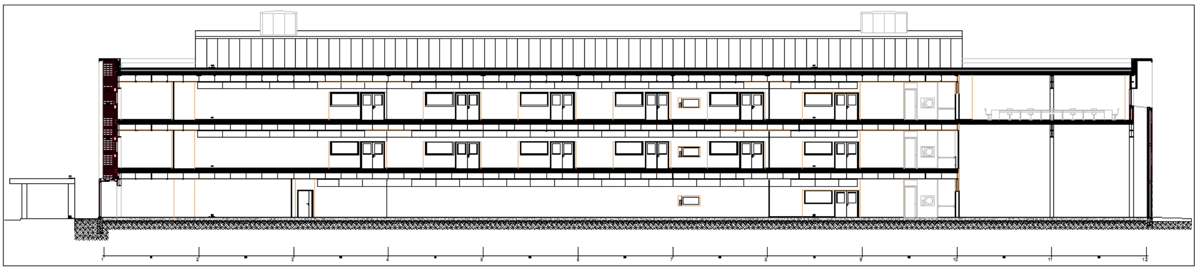

Figure 21- Longitudinal Cut

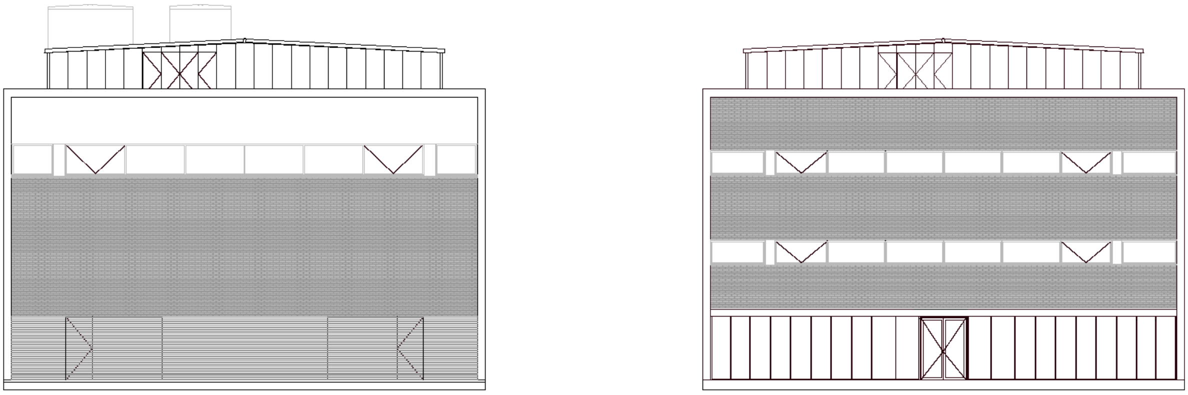

Figure 22- Rear and Front views respectively

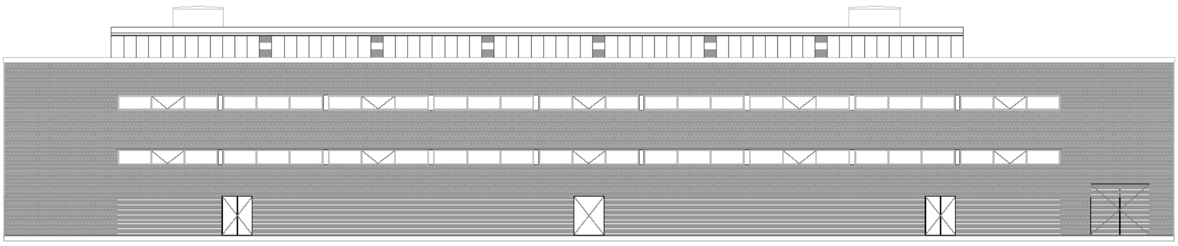

Figure 23- SE side view

4.5. Materials and Construction Characterisation

4.5.1. Materials

The building has a vast variety of materials and table 3 below shows the properties of each material used during its construction and on the simulation.

Table 3- Properties of the Materials Used

Material	Conductivity [W/mK]	Density [kg/m^3]	Specific Heat [J/kgK]
Aluminium	121	2800	795
Face Brick	1.3	2083	900
Steel	50	8000	530
Concrete	2	2400	840
XPS	0.035	25	1500
Plaster	0.25	825	1000
Wood	0.15	500	1200
PCM	0.18 or 0.14	855	2500
Floor Tile	0.14	650	1200
Acoustic Insulation	R= 0.8 m^{2}K/W		
Impermeabilization	R= 0.5 m^{2}K/W		
Double Glazing	U=1.8 W/m^{2}K		

4.5.2. Construction Characterisation

The building has a mixture of concrete and metal construction, with some elements in metal (beams, pillars) and others in concrete (slab). The PCM was included in the interior wall of the room with PCM (the room is shown on chapter 5) and on the dropped ceiling which is not described below.

Figures 24 through 26 represent the interior walls, figure 27 the exterior walls, figure 28 and 29 the floor slabs and top floor roof.

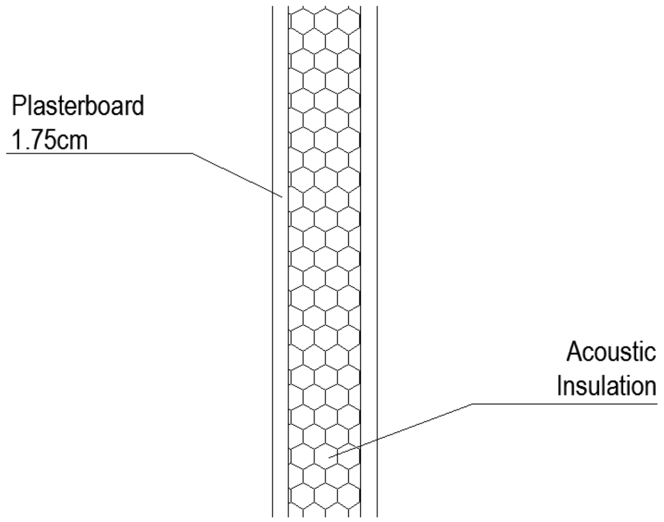

Figure 24- Interior Wall 1

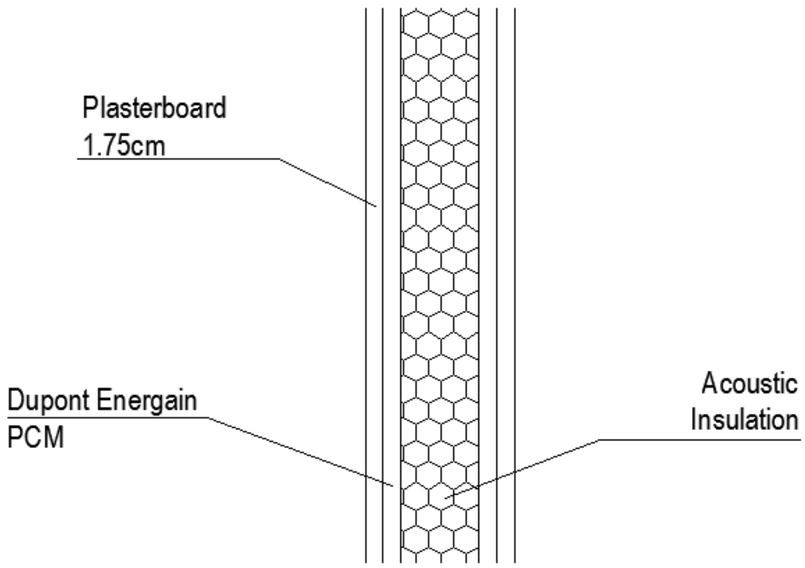

Figure 25- Interior Wall 2

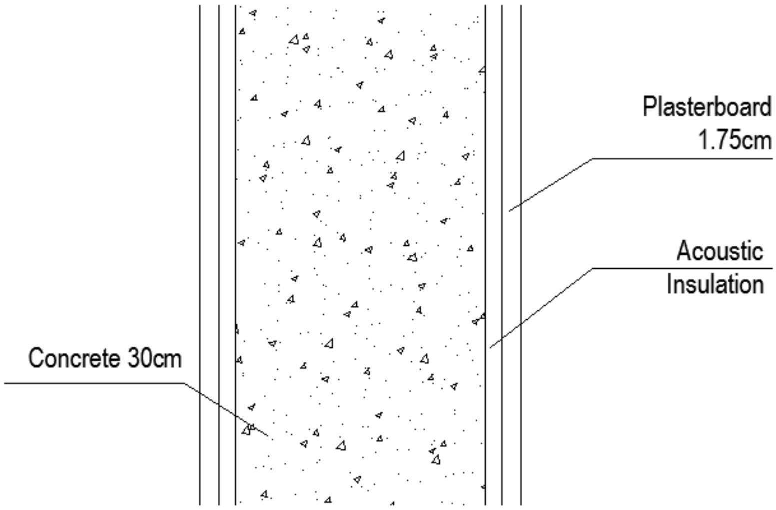

Figure 26- Interior Wall 3

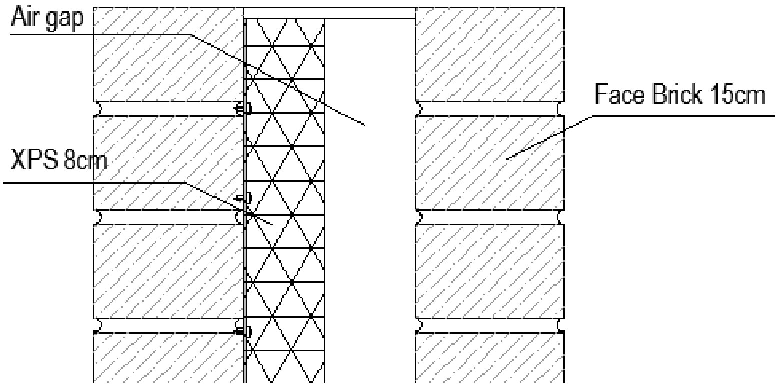

Figure 27- Exterior Walls

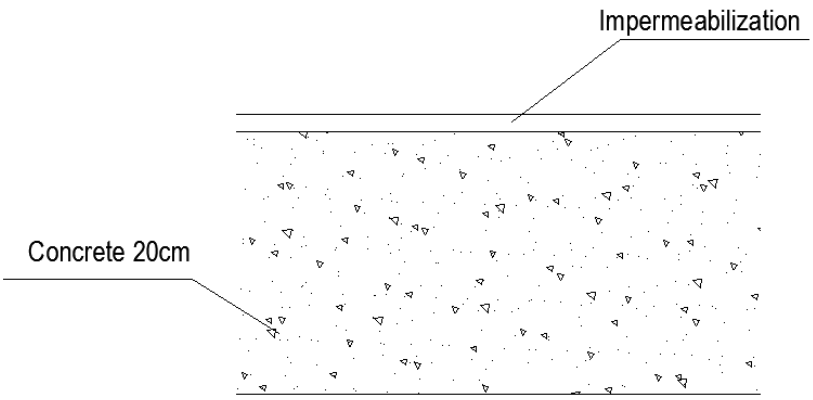

Figure 28- Top Floor Roof

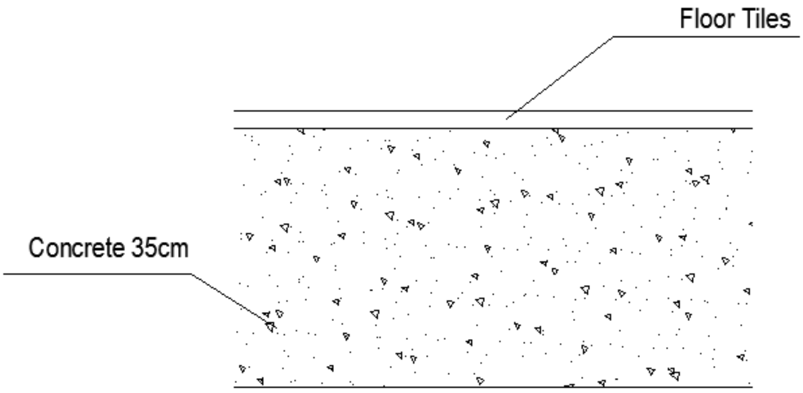

Figure 29- Floor Slabs

Thermal Bridging is an important effect to consider. Since the front and rear walls have a big area of steel in relation to the normal construction, a weighted U value was calculated which then replaces the normal U value for the construction as shown below in equations 4.1., 4.2. and 4.3.

$$U_{normal\ wall} = \frac{1}{Rface\ brick+Rsi+Rxps+Rface\ brick} = \frac{1}{0.115+0.13+2.28+0.115} = 0.38\ W/m^2K \quad (4.1.)$$

$$U_{thermal\ bridge} = \frac{1}{Rface\ brick+Rsi+Rsteel} = \frac{1}{0.115+0.13+0.005} = 4\ W/m^2K \quad (4.2.)$$

$$U_{weighted} = \frac{U_{normal\ wall}*Area+U_{thermal\ bridge}*Area}{\sum Area} = \frac{0.38*48.12+4*21.1}{48.12+21.1} = 1.48\ W/m^2K \quad (4.3.)$$

Chapter 5

Dynamic Simulation Applied to the Case Study

Chapter 5- Dynamic Simulation Applied to the Case Study

5.1. Model Drawing

<u>5.1.1.SketchUp w/ OpenStudio</u>

Considering that EnergyPlus does not have a graphical interface to draw or visualize the building, SketchUp with the legacy OpenStudio version was used. SketchUp is the drawing software, and OpenStudio bridges the gap between both softwares by allowing to:

- Create and edit EnergyPlus zones and surfaces
- Match interzone surface boundary conditions
- Search for surfaces and sub surfaces by object name
- Set and change default constructions

While OpenStudio may allow for some data inputs, all of those were made directly in EnergyPlus. Only the most important inputs will be discussed later in this chapter.

In addition, it includes a colour scheme for different surfaces so it can be easier to identify what is what in the drawing and to check for errors, and is as follows:

- Darker yellow are exterior walls exposed to the sun and wind
- Lighter yellow are interior walls bound by inside conditions
- Red are roofs
- Brown are doors
- Light blue are windows
- Purple are shading zones or devices and are only there to cast shadows

OpenStudio also has a "Render by Boundary Condition" mode in which:

- Light yellow is in contact with the soil
- Dark Blue are walls in contact with the exterior
- Light blue are openings in contact with the exterior (such as windows or doors)
- Dark green are interior walls or floors
- Light green are interior openings
- Purple are shading zones or devices

All of the above functions work towards an easier model drawing but compatibility between SketchUp and EnergyPlus is still not easy to achieve and requires a lot of trial and error. SketchUp version used was SketchUp 2014, OpenStudio v1.0.11 and EnergyPlus v8.1.

5.1.2. Geometry

The first situation to account for is that SketchUp surfaces do not possess thickness. This thickness is later considered in the materials input and the calculation of the R value. Table 4 shows the error associated with this limitation and it is minimal so the effect is then not considered.

Table 4- Error associated with SketchUp's surface drawing

Real area [m^2]	Model area [m^2]	Error [%]
129.6	126.5	2.4

As such, the interior lines of exterior walls and the middle lines of interior walls were considered for the drawing and one of the simplified floor plans (1st floor) is shown in figure 30 as a title of example.

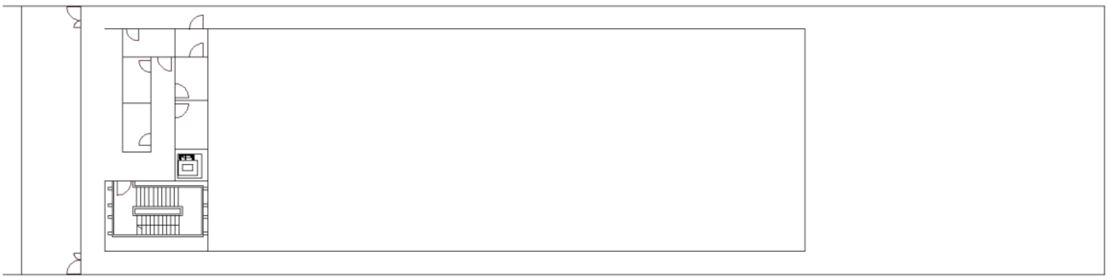

Figure 30-1st Floor simplified floor plan

Figure 31 represents an exterior view of the model by SketchUp's normal "Render by surface class" mode and figure 32 the "Render by boundary condition" mode (the drawing is cut for interior visualization). The colour schemes described in 5.1.1. can be seen in both. Figure 33 shows the rooms that were compared for the study and which one has the Phase Change Materials.

For the study, all of the doors were closed, so each room represents a different thermal zone.

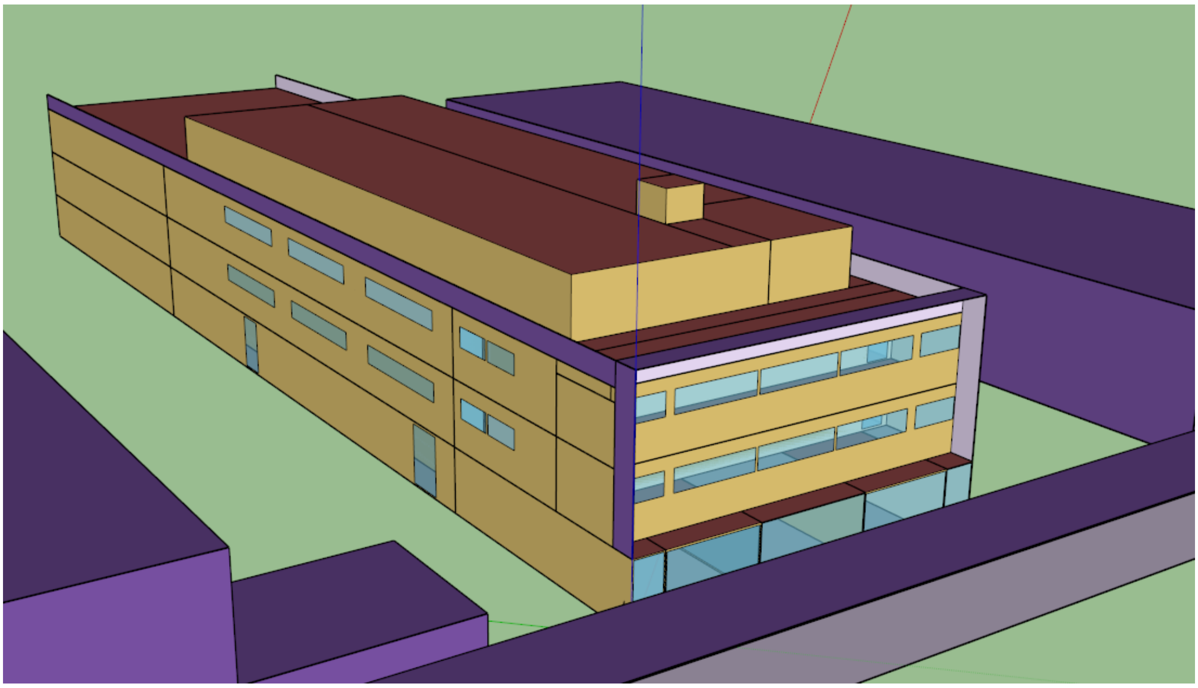

Figure 31- “Render by surface” of the studied model

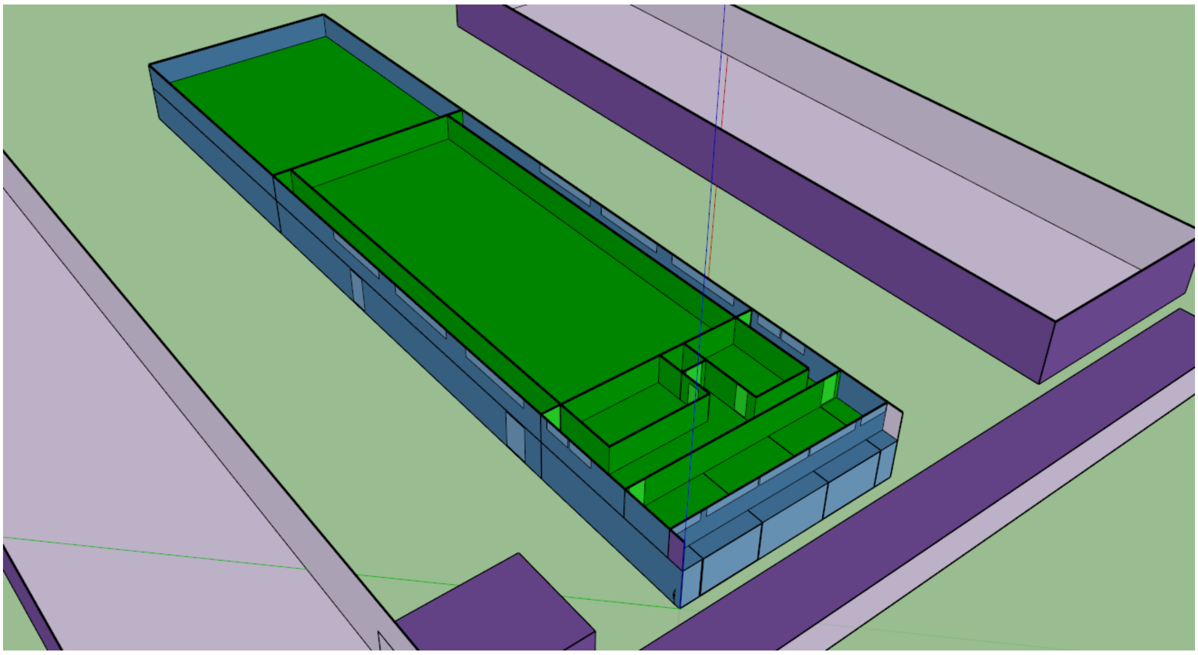

Figure 32- “Render by boundary condition” with interior visualization

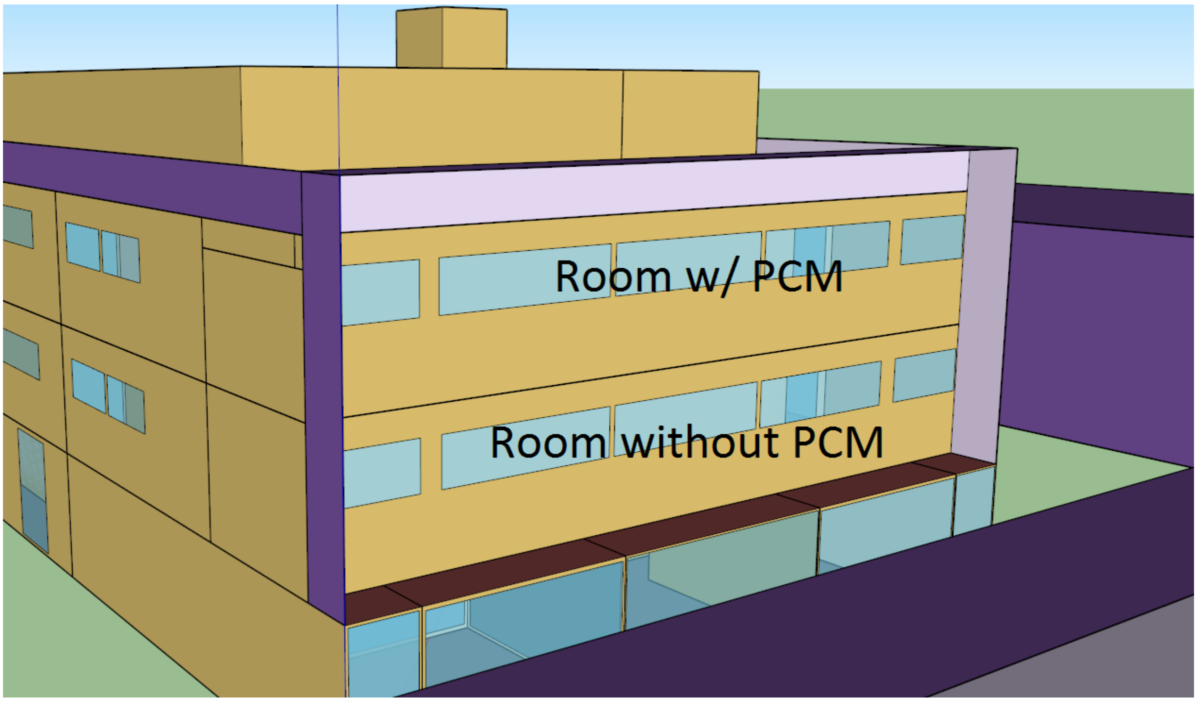

Figure 33- Model's rooms with and without PCM

5.2. EnergyPlus

EnergyPlus' zone air temperature calculation starts with equation 5.1. and after some simplifications it arrives at equation 5.2. which is the software's basis to estimate the air temperature in a certain thermal zone. This information is described in detail in EnergyPlus' documents, specifically in the Engineering Reference.

$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{Nzl} Q_i + \sum_{i=1}^{N_{Surfaces}} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{N_{zones}} m_i C_P (T_{zi} - T_z) + m_{inf} C_P (T_\infty - T_Z) + Q_{Sys} \tag{5.1.}$$

.
.
.

$$T_z^t = \frac{\sum_{i=1}^{N_{sl}} Q_i^t + m_{sys} C_P T_{supply}^t + (C_z + \frac{T_z}{\delta t} + \sum_{i=1}^{N_{surfaces}} h_i A_i T_{si} + \sum_{i=1}^{N_{zones}} m_i C_P T_{zi} + m_{inf} C_P T_\infty)^{t-\delta t}}{\frac{C_z}{\delta t} + \left(\sum_{i=1}^{N_{Surfaces}} h_i A_i T_{si} + \sum_{i=1}^{N_{zones}} m_i C_P + m_{inf} C_P + m_{sys} C_p\right)} \tag{5.2.}$$

5.2.1. Solar distribution

Solar distribution method of calculation is important since it may or not consider certain shading devices or zones. Located under building menu, the option FullExteriorWithReflections was selected as it allows for any shadow patterns on exterior surfaces caused by detached shading, wings, overhangs and exterior surfaces of all zones to be computed. Another option would be FullInteriorAndExteriorWithReflections which would mean the program will also calculate how much beam radiation falling on the inside of an exterior window (from other windows in the zone) is absorbed by the window, how much is reflected back into the zone, and how much is transmitted to the outside. This option is only usable if there are only convex zones, which is not the case. Examples of convex and non-convex zones are shown in figure 34.

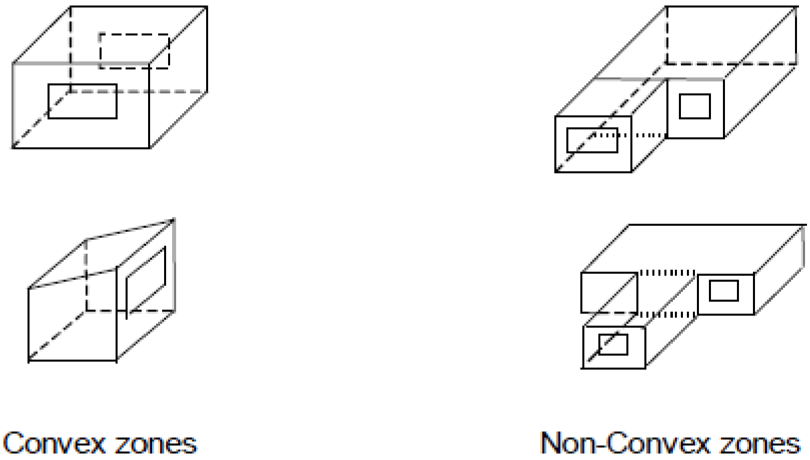

Figure 34- Examples of convex and non-convex zones (EnergyPlus documentation)

5.2.2. Heat Balance Algorithm

Since the model uses Phase Change Materials, the only viable option in this menu is the ConductionFiniteDifference or CondFD as it enables the MaterialProperity:PhaseChange and MaterialProperty:VariableThermalConductivity menus, allowing for PCM calculations. This algorithm does not take into account moisture storage or diffusion in the construction elements, which is similar in itself to the most common algorithm, "ConductionTransferFuction" or CTF.

Under HeatBalanceSettings, the default values were chosen.

5.2.3. Timestep

This number is usually known as the zone timestep. It is used in the zone heat balance model calculation as the driving timestep for heat transfer and load calculations. It corresponds to the number of timesteps to use within an hour. For example, a timestep of 6 means that the timesteps are of 10 minutes. In this case, with the CondFD algorithm it is recommended that 20 or greater timesteps be used. The minimum value of 20 was chosen, as it reduces simulation times, but a preliminary study showed that results were not changed by shorter timesteps (timestep of 20 is a 3 minute timestep)

5.2.4. Material Property: Phage Change Material w/ Variable Thermal Conductivity

The Phase Change Material used in the building, is the DuPont™ Energain® solution, which is a latent heat with paraffin kind. In addition to the properties discussed on chapter 4, EnergyPlus requires the temperature vs enthalpy of the PCM and the variable thermal conductivity if applicable. In this case both were necessary, and figure 35 shows the Temperature vs Enthalpy curve and it shows the increasing capacity to absorb heat at the melting point of 21.7 ºC. As for the variable thermal conductivity, when under the melting point of 21.7 ºC (solid state) it has 0.18 W/mK and when above 21.7 ºC (liquid state) it has 0.14 W/mK thermal conductivity. Annex B includes the product datasheet for the PCM.

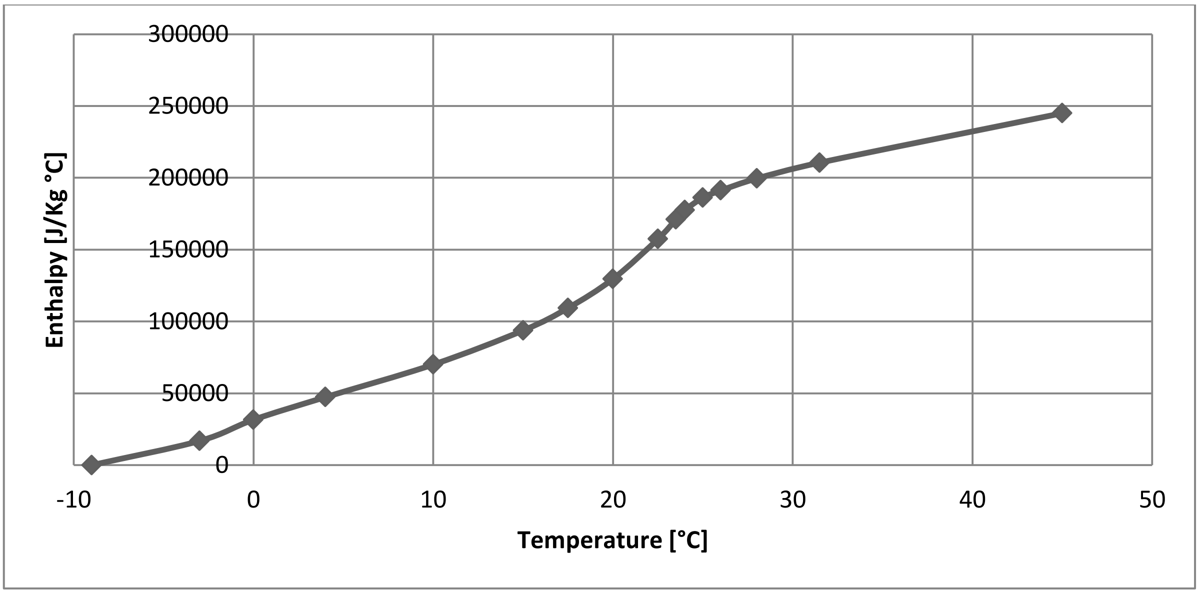

Figure 35- Temperature vs. Enthalpy of DuPont™ Energain® (adapted from Tabares *et al*, 2012)

5.2.5. Internal Gains and blackouts

Internal gains are the sum of all the energy produced by people, lighting and equipment's. At the time of the sensor data recordings, the non PCM room was occupied by people, so a registry was made during that time of the number of people, when the lights were used, how many computers in use and when the blackouts were used as well.

After the creation of the proper schedule in EnergyPlus, the value of 150 W/person was chosen as the EnergyPlus documentation mentions that it can range from 100-150 W for office activities and these values are according to 2005 ASHRAE Handbook of Fundamentals. As for computer equipment, the value of 600 W/computer was chosen.

5.2.6. Window opening and zone infiltration

For this study, as described in a previous chapter, the windows were closed in the morning and opened when nearing night time to try and make sure that the PCM cycles are fully completed. The air flow rate calculation made by EnergyPlus is shown in equation 5.3.

$$Q_w = C_w A_{opening} F_{schedule} V \quad (5.3.)$$

Where,

Q_w is the volumetric air flow rate driven by wind [m^3/s]

C_w is the opening effectiveness [dimensionless]

$A_{opening}$ is the opening area [m^2]

$F_{schedule}$ is the open area fraction [user-defnied schedule value, dimensionless]

V is the local wind speed [m/s]

The opening effectiveness, C_W, depends on the effective angle of the window, which is the direction the window is facing from the north (if it is facing north, effective angle will be 0º). In the building, all the windows subject to opening / closing are facing south-west which is 225º from the north. C_W also depends on wind direction but the weather file has this parameter.

$A_{opening}$ is the window area that is open and that allows for air to flow through.

The menu which needs to be used is the ZoneVentilation:WindandStackOpenArea which also takes into consideration the stack effect that occurs by the differential of pressure/temperature and corresponds to the air flow between thermal zones. This effect wasn't considered, as the menu ZoneInfiltration:DesignFlowRate has a similar effect and is easier to quantify.

Chapter 6

Results and Discussion

Chapter 6- Results and Discussion

6.1. Sensor data and Validation Analysis

As mentioned on chapter 4, both rooms, with and without PCM, were incorporated with a humidity and temperature sensor so the data could be analysed later and used to calibrate the base model. The recordings were done for 2 weeks starting in May 2014. Since the room without PCM was occupied by users, and even though those were inputted into the simulation through schedules, the day 10th of May was chosen for the validation. A longer period would have been better, but due to the lack of certainty of occupation, blackout and electronic equipment usage, that single day was chosen since it is a Saturday and there was no user occupation and the window opening / closing were controlled. As seen on chapter 4, figure 15 pg. 25, that day and previous week did not have average daily temperature fluctuations. Figures 36 and 37 show the 10th of May temperature comparison between Simulation and Sensor data of the room without PCM and room with PCM respectively.

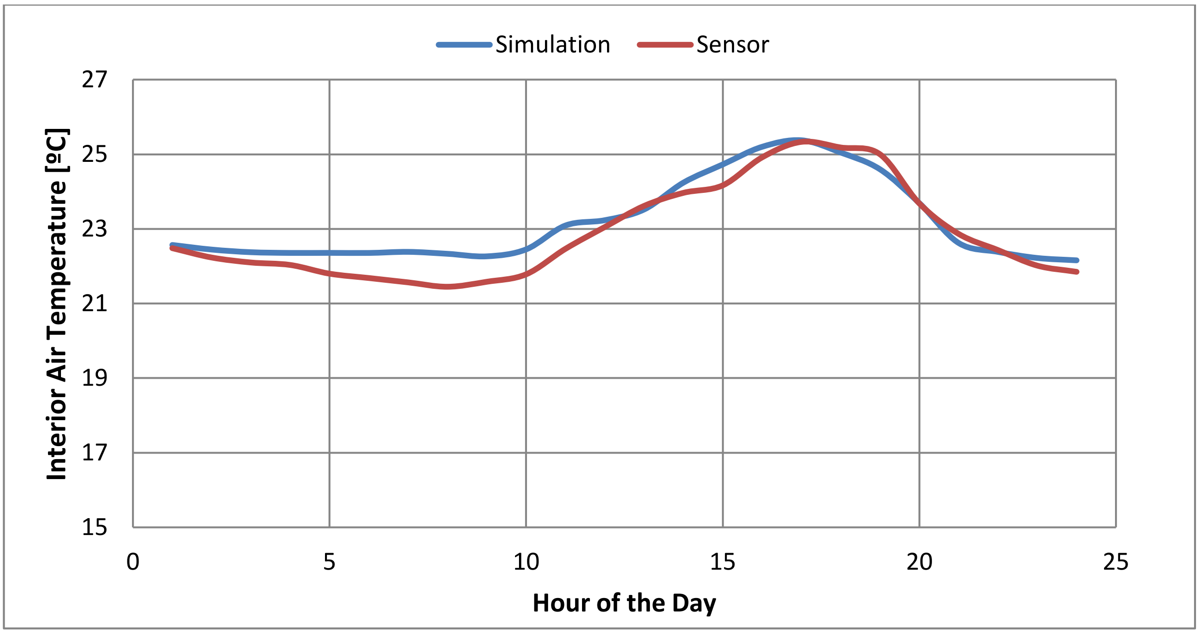

Figure 36- 10th of May temperature comparison between Simulation and Sensor data for room without PCM

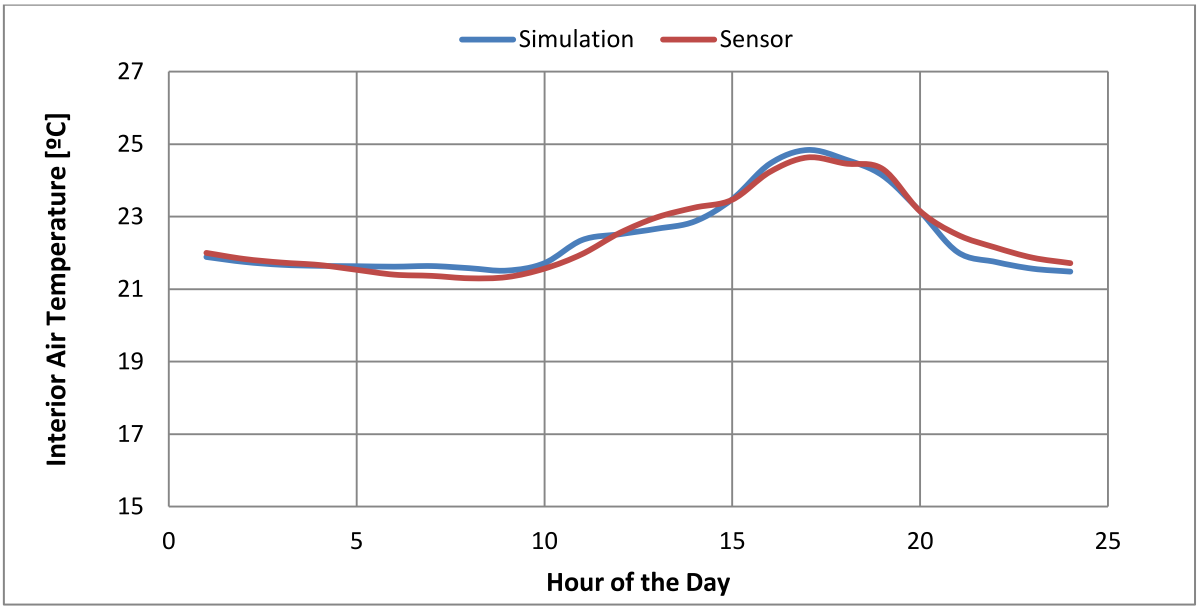

Figure 37-10th of May temperature comparison between Simulation and Sensor data for room with PCM

Through an initial analysis it's possible to determine that the room without PCM has a slightly higher temperature (0.5 ºC – 1 ºC) which can be explained by the usage of the PCM, but the temperature curve on both rooms follows the same pattern, which leads to the conclusion that PCM is in fact having a negligible effect. The lower temperature in PCM room might be explained by the fact that it has a larger area in contact with the exterior, and may be losing a greater amount of heat to the exterior through conduction.

Model validation sets a framework for the manipulation of simulation parameters like types of PCM, materials, shading devices and more, and also allow the building's behaviour to be analysed for another period in time, like heating or cooling seasons.

6.2. Thermal Comfort

Thermal comfort can refer to a person's psychological state of mind and is usually referred to in terms of whether someone is feeling too hot or too cold. It is very difficult to define because you need to take into account a range of environmental and personal factors when deciding what will make people feel comfortable. In any case, air temperature is the most important factor and is the one that will be focused on (hse, 2014).

After the occurrence of strong heat waves in the past decade in Europe and predictions for further temperature increase, the question how to maintain comfortable temperatures without increasing related greenhouse gas emissions has become a major challenge for building professionals. This refers especially to office buildings in warm climates, where internal heat gains tend to be high and occur at the same time with solar heat gains.

For naturally ventilated buildings, adaptive thermal comfort standards like EN 15251 and Ashrae Standard 55 provide a method to evaluate the acceptability of room temperatures. They are based on field studies in real buildings and relate comfort limits to feedback from the outside climate (Roetzel *et al,* 2011).

6.2.1. Standard EN 15251

Considering several studies used this standard for thermal comfort quantification, it will also be used here.

Standard EN 15251, or "Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics" focuses on temperature as the main variable for thermal comfort. It also provides a framework for analysis on buildings with natural ventilation which was the case. The standard lays out several building categories to help distinguish certain limits, as shown on table 5.

Table 5- Building Categories according to EN 15251 (Nicol *et al*, 2010)

Category	Explanation
I	High level of expectation only used for spaces occupied by very sensitive and fragile persons
II	Normal expectation for new buildings and renovations
III	A moderate expectation (used for existing buildings)
IV	Values outside the criteria for the above categories (only acceptable for limited periods)

Since the building in study is only 1 year old and hasn't been occupied for long, it will be characterized as category II, or "Normal Expectation for new buildings and renovations" Equations 6.1. and 6.2. show how to calculate the limits shown in figure 38. In this figure, θ_o is the interior air temperature and θ_{rm} the mean outdoor temperature.

For category II:

upper limit: $\theta_{i\,max} = 0.33\,\theta_{rm} + 18.8 + 3$ [°C] (6.1.)

lower limit: $\theta_{i\,min} = 0.33\,\theta_{rm} + 18.8 - 3$ [°C] (6.2.)

Where θ_{rm} is calculated by equation 6.3.:

$$\theta_{rm} = \frac{(\theta_{n-1}+0.8\,\theta_{n-2}+0.6\,\theta_{n-3}+0.5\,\theta_{n-4}+0.4\,\theta_{n-5}+0.3\,\theta_{n-6}+0.2\,\theta_{n-7})}{3.8}\ [°C] \qquad (6.3)$$

Θ_{n-i} is the daily average temperature of previous days up until a week

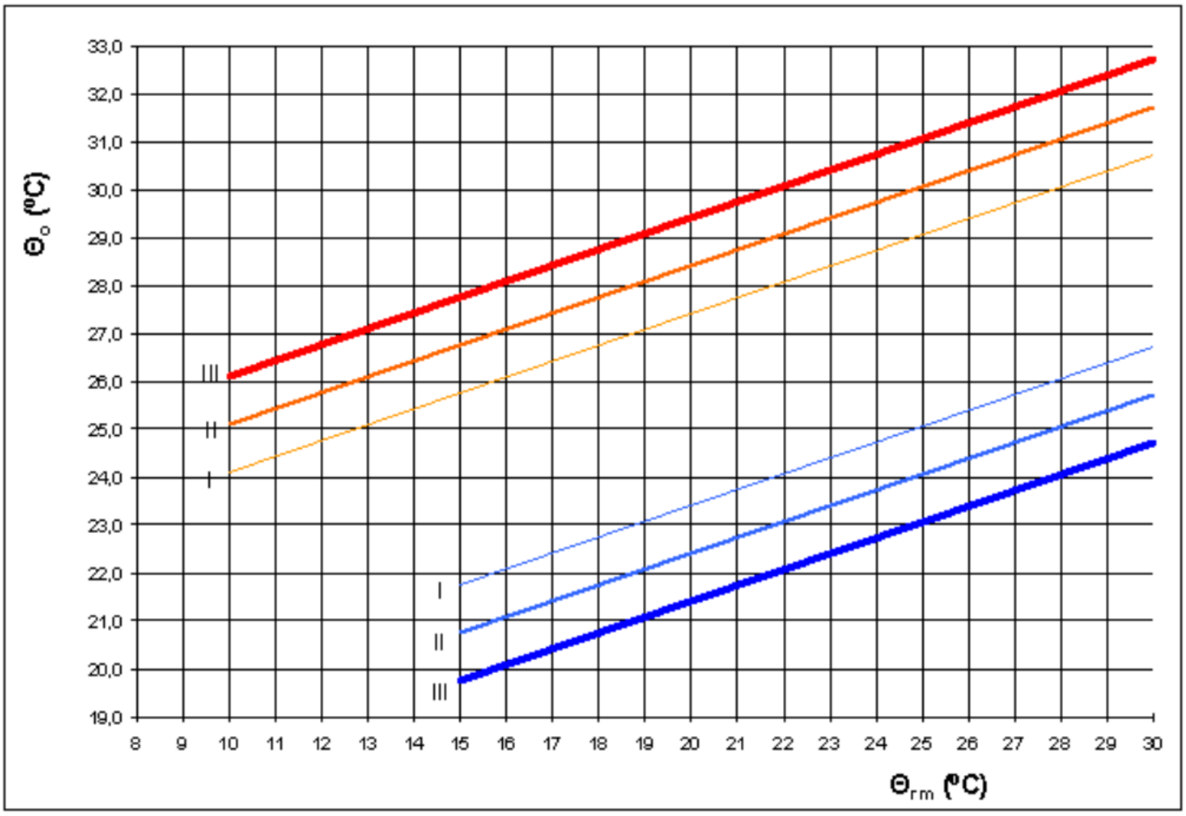

Figure 38- Upper and lower comfort limits (EN 15251, 2007)

The upper limit only applies to mean outdoor temperatures, θ_{rm}, between 10 ºC and 30 ºC and the lower limit between 15 ºC and 30 ºC. The standard instructs to use table 6's values for when the temperature is not in these ranges. Single office category II was chosen, resulting in a lower limit of 20 ºC and an upper limit of 26 ºC.

Table 6- Recommended design values of the indoor temperature (Adapated from EN 15251, 2007)

Type of building/ space	Category	Operative temperature °C	
		Minimum for heating (winter season), ~ 1,0 clo	Maximum for cooling (summer season), ~ 0,5 clo
Residential buildings: living spaces (bed rooms, drawing room, kitchen etc) Sedentary ~ 1,2 met	I	21,0	25,5
	II	**20,0**	**26,0**
	III	18,0	27,0
Residential buildings: other spaces: storages, halls, etc) Standing-walking ~ 1,6 met	I	18,0	
	II	**16,0**	
	III	14,0	
Single office (cellular office) Sedentary ~ 1,2 met	I	21,0	25,5
	II	**20,0**	**26,0**
	III	19,0	27,0
Landscaped office (open plan office) Sedentary ~ 1,2 met	I	21,0	25,5
	II	**20,0**	**26,0**
	III	19,0	27,0
Conference room Sedentary ~ 1,2 met	I	21,0	25,5
	II	**20,0**	**26,0**
	III	19,0	27,0

The result is shown in figure 39 below.

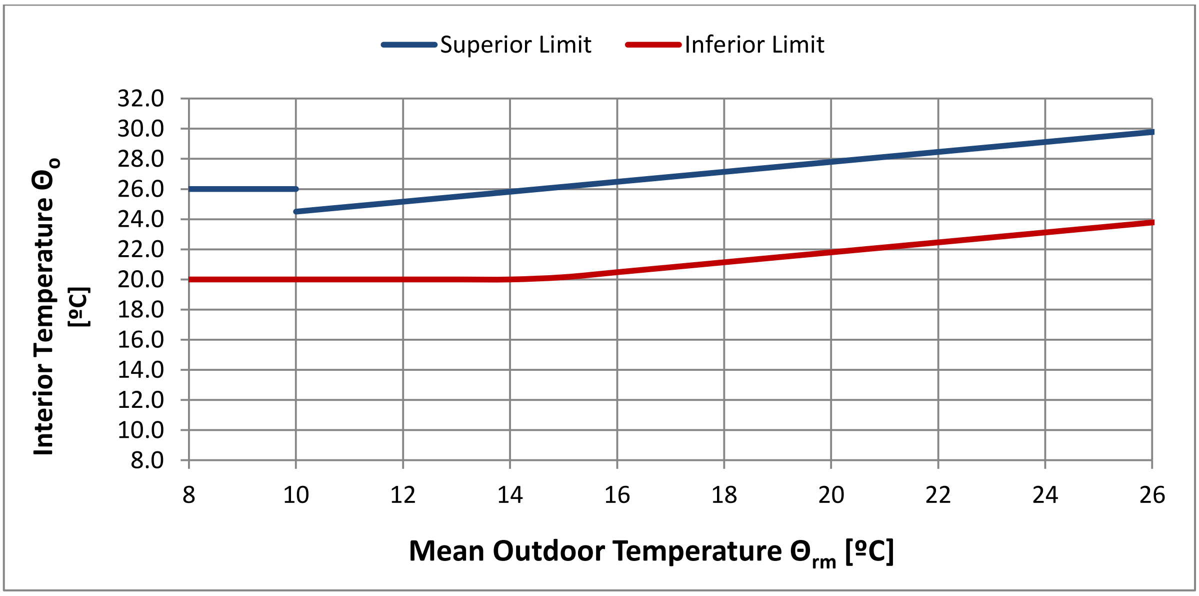

Figure 39- Upper and Lower limits for the case study according to EN 15251

6.3. Heating and Cooling Season Analysis

In this study, a cooling season will be considered as the time when outside temperatures are higher (e.g. summer time) and heating season when outside temperatures are lower (e.g. winter). To avoid too much clutter in the plot area and allow for easier interpretation, cooling and heating seasons will be limited to only 6 weeks, specifically from August 1st to September 15th and January 1st to February 15th respectively. These periods were chosen due to them being on average the hotter / colder times of the year. Due to the nature of the standard as described on 6.2., the first week will be used strictly for the θ_{rm} calculation.

Every model analysis will be paired with a 11 day temperature graph corresponding to the coldest days of the heating season and hottest days of the cooling season. There will also be a comfort graph according to EN 15251 and the percentage of days in discomfort, also according to EN 15251's limits. As a reminder, the PCM's melting point is 21.7 ºC.

All models had the windows closed during the heating season and opened during the day during cooling season.

<u>6.3.1. Original Model</u>

This is the model based on the real building and includes no alterations to its characteristics. Figures 40 and 41 show the temperature graphs for both seasons over a period of 11 days.

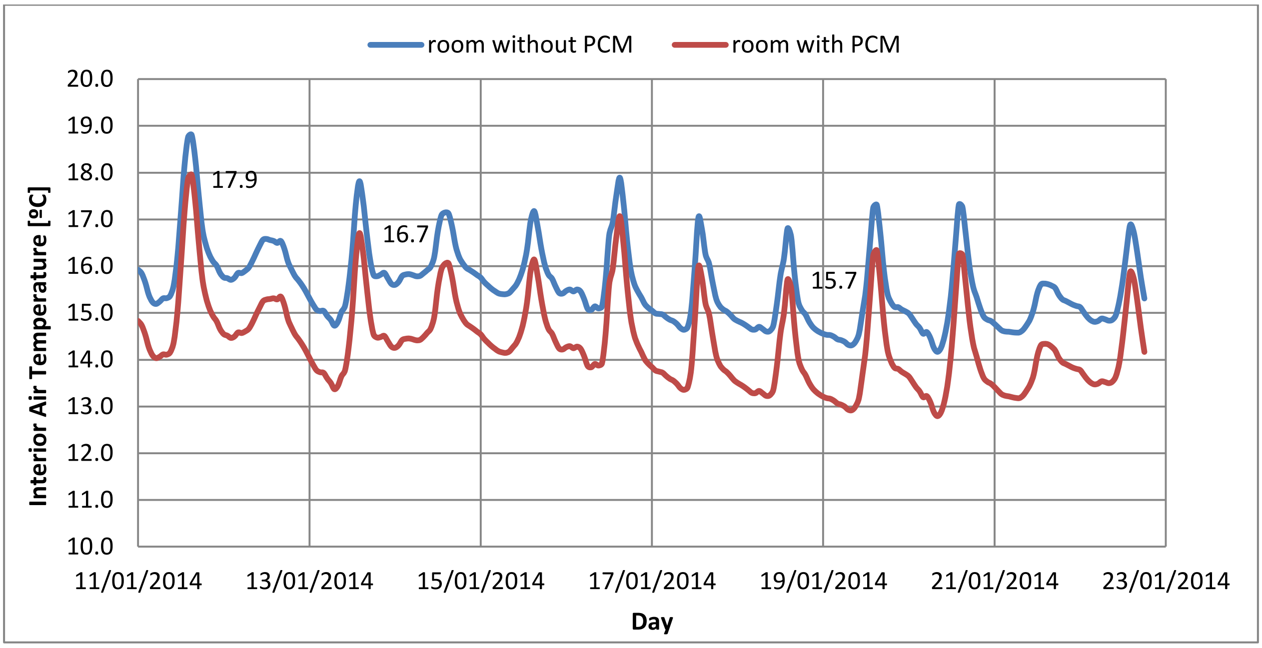

Figure 40- Heating season temperature graph for original model from 11/01/2014 to 23/01/2014

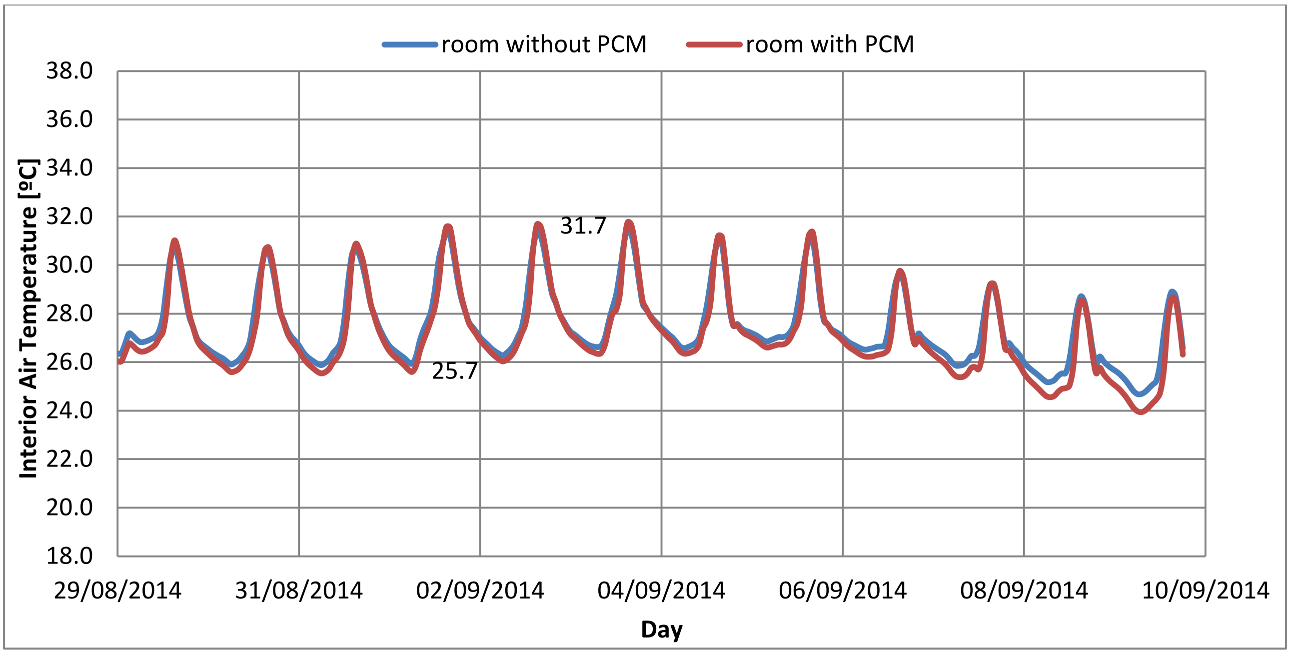

Figure 41- Cooling season temperature graph for original model from 29/08/2014 to 10/09/2014

The temperature difference seen on figure 40 between room without PCM and room with PCM could be explained by the existence of PCM but on 6.4.2. it's observable that that's not the case.

In the cooling season, there is only slight low peak temperature difference of about 0.8º C in the best case.

Figures 42 below shows that during the heating season, both rooms are always in discomfort although the room without PCM has a slightly higher percentage of comfort and figure 43 shows that during the cooling season, the building is within comfort limits (no real difference between rooms), although figure 41 shows that the highest temperature is 31.7 ºC which can be quite uncomfortable. Rooms are always in discomfort during heating season and always in comfort during cooling season.

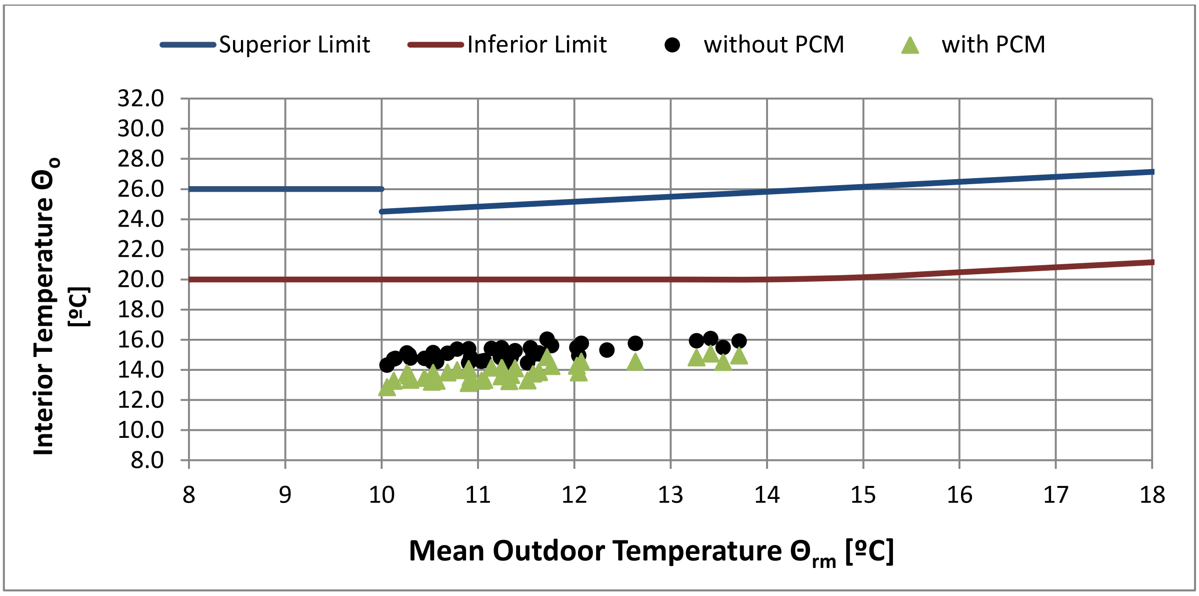

Figure 42- Heating season comfort graph for original model from 01/01/2014 to 15/02/2014 according to EN 15251 limits

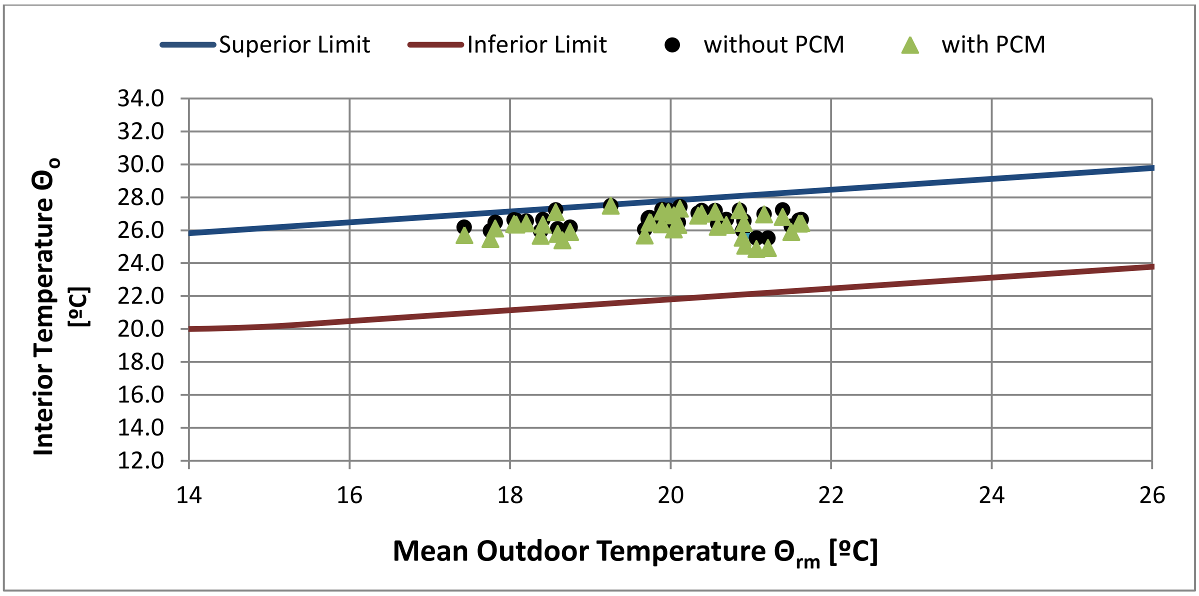

Figure 43- Cooling season comfort graph for original model from 01/01/2014 to 15/02/2014 according to EN 15251 limits

6.3.2. Without PCM

The only difference between this model and the original model is the removal of PCM from the dropped ceiling and interior wall. Figures 44 and 45 are the temperature graphs for the same periods.

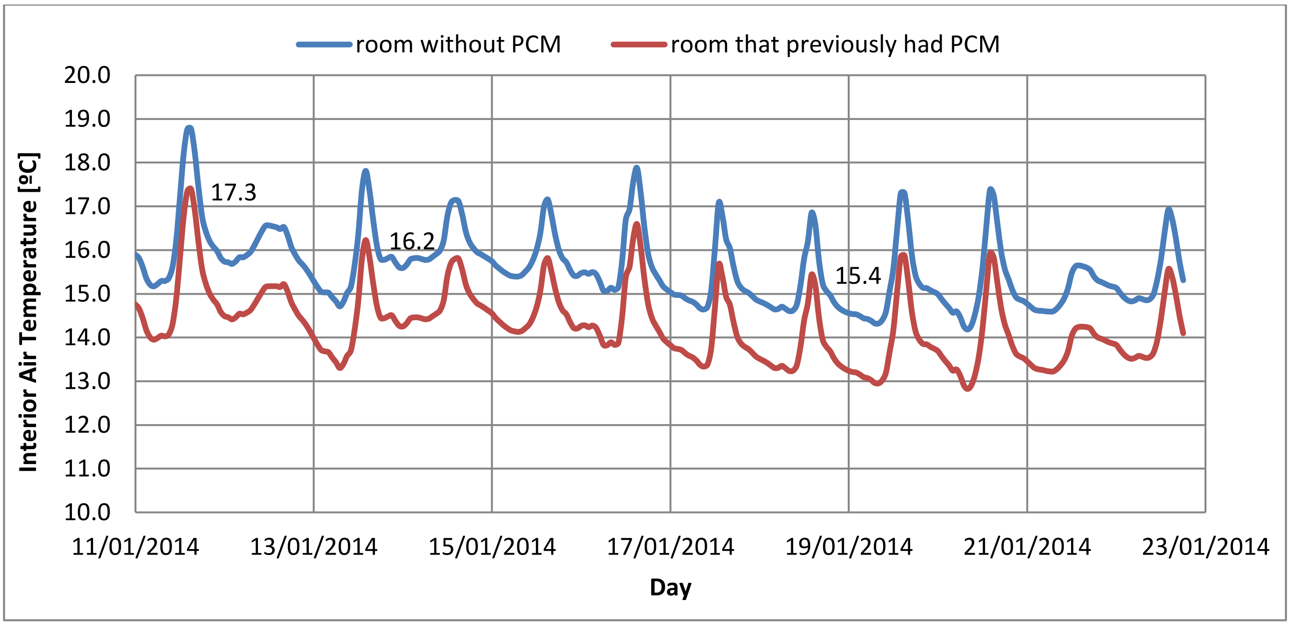

Figure 44- Heating season temperature graph for model without PCM from 11/01/2014 to 23/01/2014

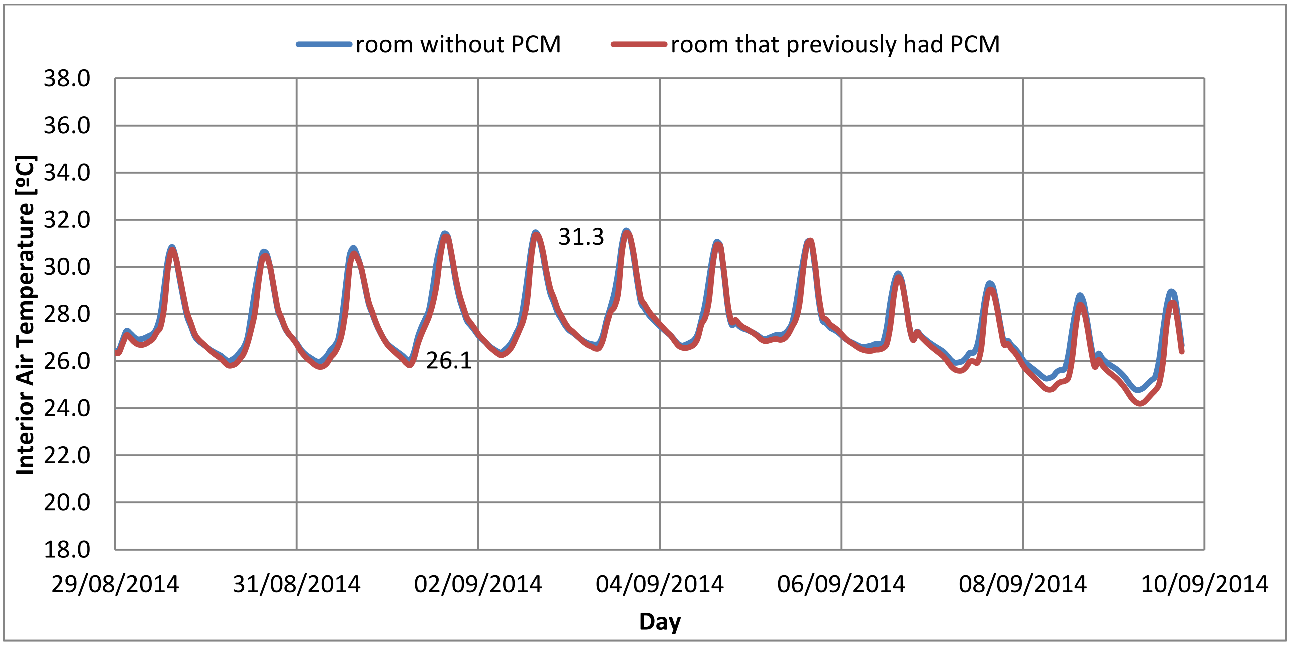

Figure 45- Cooling season temperature graph for model without PCM from 29/08/2014 to 10/09/2014

It's possible to observe the effect of the PCM now. In the heating season (fig. 40 vs. fig. 44) the temperature has increased from 17.3 ºC to 17.9 ºC for the same time and day. That means PCM is having a positive effect in the winter by retaining some heat in the room.

However, during the cooling season (fig. 41 vs. fig. 45) the PCM is having a similar effect by increasing the temperature slightly, from 31.3 ºC to 31.7 ºC. Also its possible to note that there is no noticeable delay when temperature decreases on either season.

The difference of temperature in the heating season on both models can now be possibly explained by the fact that the room without PCM is in contact with other thermal zones but PCM room has more area in contact with the exterior. Another contributing factor is that the bottom floor is comprised of almost 100% glazing area (the façade facing the sun set), which means that during the heating season when the sun's angle of incidence is lower, these thermal zones receive a bigger percentage of radiation then they would during the cooling season, thus transferring some of that heat to the middle floor (without PCM).

Figures 46 and 47 show the same comfort levels as the original model according to EN 15251.

Rooms are always in discomfort during heating season and always in comfort during cooling season.

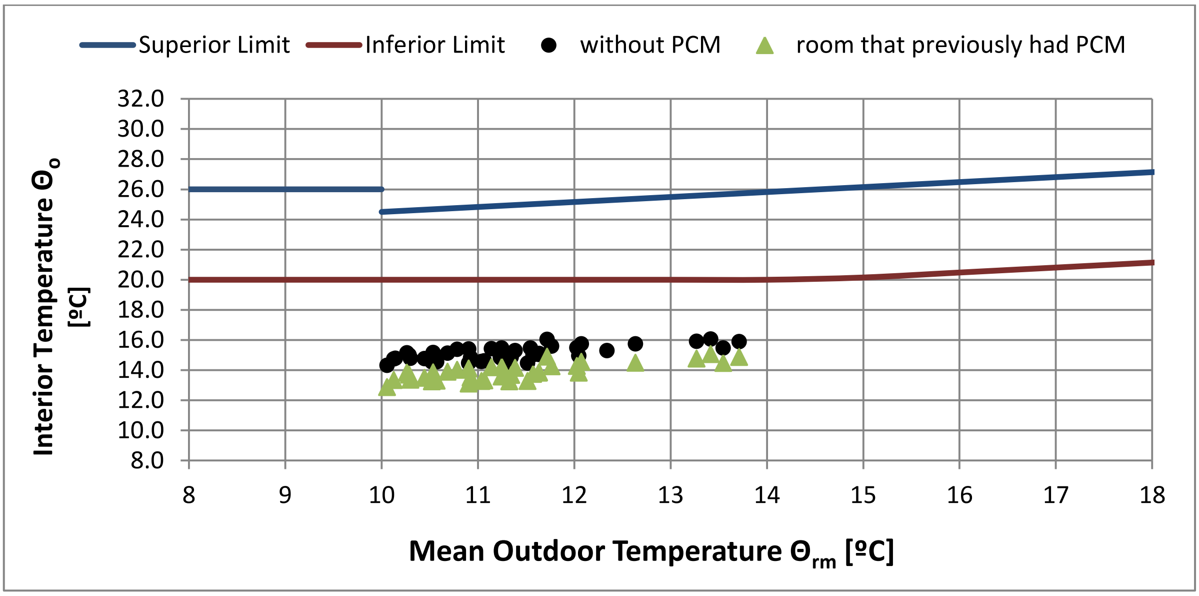

Figure 46- Heating season comfort graph for model without PCM from 01/01/2014 to 15/02/2014 according to EN 15251 limits

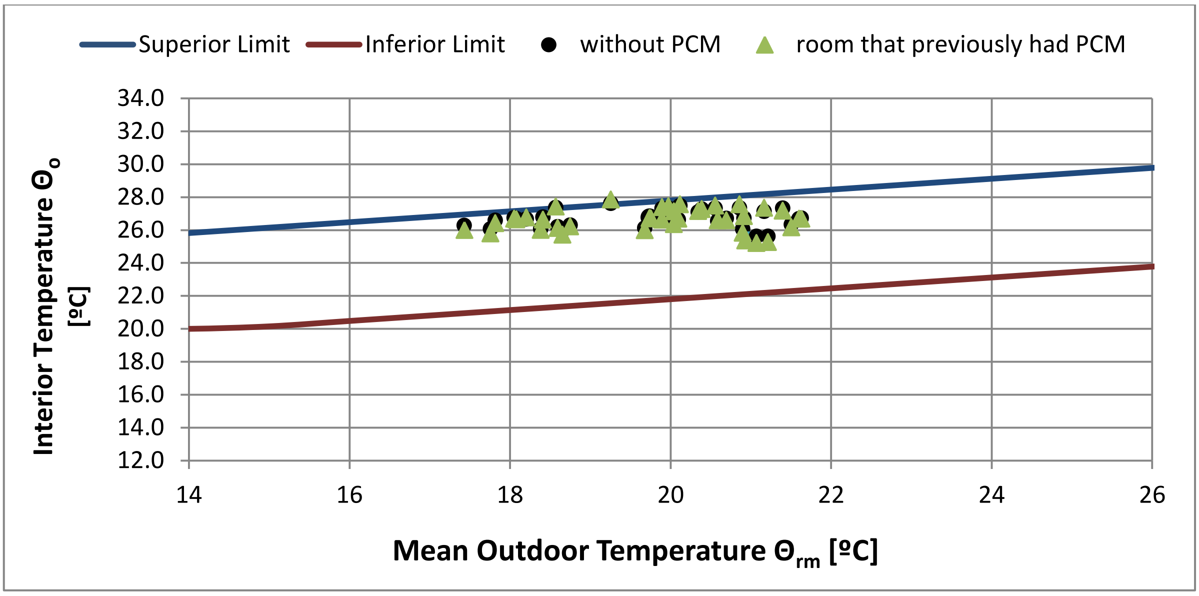

Figure 47- Cooling season comfort graph for model without PCM from 01/01/2014 to 15/02/2014 according to EN 15251 limits

6.3.3. With PCM ClimSel C32

To try and alleviate the high temperatures during the summer, a model with a different kind of PCM that changes phase (or melting point) at a higher temperature was tested. The one used was ClimSel C32 by Climator. It is based on a salt hydrate material instead of paraffin. Its properties are on table 7 and the Temperature vs. Enthalpy graph is located on figure 48 which shows the higher capacity to absorb heat at higher temperatures.

Table 7- Thermal Properties of PCM ClimSel C32 (source: climator.com)

Property	solid	liquid
Thermal Conductivity [W/mK]	0.7	0.5
Specific heat [J/kgK]	2120	
Density [kg/m^3]	2000	
Melting Point [°C]	32	

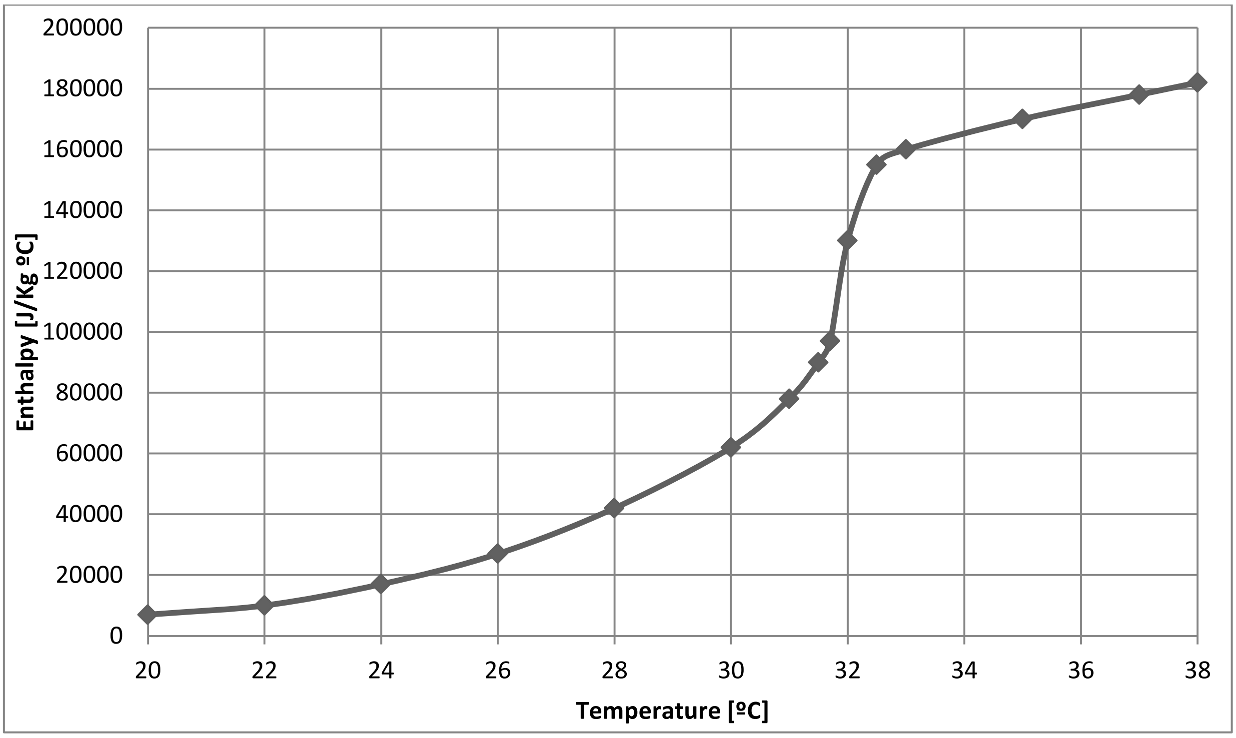

Figure 48- Temperature vs. Enthalpy of ClimSel C32 (adapted from climator.com)

By comparison (fig 40 vs. fig. 49) the different PCM has no effect for lower temperatures due to both having low enthalpy for these temperature ranges. However (fig. 41 vs. fig. 50), the room with PCM is always cooler than the room without and between PCM's there's on average a high peak temperature difference of 0.7 ºC.

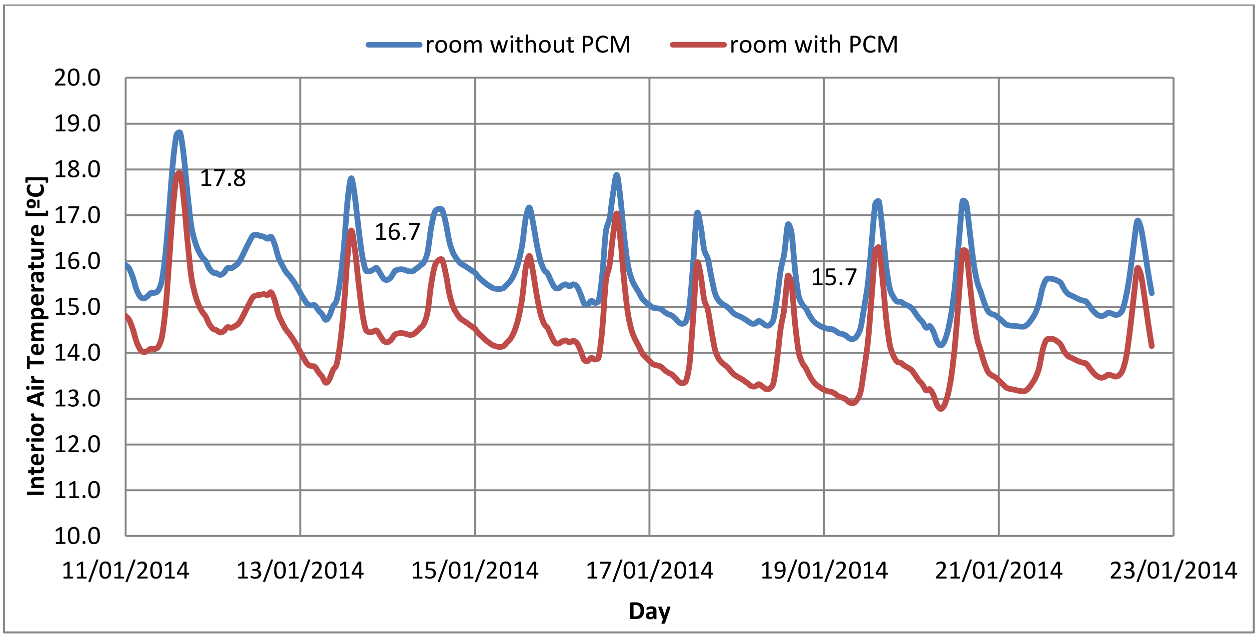

Figure 49- Heating season temperature graph for model with PCM ClimSel C32 from 11/01/2014 to 23/01/2014

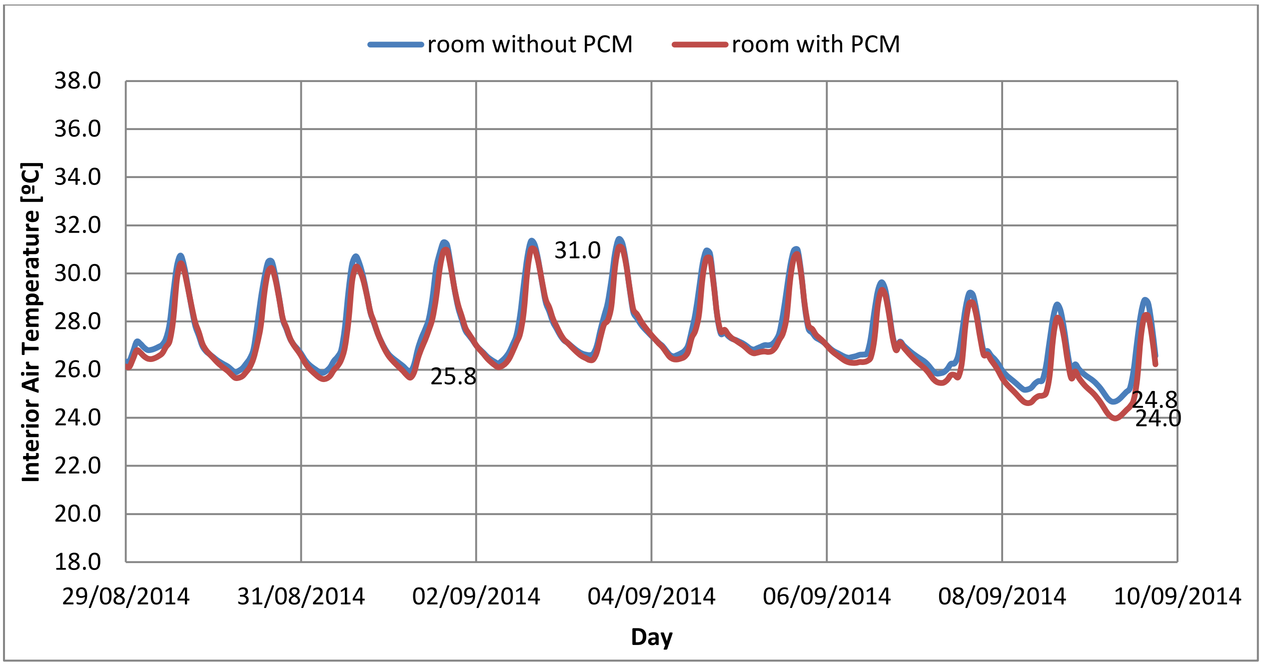

Figure 50- Cooling season temperature graph for model with PCM ClimSel C32 from 29/08/2014 to 10/09/2014

Comfort levels remain relatively the same, as shown by figure 51 and 52.

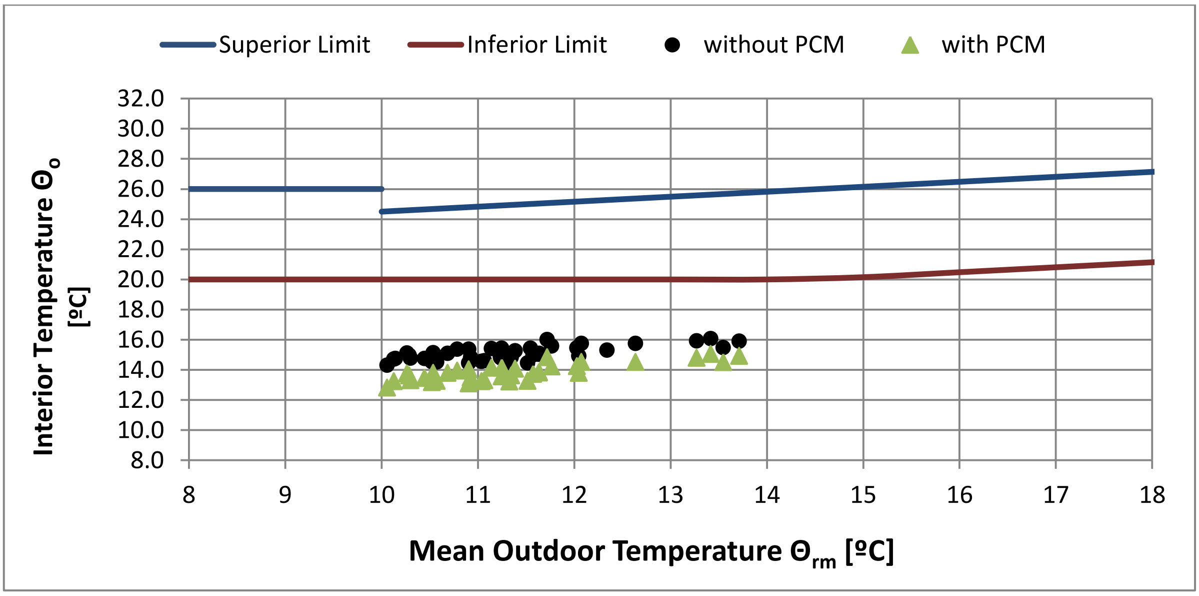

Figure 51- Heating season comfort graph for model with PCM ClimSel C32 from 01/01/2014 to 15/02/2014 according to EN 15251 limits

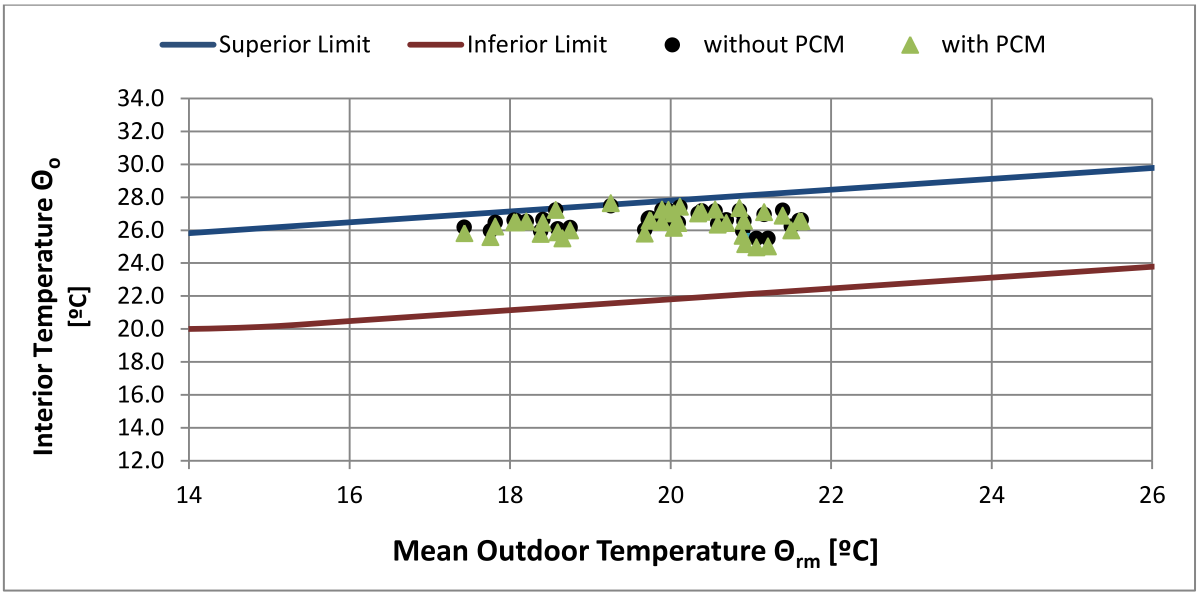

Figure 52- Cooling season comfort graph for model with PCM ClimSel C32 from 01/01/2014 to 15/02/2014 according to EN 15251 limits

Rooms are always in discomfort during heating season and always in comfort during cooling season although with some lower values in the latter.

6.3.4. Exterior walls incorporated with PCM DuPont™ Energain® and PCM room divided in two

To test if the PCM is having a negligible effect due to the low material to room area ratio, PCM was included on all exterior walls and roof. The PCM room was also divided into two separate ones. For reference, the 1st half of the division is the one less exposed to radiation. Figures 53 and 54 show the temperature graph for both seasons.

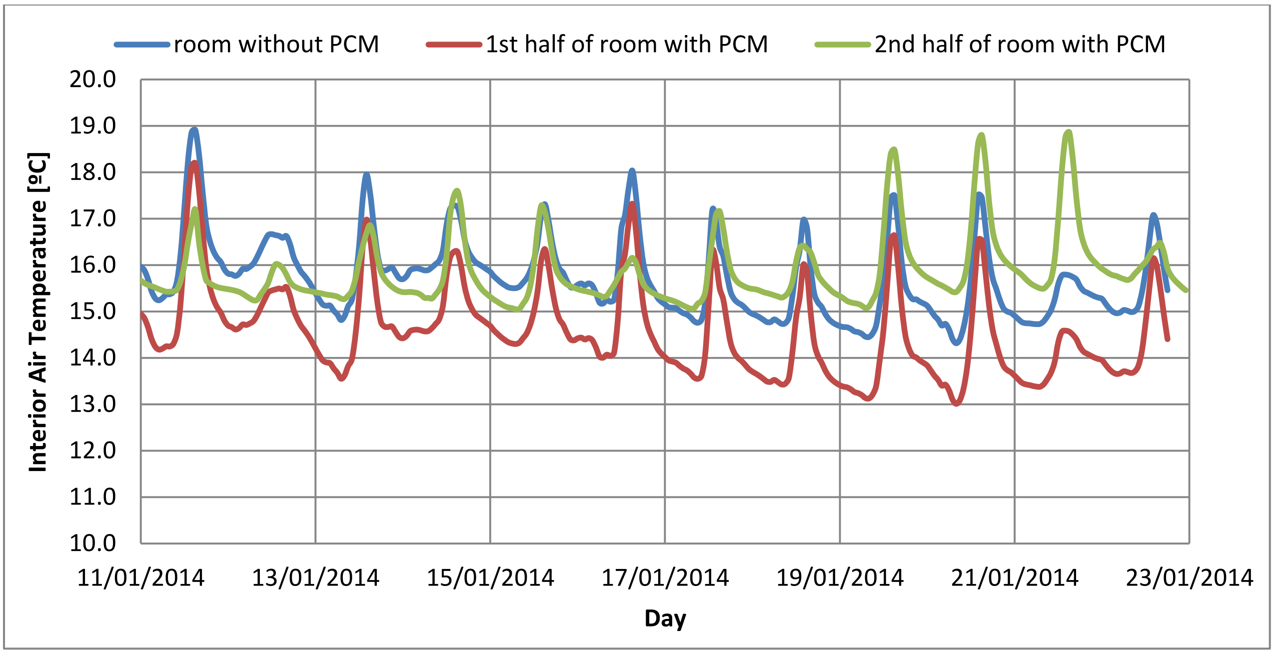

Figure 53- Heating season temperature graph for model with PCM on exterior walls and room division from 11/01/2014 to 23/01/2014

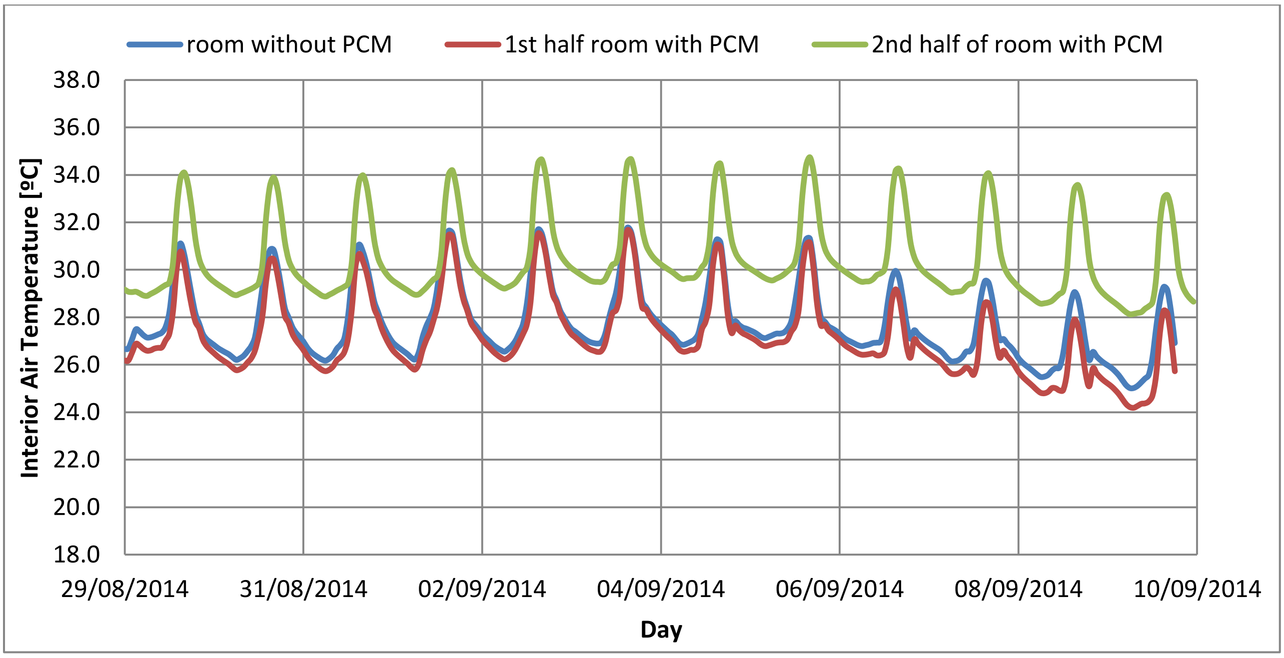

Figure 54- Cooling season temperature graph for model with PCM on exterior walls and room division from 29/08/2014 to 10/09/2014

With a lower room area during heating season, temperature stabilization begins to be noticeable on the room exposed to more radiation. Behaviour for the other rooms remains the same. During cooling season, considering the 2nd half of the room with PCM is exposed to more radiation it is only normal it has higher overall temperatures. There is only a small noticeable delay between temperature peaks.

Figures 55 and 56 show the comfort levels for the room without PCM and the division more exposed to radiation. It's possible to see that heating season comfort has not changed, and cooling season comfort has worsened, and is now 95% of the time in discomfort.

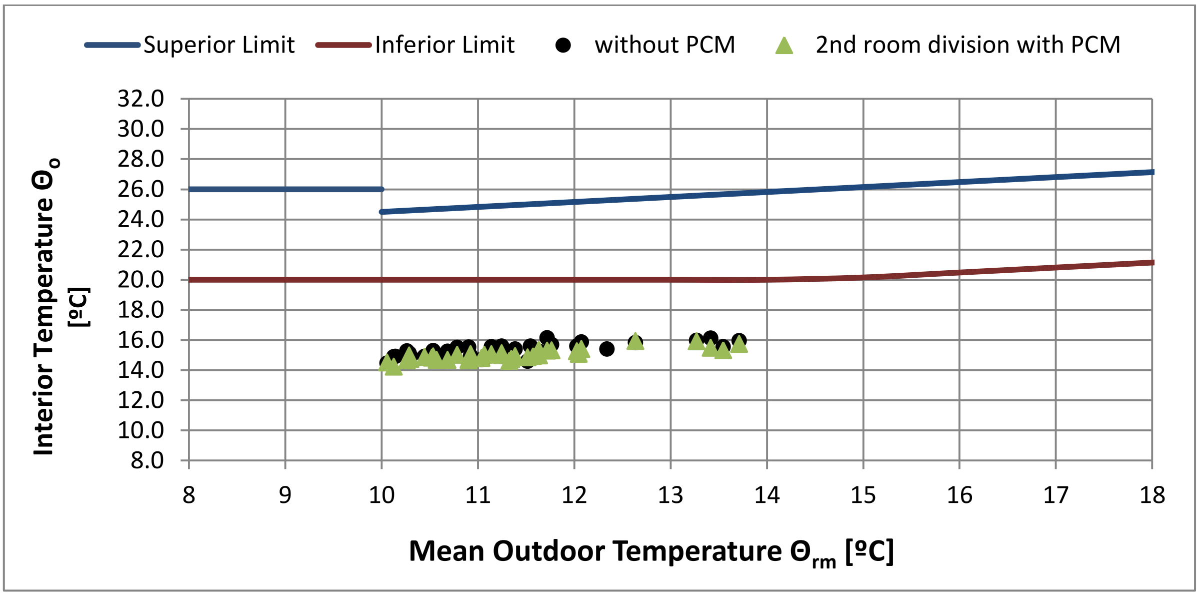

Figure 55- Heating season comfort graph for model with more PCM and room division from 01/01/2014 to 15/02/2014 according to EN 15251 limits

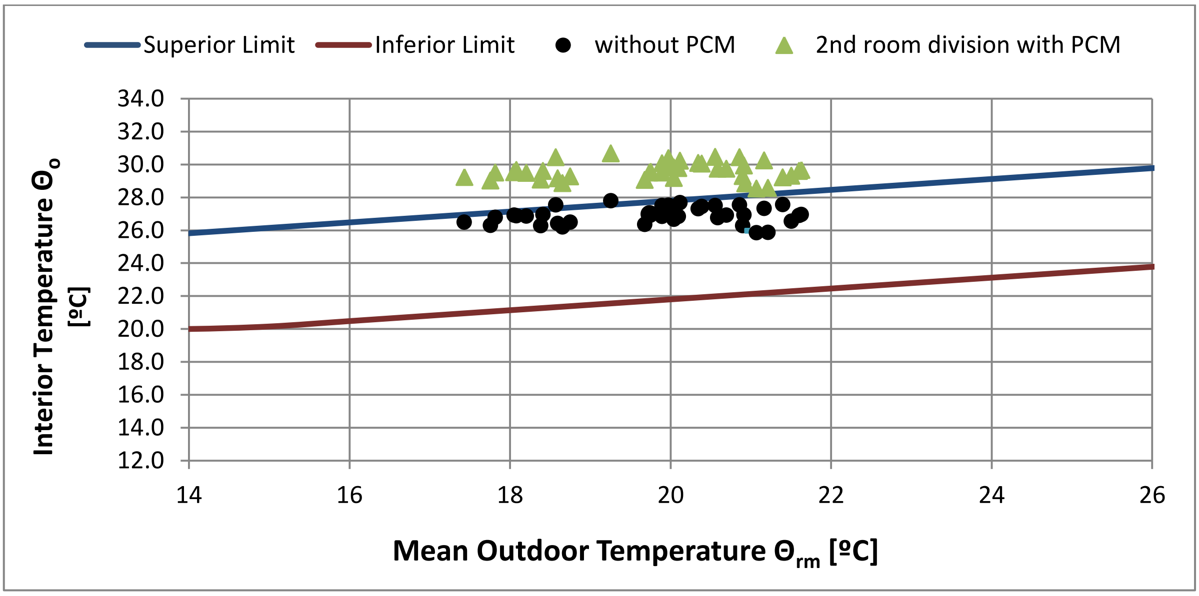

Figure 56- Cooling season comfort graph for model with more PCM and room division from 01/01/2014 to 15/02/2014 according to EN 15251 limits

6.3.5. Optimized model for better overall comfort

Due to the fact that some of the explored options above are not achievable or possible, if there was to be a renovation plan to improve overall comfort, one of the possible solutions would be the following:

- Extra insulating layer on all walls, including interior walls
- Current PCM layers can be kept
- Replace double glazing with triple glazing to reduce the rate at which heat is lost
- Install retractable shading devices only to be used during the summer (figure 57)

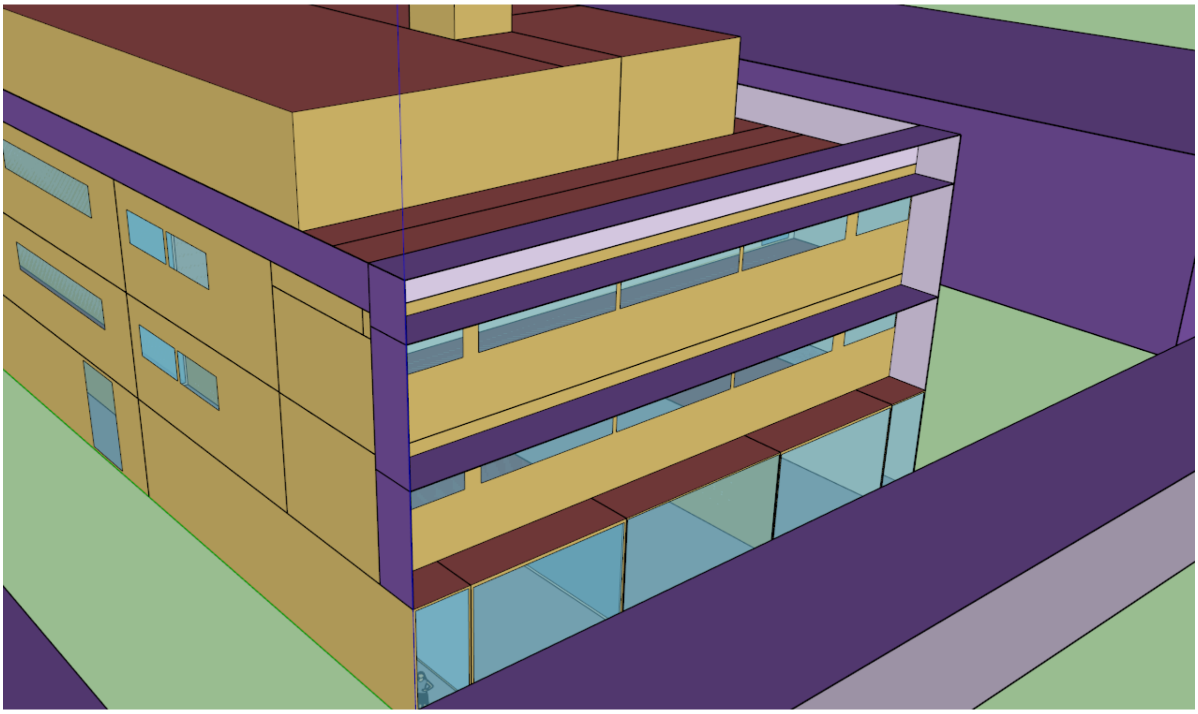

Figure 57- Possible shading device configuration

Figures 58 and 59 show the temperature graphs for both seasons.

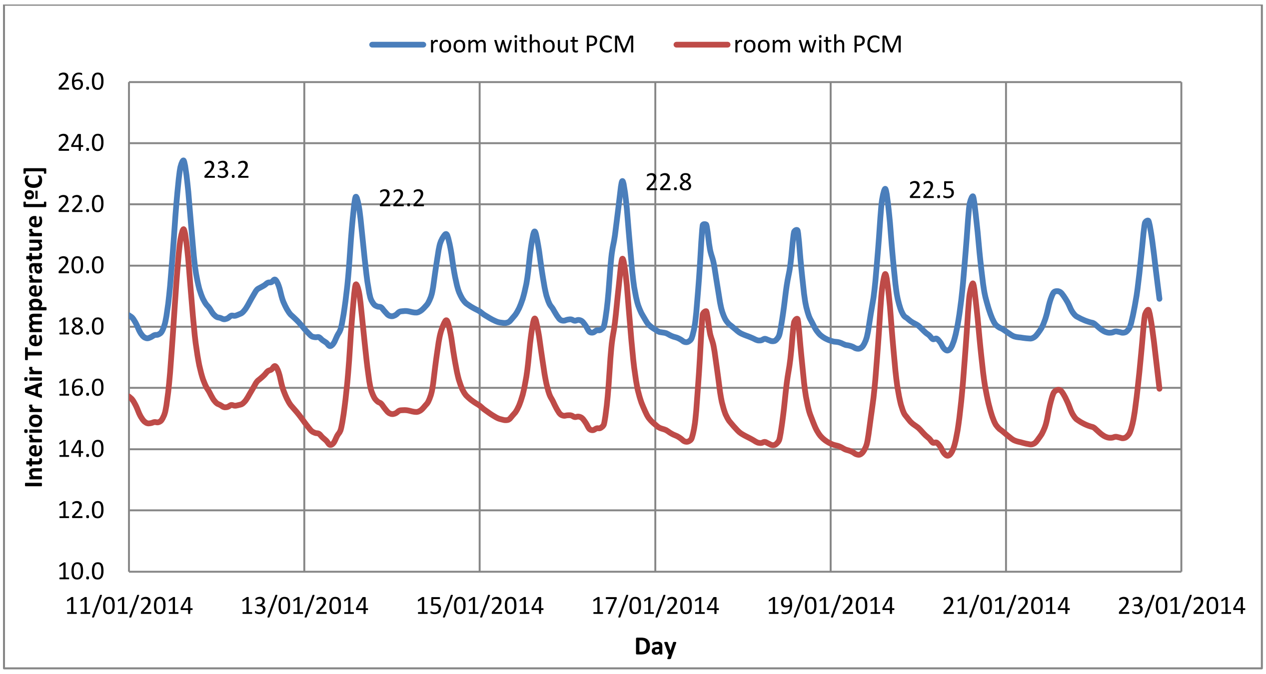

Figure 58- Heating season temperature graph for optimized model from 11/01/2014 to 23/01/2014

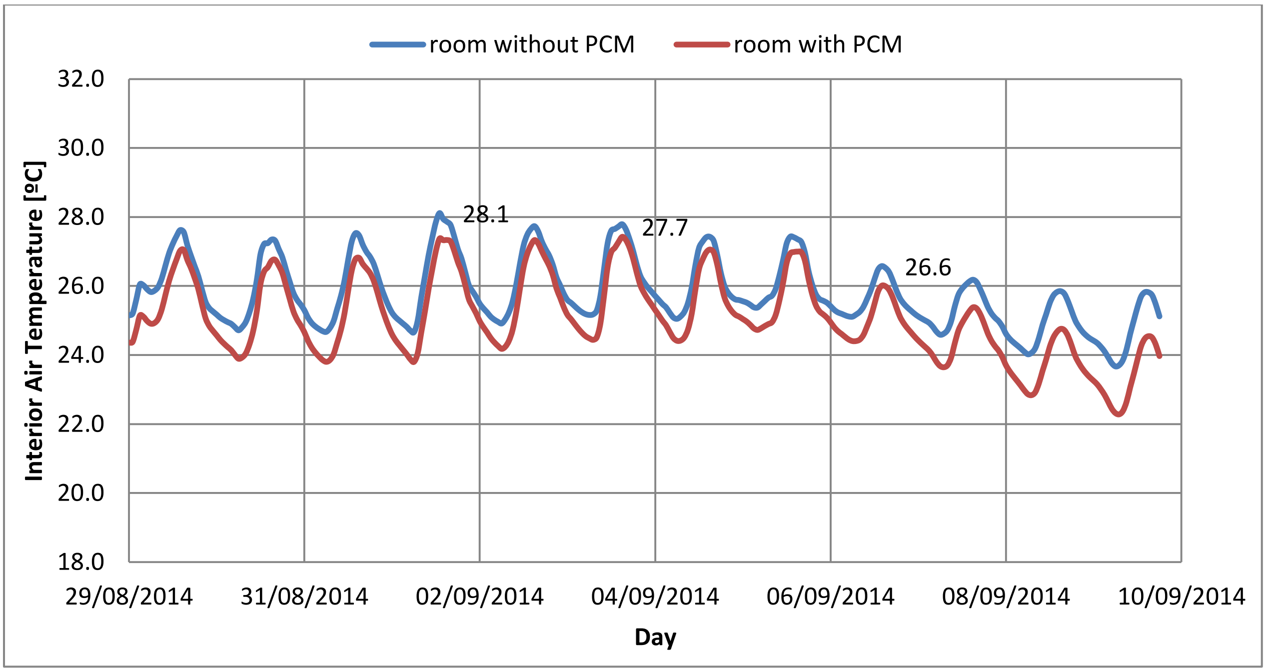

Figure 59- Cooling season temperature graph for optimized model from 11/01/2014 to 23/01/2014

As seen on figure 60, temperature ranges for the heating season and room without PCM are now within more acceptable values (between 18 ºC and 22.5 ºC on average) but the room with PCM is still a lot more colder which means passive methods of retaining heat are not enough and additional measures like mechanical ventilation (HVAC) would be required.

For the cooling season (fig. 61), the shading device is very helpful in reducing temperatures by blocking the sun's radiation and preventing such high temperature peaks as seen on the original model (highest temperature reached of 31.7 ºC), thus also reducing temperature fluctuations.

Figures 60 and 61 show the comfort analysis.

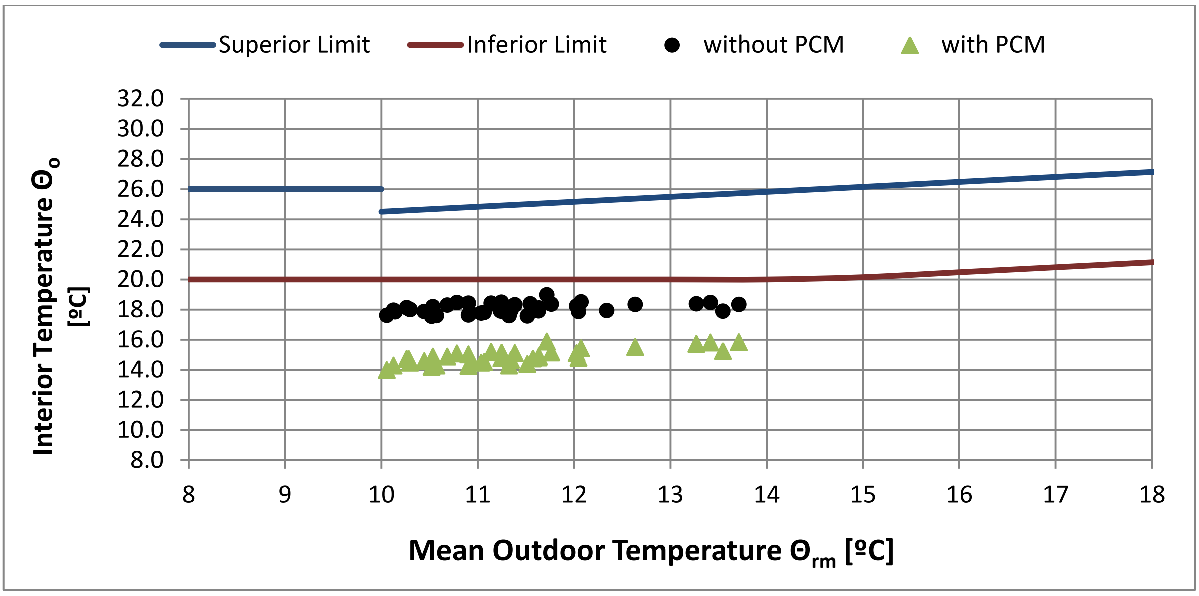

Figure 60- Heating season comfort graph for optimized model from 01/01/2014 to 15/02/2014 according to EN 15251 limits

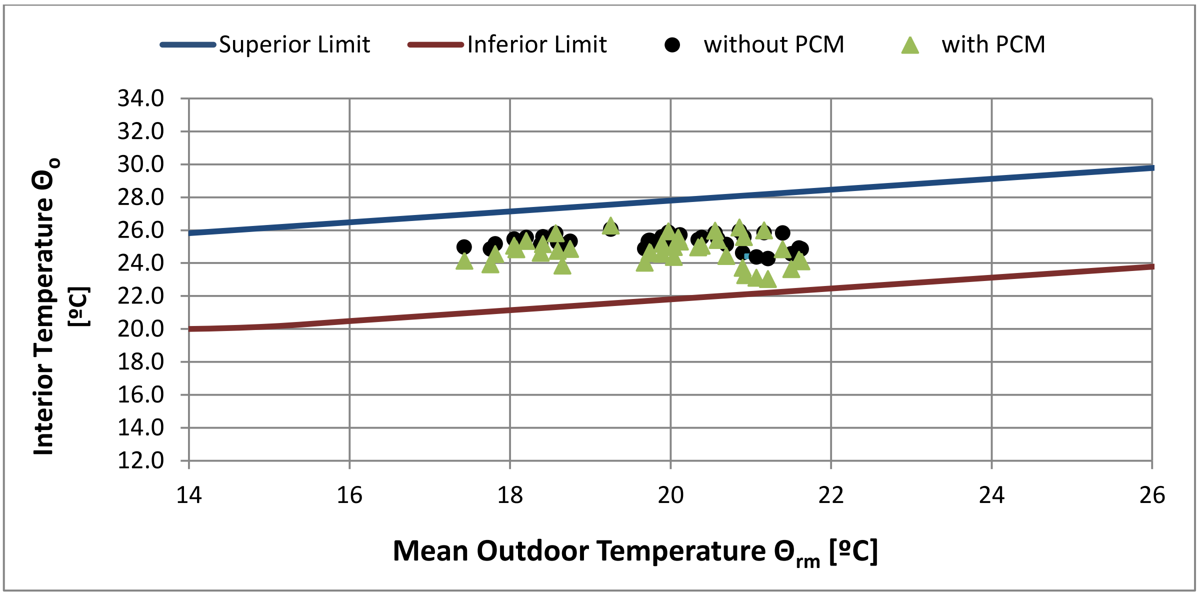

Figure 61- Cooling season comfort graph for optimized model from 01/01/2014 to 15/02/2014 according to EN 15251 limits

As seen on figure 60, the room without PCM is almost within the comfort range, with average daily temperatures being around 18º C to 19º C. Considering that comfort depends on several factors and not just air temperature, and that to some people the temperature of 18º C is considered a comfortable one the room is almost in a good place. Internal gains such as people and equipment could also increase further these temperatures, but were not considered because since it's a work or office environment, there is never enough certainty to how many people will occupy the room, so it's better to analyse as is.

During cooling season (fig. 61), the shading device has achieved better comfort levels by lowering average temperatures.

Chapter 7

Conclusions and Future Work

Chapter 7- Conclusions and Future Work

7.1. General Comments

Although some of the knowledge required was acquired before the dissertation, a lot of definitions and thermal behaviours had to be learned and interpreted, in addition to having to learn how to work with SketchUp, OpenStudio and EnergyPlus which can be very arduous task on its own due to the numerous complications that emerge with each line drawn or each parameter inputted. But in general, the main objectives were achieved.

7.2. Main Conclusions

SketchUp with OpenStudio plugin requires a correct method of drawing and setting up thermal zones, or a lot of errors like surfaces without any properties and others arise. This caused a large amount of time to be spent on the drawing of the building in addition to the time spent in EnergyPlus figuring out which menus need to be filled out and the values for those menus. The benefits however are great, since dynamic simulation allows the user to test out how a parameter affects the thermal behaviour of the building (for example the effect of PCM).

In this study, it was concluded that the PCM or Phase Change Material that was used in the building is only having a slight positive effect in the heating season by increasing the temperatures slightly. In the cooling season the effect is negligible and PCM is not having the desired effect.

For the heating season, the building is always in discomfort according to the standard EN 15251 and for the cooling season it is within the standard’s comfort limits, although the rooms reach high temperatures like 32º C during high peak. For this reason, it’s possible to conclude that the standard is somewhat limited by only considering air temperatures and only the average daily temperatures, meaning that high ranges of temperature (e.g. going from 20º C to 30º C in the same day) could be considered comfortable, but this can cause discomfort because users have to constantly adapt. Another limitation as mentioned before is that high peak temperatures can be considered comfortable because the daily average falls within the limit but this can also cause discomfort.

The change of type of PCM only slightly increased cooling season comfort but not by a lot while the heating season remained the same.

Dividing the room with the PCM and including more PCM where it previously had none, showed a beneficial effect by slightly stabilizing temperatures during the heating season by lowering the maximum temperatures and increasing the minimum temperatures. During the cooling season, this provided the room with a slight delay in temperature peaks. This leads to the conclusion that the rooms in which it was installed have too much area and there is not enough PCM.

To achieve comfort levels, one possible solution, that is also possible for a future renovation, is to add an extra insulating layer to interior and exterior walls, replace double glazing with triple glazing to prevent the loss of heat during the heating season and to install a retractable shading device during the summer to bring the temperatures to more acceptable ranges. In addition, the replacement of the glazing and framework could also improve air tightness and prevent air infiltrations thus increasing the interior air temperature further. Heat gains can also improve on the rooms' comfort but were not considered in this study due to their uncertain nature. This solution may not be the most conventional but is one of the only viable, passively speaking.

The room with PCM did not reach acceptable comfort levels under any condition or model in the heating season (using only passive methods), which warrants the use of mechanical ventilation such as HVAC or a heat recovery system during this season.

7.3. Future Work

Phase Change Materials may be more suited for residential buildings which in general have smaller rooms. A similar study to this one could be conducted on that type of building, with real time information to calibrate the model and obtain more precise results and determine their effect. Paired with this analysis, energy consumption in buildings can also be taken into consideration. Some standards like PassivHaus have strict consumption requirements, and PCM could be a valid method of increasing thermal inertia of buildings to reduce mechanical ventilation loads.

The current methods of determining thermal comfort are not ideal since they mostly only take into consideration one or two parameters like air temperature, distance to heat sources and others. Although difficult, a physocological study could be conducted to determine the most important factors that influence comfort on people and create a more precise method that takes these into consideration (e.g. 1º C variation in 5 to 10 minutes can cause discomfort.

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Annex A

Product Datasheet of Temperature and Humidity Sensor ‘Testo 174H’


testo
Committing to the future
testo 174H
Reliable humidity and temperature monitoring
... because you don't know until you measure
NEW!
Free logger software download at:
www.testo.com
Accurate and reusable
humidity and temperatue monitoring
• View • Analyze • Report
testo
174H
45.3
%rH
Go

Temperature and humidity measurement with the testo 174H mini data logger

Actual size

- Humidity sensor with proven long-term stability
- Secure data protection, even with drained battery
- Large memory: up to 16,000 values
- Displays both current temperature or humidity value
- Large measuring range: -22 to +158 F, 0 to 100% RH
- Alarms easily viewed on display
- Data transfer to the PC via USB interface
- Measuring cycle: 1 min. to 24 hr. (user selectable)

ISO 9001 TESTO QUALITY certified

testo 174H mini data logger, 2-channel, incl. wall bracket, battery (2 x CR 2032 lithium) and Certificate of Conformance

Part No. 0572 6560

The testo 174H mini data logger monitors your indoor climate conditions, such as in warehouses, offices, schools, new construction, production areas, even confined spaces.

testo 174H Starter Kit *, includes...

testo 174H mini data logger set, 2-channel, incl. USB interface for programming and reading out the logger, wall bracket, battery (2 x CR 2032 lithium) and Cert. of Conformance

Order. No. 0572 0566

* Download ComSoft Basic V5 software free of charge at: www.testo.com, or order software CD 0572 0580 separately

testo 174 logger software comsoft Basic V5

With the ComSoft testo 174 software the data logger can be configured and read out easily via USB interface. Measurement data can be analyzed quickly and intuitively.

0981 5764 /Sd/XX/Q/03.2010 USA Subject to change without notice.

Technical data

Probe type	Internal NTC temperature sensor and internal capacitive humidity sensor
Measuring range	0 to 100 %RH, -4 to +158 F (-20 to +70 °C)
Humidity accuracy	±3 % RH (2 %RH to 98 %RH) ±1 digit +0.03 %RH/K
Temperature accuracy	±0.5 °C (-20 to +70 °C)
Resolution	0.1 % RH, 0.1 °C
Operating temperature	-4 to +158 F (-20 to +70 °C)
Storage temperature	-40 to +158 F (-40 to +70 °C)
Battery type	2 x 3 V button cell (2 x CR 2032 lithium), user replaceable
Battery life	approx. 1 year (15 min measuring cycle, +25 °C)
Protection class	IP20
Meas. cycle	1 min. to 24 hr (user programmable
Memory	16,000 readings
Software	Operating System: Windows XP, Vista, Win7

Accessories

	Order No.	
USB interface for programming and reading out testo 174T and testo 174H loggers	0572 0500	
ComSoft Basic V5 CD (if free download from website is not desired)	0572 0580	
Lithium battery CR 2032 button cell, please order 2 batteries per logger	0515 0028	
NIST calibration certificate humidity, 11.3 % RH; 75.3 % RH at +25 °C/+77 °F; per channel/instrument	400520 2601	
NIST calibration certificate temperature; 3 standard points per channel/instrument	400520 1901	

testo inc. 40 White Lake Road Sparta, New Jersey 07871
Telephone: Toll Free 1-800-227-0729 862-354-5001 Fax: 862-354-5020
E-mail: info@testo.com
Web: www.testo.com

Annex B

Product Datasheet of DUPONT™ ENERGAIN™

The miracles of science™

DUPONT™ ENERGAIN®

Energy-saving thermal mass systems

THERMAL MASS PANEL

Descriptive properties		Unit	Value
Thickness		mm	5.2
Width		mm	1000
Length		mm	1198
Area weight		kg/m²	4.5
Aluminium thickness (sheet)		µm	100
Aluminium thickness (edges)		µm	75
Thermal properties	**Test Method**		
Paraffin loading	Comparative test by DSC	%	60
Melt point (paraffin)	DSC method (1°C/min)	°C	21.7
Latent heat storage capacity (0°C - 30°C)	DSC method (1°C/min)	kJ/kg	> 70
Total heat storage capacity (Temperature range 0°C to 30°C)	DSC method (1°C/min)	kJ/kg	~ 140
Physical properties			
Aluminium sheet delamination force	Internal DuPont test method	N/cm	> 20
Conductivity solid	BS EN 12667-2001	W/(m.K)	0.18
Conductivity liquid	BS EN 12667-2001	W/(m.K)	0.14
Flash Point (paraffin)	ASTM D56	°C	148

PRODUCT DESCRIPTION

The panel is a fine mixture of ethylene based polymer (40%) designed by DuPont and paraffin wax (60%) laminated on both sides with a 100 µm aluminium sheet. The edges are closed with a 75 µm aluminium tape.

REACTION TO FIRE

Single-flame source test	EN 11925-2	Class E
Surface spread of flame test	BS476-7	Class 1

DURABILITY

Predicted to be durable for the life-time of a building

Chemically inert with most materials

ALUMINIUM TAPE

Descriptive Properties	Unit	Value
Thickness	µm	75
Width	mm	50

DuPont patented technology

All values correspond to average results obtained in our laboratories and outside institutes and are indicative.

The right is reserved to make changes at any time without notice.